Biblid: 1450-5029, (2023) 27; 2; p 58 - 62
UDK: 664.336
DOI: 10.5937/jpea26-46734

Original Scientific Paper
Originalni naučni rad

DECARBONIZING THE MARGARINE PRODUCTION PROCESS WITH ROOFTOP PHOTOVOLTAICS AND COGENERATION

DEKARBONIZACIJA PROCESA PROIZVODNJE MARGARINA KORIŠĆENJEM KROVNIH FOTONAPONSKIH PANELA I KOGENERACIJE

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ABSTRACT

The paper proposes a methodology for defining the optimal solution for the integrated usage of cogeneration and rooftop photovoltaics. The purpose is to minimize CO_2 emissions in industrial plants. The methodology is founded on the integral use of energy audit techniques (analyzing energy and material flows in a production process and the dependence of electricity and heat consumption on a production volume) and mathematical optimization (linear programming). In accordance with the obtained consumption profiles, technical limitations, and legal regulations, the potential for installing rooftop photovoltaic (PV) panels at appropriate locations and the implementation of appropriate cogeneration technologies were analysed. The proposed methodology was tested on a local margarine production facility. The integrated application of cogeneration (gas engines) and photovoltaics can reduce the current CO_2 emission by 56% if PV panels are installed on the entire accessible rooftop surface, i.e. up to 44.5% if 150 kW PV panels are installed as the new national regulation proposes.

Keywords: *food industry, decarbonization, PV panels, cogeneration.*

REZIME

U radu je predložena metodologija za definisanje optimalnog rešenja integrisane primene kogeneracije i krovnih fotonaponskih panela, sa ciljem minimizacije emisije CO_2 u industrijskom preduzeću. Metodologija se zasniva na integralnom korišćenju tehnika izrade energetskih pregleda (analize tokova energije i materijala u proizvodnom procesu i definisanja zavisnosti potrošnje električne energije i toplote u funkciji od obima proizvodnje) i matematičke optimizacije (linearno programiranje). Na osnovu kreiranih profila potrošnje, tehničkih ograničenja i zakonske regulative razmatrana je mogućnost za postavljanje krovnih fotonaponskih PV panela na odgovarajućoj lokaciji i implementacija odgovarajućih kogeneracionih tehnologija. Predložena metodologija je primenjena i testirana na postrojenju za proizvodnju margarina. Integrisanom primenom kogeneracije (gasnih motora) i PV panela, ukupno smanjenje emisije CO_2 bi iznosilo 56% ukoliko bi PV paneli bili instalirani na kompletno dostupnoj površini krova, odnosno do 44,5% ukoliko bi bilo insalirano 150 kW u skladu sa novopredloženom nacionalnom regulativom.

Ključne reči: *prehrambena industrija, dekarbonizacija, fotonaponski paneli, kogeneracija.*

INTRODUCTION

After the Paris Agreement (COP21) and United Nations Climate Change Conference (UNFCCC), which focused on mitigating the effects of global warming, the defined limit for temperature increase is now set at +1.5°C with respect to the pre-industrial levels and is not to surpass 2°C. In order to limit temperature increase at 1.5°C, it is necessary to reduce GHG emissions by 50% during the following decade and reach net zero CO_2 emission by the middle of the 21st century. Consequently, COP27 in Egypt ended with the conclusion that the use of the most modern technology and ecologically acceptable methods is a priority (*Arora P. and Arora N., 2023; Yadav et al., 2023*). It has been estimated that about 26% of the global greenhouse gases (GHG) originate from industries (*IEA, 2023*). If industries fail to reduce their emissions, it is very likely that the aforementioned goal will not be accomplished.

