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ENVIRONMENTAL PERFORMANCE EVALUATION FOR A SMALL SCALE TRIGENERATION SYSTEM

BY

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Abstract. The modern buildings must have very high standards and require highly efficient energy supply systems due to space limitations for renewable installations. Electricity and thermal energy can be produced simultaneously with a photovoltaic-thermal (PVT) system. In the paper, an innovative concept of PVT system for a hospital is studied. PVT collectors serve as both a heat source and a heat sink for a reversible heat pump in the examined system. Due to the reduced electricity consumption from the network for heat rejection, the overall efficiency was improved by using a reversible water-to-water heat pump as heat and cold source compared to a conventional solar cooling system. Primary energy savings can be achieved with a maximum utilization of PV for electricity, heating and cooling (as air conditioning). The paper presents an original methodology for determining the environmental impact of the real PVT operation. The case study shows that for a real 4kWp PVT, the yearly energy savings reduce the greenhouse gas (GHG) emissions with 281.8 kg/year for SO_2 and 152.4 for CO_2.

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1. Introduction

The tertiary sector contributes significantly to climate change, accounting for 45% of final energy consumption and 20% of greenhouse gas emissions (Quitmann *et al*., 2021). In order to achieve the objectives set by the European Union in terms of GHG reduction, three action levels were applied (Strielkowski *et al*., 2021): reducing the need for energy by improving the insulation of existing end-users, improving energy efficiency by increasing the performance of various energy-consuming appliances, and replace fossil fuels with decarbonised energy sources, preferably renewable and sustainable.

The trigeneration concept is defined as the process that allow the simultaneous or separate generation of three types of energy (heat, electricity and cold), and covers all demands of the tertiary sector (Marques *et al*., 2021). Currently, very few trigeneration technologies are commercialised. If some technologies are relatively mature, the investment required is still too high to allow their implementation on the market. Generally, the trigeneration systems are combined processes between the cogeneration and one of the cooling processes. This coupling can be realised in different ways, as assembly of photovoltaic panels and a heat pump, or an organic Rankine cycle (ORC) whose turbine is mechanically coupled to the compressor of a mechanical steam compression machine (Tzivanidis and Bellos, 2020). Nevertheless, the energy conversion chain of these processes is often inefficient and penalises their overall performance. The trigeneration is therefore a very interesting option for mitigating climate change.

Trigeneration is particularly suitable when there is a need for cooling in addition to electricity and heat. It can be used to improve the energy efficiency through refrigeration systems. Indeed, the demand for refrigeration is often more constant than the demand for heat in the industrial process. In addition, trigeneration can be beneficial for all buildings using air conditioning (very energy intensive during the summer). Thus, the installation of a system working on this principle could be very profitable on all types of buildings of different sizes. The connection of a trigeneration system to a local cooling and heating network is, like cogeneration, a very interesting application for distributing the heat and cold produced by the system. The heat and cold produced at the same time reduce greenhouse gas emissions, especially by replacing conventional compression chillers using refrigerants with a high greenhouse effect (da Costa Garcia *et al*., 2021).

The recovery of thermal energy from solar collectors has led manufacturers to use it for other applications and thus contributed to the concept of photovoltaic and thermal energy harvesting using photovoltaic-thermal (PVT) panels (Joshi *et al*., 2016). Most PV cells convert a small fraction of the incoming solar radiation into electricity, and the rest of the energy is lost as heat. PVT is therefore a new configuration of a solar system that has been built based on the combination of a photovoltaic module with a thermal collector. This PVT system is capable of exploiting solar radiation to generate electricity and heat simultaneously. In a PVT collector, the PV module is attached to a heat exchanger containing either air or water as a cooling medium, which converts more solar energy per unit area than the corresponding cooperation of a separate PV module and a solar thermal collector. This leads to a reduction in manufacturing and installation costs (Ramos *et al*., 2019).

In recent years, serious efforts have been made to deploy PVT modules to meet the needs of households, especially in places with limited space for both PV panels and thermal collectors. One of the main advantages of this technology is the compact construction compared to conventional thermal collectors with robust design (Zondag *et al*., 2005). Moreover, there is low industrial involvement in large-scale production of PVT modules and their use should be encouraged according to the optimistic results of recent times (Diwania *et al*., 2020).