The food industry is a moderately intensive industrial sector in terms of energy consumption (*Morvay and Gvozdenac, 2008*). However, the food industry is one of the sectors with significant CO_2 emission, due to the rapid and substantial increase in the use of energy, especially for cooling processes, steam generation and utilisation, and pasteurization (*Gerres et al, 2019; Josijević et al., 2020*). The implementation of energy-efficient technologies and renewable sources can contribute to the decarbonization of entire production processes to a great extent. One review paper systematizes 78 novel, commercially available and experimental solutions for decarbonizing production processes in the food industry (*Sovacool et al., 2021*). Taking into consideration that these businesses operate with relatively low margins, decarbonization processes can make them more competitive in the market. The recommended measures for reducing CO_2 emissions will decrease energy costs (*Živković et al., 2022*) and potential costs for environmental taxation, i.e. for carbon taxes (*Đurišić and Škrbić, 2022*).

The global paradigm of industrial decarbonization in the food industry primarily relies on electrification processes, i.e. supplying plants with more electricity derived from renewable sources (RES). The transformation of solar energy into electricity with PV (photovoltaic) panels is one of the leading methods for using RES locally (*Čorba et al., 2023*). Whether it is possible to use PV panels depends mostly on the technical requirements for their installation (*Dragićević et al., 2022*). Taking into consideration the limited availability, prices and desire to keep ground vacant, PV panels are primarily installed on the available rooftop surfaces of production facilities (*Lee and Trcka, 2012*). However, food production and processing operations require more electricity than one industrial plant can generate with PV panels, so the emission factor of the connected grid still has a significant share in total emission levels (*Gordic et al, 2023*). Consequently, this paper advocates for the concurrent use of CHP (Combined Heat and Power) as the most effective technology for the simultaneous generation of both electricity and heat. The paper proposes the methodology for analyzing technical solutions and identifying the most optimal one, i.e. the one which would enable the most suitable form of the integrated application of rooftop PV panels and cogeneration.

MATERIAL AND METHOD

An analysis of whether it is possible to integrate rooftop PV panels and CHP, as well as the selection of the most suitable solution, is crucial for accomplishing maximum effects. The methodology for analyzing such possibilities has been developed by the authors (Figure 1). The first step is a detailed energy auditing of industrial processes (according to ISO 50002). Energy auditing relies on taking detailed measurements of the process parameters in order to locate energy consumption centres. Such measuring is conducted with equipment that can be found in a plant and/or with portable equipment. The audit has to determine: (1) the functional dependence of energy consumption (electricity and fuel) on production volume, (2) monthly profiles of electricity and heat-energy consumption, and (3) annual emission of CO_2 (i.e. carbon footprint). To determine the potential for using PV panels and CHP, numerous factors have to be taken into consideration. The main indicators include: a profile of electricity consumption, allowed power, available rooftop surface, and a possibility to acquire the prosumer status. According to the current legislation, the power of an installed PV panel cannot surpass the allowed power. The proposal of the new legislation limits installed power at 150 kW for the plants which seek to have the prosumer status. It should become effective on the 1st of July, 2024 (*Ministry of Mining and Energy, 2023*).

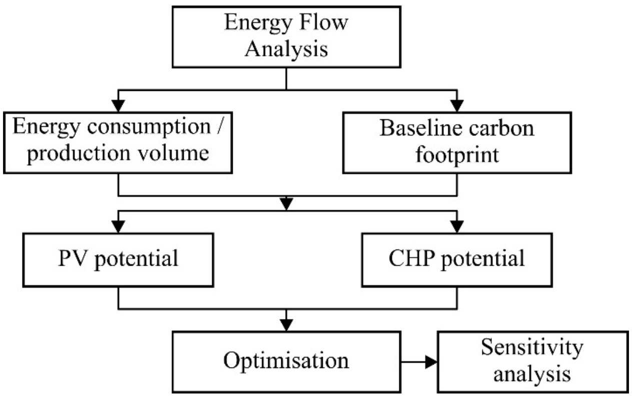


Fig. 1. Methodology for determining an optimal solution

The surface available for installing PV panels and construction parameters has an impact on the power that could technically be generated. For any selected surface, a profile of electricity production per month can be created with specialized databases (such as PVGIS, and K2 system Base) based on the arrangement of panels and their orientation and slope. The profiles of electricity production from PV panels are the foundation for selecting a suitable solution. A comparison of this profile with a profile of electricity consumption can also indicate when a plant can be expected to distribute excessive amounts of electricity to the electro-distributive network. On the other hand, it can indicate when a plant can be expected to need electricity from the network. Since the prosumer status imposes a strict requirement that a prosumer can not make a profit from distributing excessive electricity to the network at the end of the accounting year, the total annual electricity production from PV panels and CHP should not surpass the annual needs of a plant (production processes and other consumers).

A profile of consumption/heat load is equally relevant. Since efficiency varies with load changes, using CHP at a constant load (with minimum variations) is recommended during its entire operation. In the production processes which use process heat, CHP technology can be used during the entire year. The only limitation in this case is that heat production should be in compliance with a heat consumption profile. In contrast with electricity which can be distributed to the local network, the excessive heat produced by a CHP unit is released to a sewerage system as hot water. Alternatively, it is possible to install reservoirs for temporary heat storage. However, plants usually struggle to provide vacant space needed for their storage. Consequently, it is recommended to generate enough heat to satisfy the base or intermediate loads of a plant. Peak demands and peak loads are satisfied by using the existent heat sources, i.e. boilers.

Taking into consideration all the aforementioned factors, a mathematical optimization model (linear programming) was developed. The model defines the optimal solution based on the given objective function. The mathematical model was defined by taking into consideration electricity sources (*chp*, *pv*, and *grid*) and two periods during a year: *jz*, i.e. heating season, and *jl*, i.e. non-heating season. Since the final goal is to decarbonize a production process, the minimization of CO_2 emission is selected as the objective function. It can be presented as follows (1):

$$z = \sum_i \sum_{jz} x_{i,jz} \cdot f_i^{CO_2} + \sum_i \sum_{jl} x_{i,jl} \cdot f_i^{CO_2} \tag{1}$$

where: z [t] - the objective function, i.e. CO_2 emission and f^{CO_2} [t/kWh] - an emission factor of an i source. with the following boundaries:

$$\sum_i x_{i,jz} \le E_{jz} \tag{2}$$

$$\sum_i x_{i,jl} \le E_{jl} \tag{3}$$

$$\sum_i 1.6209 \cdot x_{chp,jz} \le Q_{jz} \tag{4}$$

$$\sum_i 1.6209 \cdot x_{chp,jl} \le Q_{jl} \tag{5}$$

$$\sum_i \sum_{jz} x_{i,jz} + \sum_i \sum_{jl} x_{i,jl} = TEE \tag{6}$$

$$x_{chp,jz} = x_{chp,jl} = const \tag{7}$$

where: E [kWh] – electricity consumption in *jz* and *jl* months; Q [kWh] – heat needed in *jz* and *jl* months; TEE [t/kWh] – total annual electricity consumption;

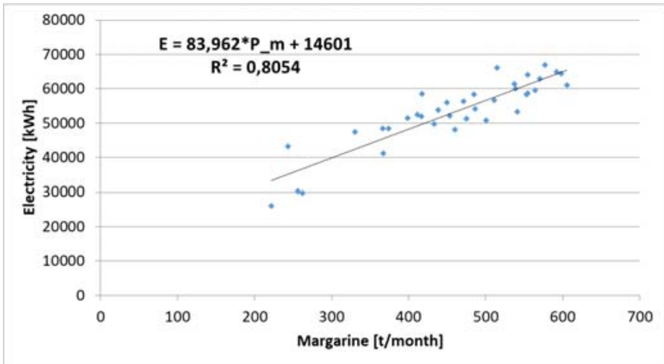
Electricity consumption E [kWh] in *jz* and/or *jl* months is a function of the production volume Pm [t] during the given time period:

$$E_{jz} = f(Pm_{jz}) \wedge E_{jl} = f(Pm_{jl}) \tag{8}$$

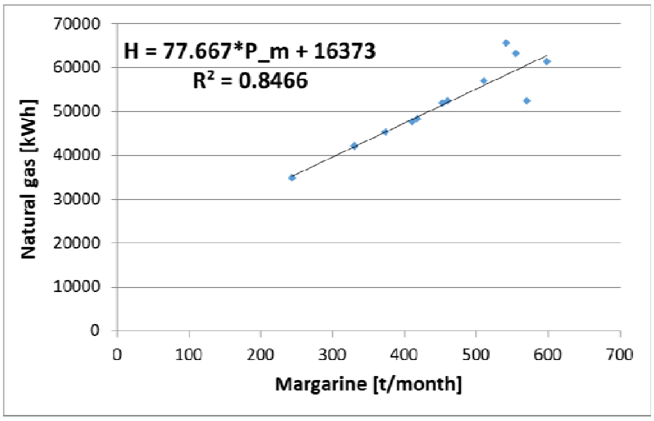
The obtained optimal solution, i.e. obtained profiles for (1) electricity generated from PV panels and CHP technology and (2) for heat acquired with CHP technology, depend on production volume. If volumes change, profiles of electricity and heat production will also change in accordance with the defined dependences. Consequently, a sensitivity analysis should be the last step of the proposed methodology.

RESULTS AND DISCUSSION

The developed methodology is used in a case study of a local margarine production plant. Based on the conducted energy audit and the data collected on monthly electricity consumption, monthly natural gas consumption and monthly production volume for three consecutive years, the function of monthly electricity consumption [kWh] and natural gas used to generate heat [kWh] dependences on margarine production volume [t] were obtained (Figure 2). Data on the consumption of natural gas for space heating was excluded in Figure 2a.



(a)



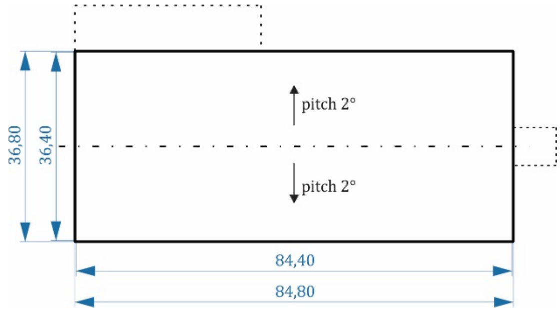
(b)

Fig. 2. Electricity consumption (a) and natural gas consumption (b) depending on the production volumes

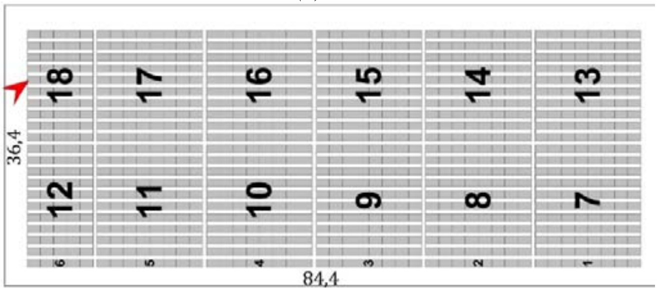
The presented functional dependences were further used to determine the profiles of monthly electricity and heat consumptions for the given production volume. The annual emission of 620 tCO_2 is calculated based on the known annual energy consumption values for the given production volume (712.83 MWh of natural gas and 644 MWh of electricity) and the following emission factors: 0.18 t/MWh for natural gas, 0.04 t/MWh for PV, and 0.763 t/MWh for grid electricity (*Gordic et al., 2023*).

The value for the maximum power that can be installed (311 kW) is calculated via the analysis of the available rooftop surface and multiple possible PV panel arrangements (Figure 3). It is considerably lower than the allowed power and, hence, in accordance with the legislation. The presented PV system, if installed on the rooftop of this plant, could generate 327 MWh of electricity.

If the installed power is limited to 150 kW, the PV panels can generate 162.5 MWh of electricity. Monthly variations in electricity production are presented in Figure 4. In both cases, the PV electricity should not surpass monthly consumption for the given production volume, so it would be necessary to include additional electricity either from the grid or from a CHP system. Since the facility is connected to the gas network and uses natural gas for heating, the possibility of using a CHP unit with an engine with internal combustion (a gas engine) was considered.