According to the PVT design principle, the thermal collector in a PVT module captures excess heat generated by means of a fluid, either for heat recovery or for cooling the PV module (Shakouri *et al*., 2020). In this process, solar radiation reaches the PV module, where a fraction is lost to the ambient environment, while there is heat loss on the one hand, as well as a working heat that supports the PV module with a certain electrical efficiency. The accumulation of solar energy increases the temperature of the PV module and generates heat power, which is transferred to the thermal module through a heat transfer mechanism depending on the fluid environment and the design of the module with a corresponding thermal efficiency. Finally, thermal insulation makes the whole PVT system more efficient by reducing and eliminating side and back heat losses.

The performance of series-connected air-based PVT modules has also been studied by researchers, and the results indicated a high potential for this technology to be integrated into buildings (Dubey *et al*., 2009). In another scientific work, a PVT module was studied that includes air ducts modified with single-row slant plates to help the direction of thermal energy flow at the system level (Ali *et al*., 2010). A major improvement in module design was achieved as selective fins were introduced into the PVT configuration. Furthermore, researchers investigated the effects of vertical fins inside a double-pass air-based PVT module and found that their presence significantly lowered the cell temperature, which also improved heat exchange with the thermal module (Kumar and Rosen, 2011). A ventilated multi-operational PVT module was implemented for integration with a commercial building as a roof-mounted module (Cartmell *et al*., 2004). The agricultural field is a key area for PVT module integration (Tiwari *et al*., 2018). In the literature, different types of solar cells have been used in PVT modules. Crystalline solar cells have been tested in an air-based PVT system connected to a typical residential building as a stand-alone system in (Farshchimonfared *et al.*, 2016). Also, in (Othman *et al.*, 2016) a double-pass air-based PVT module using transparent solar cells is introduced. In this research, they used two parallel transparent PV modules for power generation.

Thin-film PV cell technology has also been used for PVT development, in the way a simple ultra-thin and PVT ultra-thin systems without a styrene layer were proposed (Hischier *et al.*, 2017). In another study (Nualboonrueng *et al.*, 2012), polycrystalline and amorphous silicon solar cells were compared to find the best option for a PVT module operating in a tropical climate. PVT modules can be classified based on different criteria such as heat extraction mechanism, application, and solar collector design and heat exchange medium.

In this paper, the efficiency of a real PVT system designed for a metropolitan hospital is studied. The proposed PVT systems uses collectors as a heat source and a sink as a reversible heat pump. The main objective of the proposed PVT system was to intensify and deepen sustainable economic, social and environmental cooperation in the cross-border area between Romania and the Republic of Moldova by developing a system for generating electricity, hot water and cold with photovoltaic panels through trigeneration from solar renewable energy sources. The project aims to stimulate the efficient use of renewable energy sources in the cross-border area.

The overall efficiency was improved by using a reversible water-to-water heat pump as heat and cold source compared to a conventional solar cooling system. In this context, in a first step, the PV generate electricity, heating and cooling (as air conditioning), obtaining an energy savings, in particular by not using other sources of heating and cooling production. In the second step, an original methodology for assessing the impact of the PVT operation on yearly greenhouse gas (GHG) emissions reduction was developed.

The remainder of this paper is organized as follows. In Section 2, the PVT systems are briefly presented. Section 3 presents a methodology for computing the GHG emissions reduction due to the energy savings. Section 4 provides the results of a case study. The paper ends with conclusions.

2. Small-Scale Trigeneration Systems Applied for Hospitals

In a previous paper (Tirsu *et al.*, 2021) the authors presented the theoretical aspects regarding the development of a photovoltaic panel combined with a solar water heater for more efficient generation of electricity and hot water. Now PV panels are used only to generate electricity. Their power depends on the value of the solar radiation and the temperature of the cells. In the summer, when the radiation is the highest, the losses are high due to the excess of temperature. Losses of crystalline silicon cell panels represent 9.4% of the annually generated energy. PV panels have a solar energy conversion efficiency of less than 20%, the rest of the energy being turned into heat, which in addition reduces the amount of the generated energy. That is why the project envisages the equipping of PV panels with tubular capillary mats through which antifreeze will circulate and will cool the panels. The mats will be joined together in a closed circuit by a heat exchanger placed in a boiler. Heat extraction will keep the cells at a lower temperature maintaining higher electricity yield simultaneously heating water in the boiler. The calculations show that PVT will generate 5% more electricity annually. Its average annual efficiency will be 44%, compared to the usual 11% of PV panels.