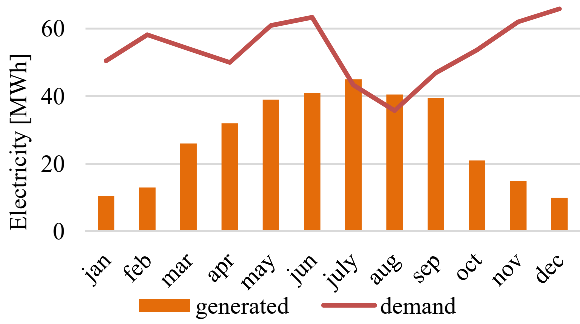
(a)



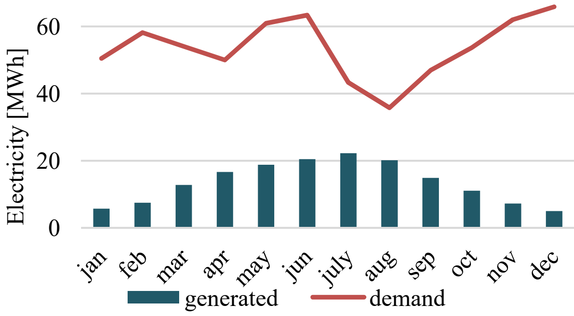
(b)

Fig. 3. Rooftop size available for installing PV panels (a); Proposed arrangement and module grouping (b);

If the installed power is limited to 150 kW, the PV panels can generate 162.5 MWh of electricity. Monthly variations in electricity production are presented in Figure 4. In both cases, the PV electricity should not surpass monthly consumption for the given production volume, so it would be necessary to include additional electricity either from the grid or from a CHP system. Since the facility is connected to the gas network and uses natural gas for heating, the possibility of using a CHP unit with an engine with internal combustion (a gas engine) was considered.



(a)



(b)

Fig. 4. The estimated annual electricity production from PV panels: (a) 311 kW and (b) 150 kW

By using mathematical optimization with set input parameters and limitations, the quantity of electricity that can be derived with PV panels and CHP was obtained (Figure 5). In this case, the option that the facility is not a prosumer and that installed power is 311kW was considered. The heat generated every month from a CHP unit (a gas engine with nominal electric power of 50 kWe and heat power of 65 kWt) amounts to 36.22 MWh. For the first scenario (311 kW PV panels and 40 KWe gas CHP unit), the annual CO_2 emission would be 146 tCO_2. In other words, the emissions from electricity consumption would be reduced by 70.3%. For the second scenario (150 kW PV panels and 40 kWe gas CHP unit), the annual CO_2 emission would be 223.6 tCO_2. The reduction in the emissions from electricity would be 54.5%.

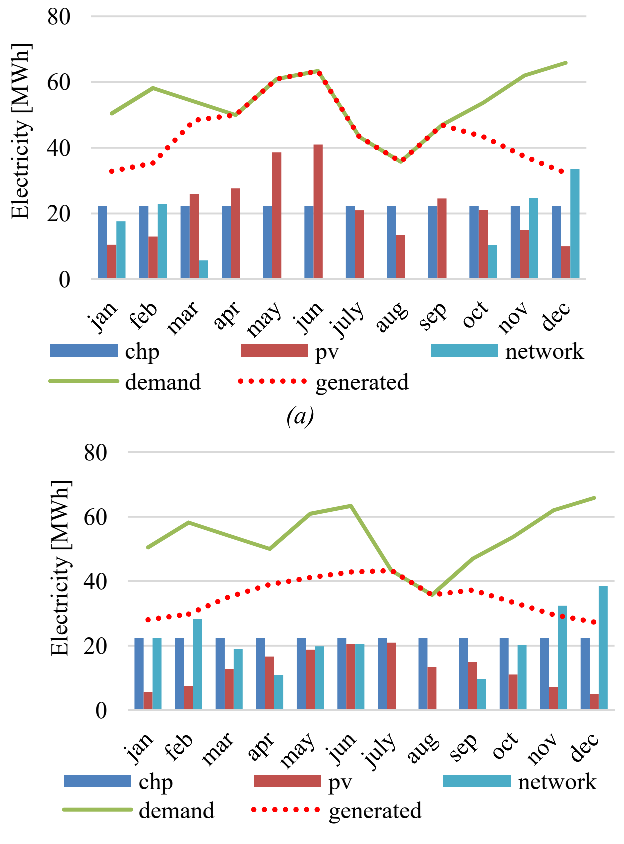


Fig. 5. The estimated annual electricity production from PV panels and CHP: (a) PV – 311 kW without prosumer status; (b) PV – 150 kW;

On the other hand, if the facility had the prosumer status and the installed power of 311 kW, it would be able to distribute the excess electricity to the grid during a certain period of a year. This contribution would be sufficient to cover the plant's electricity needs from October to December. This means that the instalment of such a system would result in consuming energy from the network and paying for it only in January and February (Figure 6). In this case, the emission of CO_2 would reach 141.9 tCO_2. In other words, the emissions from electricity would be reduced by 80.53%.

Due to the need to increase the production volume, three possible scenarios were analyzed, i.e. 125%, 150%, and 175% of the current production volume. Since energy consumption depends on production volume, it is crucial to analyze the potential solution that would fit the new circumstances. In all scenarios, the value of 311 kW for PV panels was adopted. In all cases, there would be an increase in heat demand, which would impact the selection of a CHP unit. If the production volume increases by 25%, a CHP unit should have a nominal electric power of 50 kWe and heat power of 79 kWt. For 50% and 75% growth of production volume, the CHP units should be 55 kWe/85 kWt and 60 kWe/95 kWt, respectively. The emissions resulting from electricity consumption for scenarios are given in Table 1.

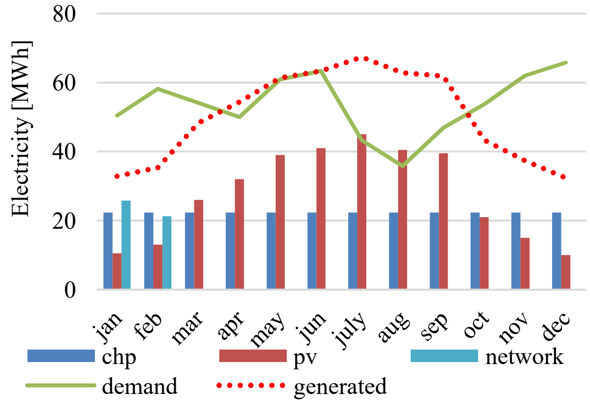


Fig. 6. The estimated annual electricity production from PV panels (311 kW) and CHP with prosumer status

Table 1. The impact of increasing production capacity on the reduction of emissions due to electricity consumption

Production capacity	Emission without PV + CHP [tCO2]	No prosumer [tCO2]	Changes [%]	Prosumer [tCO2]	Changes [%]
100%	491.65	146.18	-70.27%	97.47	-80.18%
125%	579.16	191.98	-66.85%	107.18	-81.49%
150%	666.67	250.89	-62.37%	114.51	-82.82%
175%	754.17	218.65	-71.01%	122.50	-83.76%

As can be seen in the table above, regardless of whether the plant has prosumer status, the expected reductions of CO_2 emissions are considerable (above 60%).

CONCLUSION

The integral application of photovoltaics and CHP in the food industry can result in significant CO_2 emission reductions. In our case study, the plant can achieve reductions of 44.5%, i.e. 56%, if there are no changes in production capacity, grid electricity emissions factor and space heating demand. The emission could be further reduced by substituting natural gas with fuels which have lower emission factors (biofuels). The existent mathematical model can be easily adapted to include financial parameters, such as net annual saving, payback period, net present value, and net present value quotient.

It should be also emphasized that the approach is slightly different from the global paradigm of industrial decarbonization in the food industry. The proposed concept is not related to the electrification of thermal processes, since the electricity from the Serbian grid can not be considered as „green". The process of electrification will be meaningful only when the RES transition of electricity production in Serbia is more advanced. Considering the reduction of emissions obtained with the approach, the proposed solution presents a transitional solution towards net zero production facilities.

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Received: 25.09.2023. Accepted: 23.10.2023.