The innovative aspects were to demonstrate the opportunity of air-cooling in hospitals by using PVT hot water. It involves connecting the boiler with PVT, on the one hand, and with the absorber chiller inputs, on the other hand. Cold water obtained in the chiller will be pumped to the air-cooling equipment inlet. The temperature of hot water at the chiller input will be 65-90°C. The outlet cooled water temperature will be 7-20°C. The small absorption chillers can operate with a coefficient of performance (COP) of 0.56. Therefore, COP is small compared to compression coolers, but it's great enough, because it works with "residual" hot water. The water temperature at the other cooler outlet will be 45-50°C that can be used as domestic hot water. As a result of the research, it will be demonstrated the possibility of air cooling in buildings from PVT and for which will be needed annually 400 kWh/kWp.

The hospital has a PVT power plant with a power of 4 kWp on a flat roof. It contains 12 panels with a power of 340Wp each and will be installed in a row. It will occupy 19.5 m^2. The electrical output will be connected to the electric inverter, which will convert direct current into 3-phase alternative current. The thermal part contains a system of polypropylene pipes and capillaries, installed in the photovoltaic-thermal panels. Each cold liquid inlet will be connected to the cold liquid main pipe and each hot liquid outlet will be connected to the hot liquid main pipe. The main cold liquid and hot liquid pipes will be connected to the inlet of the heat pump by means of an expansion vessel forming the first loop. A hydraulic pump will be installed in the loop, which will pump the glycol through the loop. The system will be filled with glycol, which freezes at -25°C. The outlet of the heat pump will be connected to the hot water accumulator by means of the main pipes of cold and hot polypropylene liquid forming the second loop.

The measurements carried out in the system of the sanatorium "Bucuria Sind" (Vadul lui Voda, Chisinau) with hot water and electricity generation between 11.04.22 and 03.05.22 as shows the results presented below.

Initial data. Photovoltaic-thermal panels of 5.2 kWp (16 panels of 320W each) and photovoltaic panels of 5.2kWp - (16 panels of 320W each), installed on the flat roof of the building, together with the brine-to-water heat pump with nominal thermal power of 15.28 kW (10°C/35°C), and electrical power - 2.72 kW. The PVT are connected to the heat pump by a liquid piping system at the inlet and 1.0 m^3 boilers at the outlet. The system operates in continuous water heating mode with delivery to the sanatorium system, and electricity is delivered to the local electricity supplier's grid. During this period the minimum temperature varies between 2°C and 7°C, and the maximum - between 12°C and 19°C, the average temperature was 12°C, and the sky was 58% cloudy on average.

Results. The PVT systems generate 1102 kWh electricity and 3528 kWh heat energy. The electricity is generated by the PV-thermal panels together with the photovoltaic panels, and thermal energy - only by the PV – thermal panels connected with the heat pump. The average coefficient of performance of the heat pump was 2.9 with variations between 2.7 and 5.5.

The environment conditions of the Vadul lui Voda town, and Răducăneni village, are similar and the generation power does not differ much, therefore it is easy to forecast the electrical and thermal capacity of the PVT system in Răducăneni. So, the PVT system from Vadul lui Voda in the cold season operating in relatively cloudy skies, generate for only 22 days 50.1 kWh electricity and 160.3 kWh heat daily. The water is heated from 10°C to 50°C and delivered to the sanatorium's hot water system. Electricity generation is known and easily calculated, while thermal energy - still needs further research to be done. However, the experimental results show that the system can operate autonomously in net-metering mode and generate electricity, domestic hot water for heating the building and cold air for air conditioning all year round.

To highlight the of 4 kWp PVT performance the PVGIS (Gómez-Gil *et al.*, 2012) web interface to produce calculations of solar radiation and PV system energy production was used, considering the real location of the considered hospital. Thus, in section 4, the results were presented as input information for the simulation process.

3. GHG Emissions Evaluation based Approach Using the Energy Labels

This section proposes an original deterministic methodology for evaluating the impact of energy savings (by using PVT) on GHG emissions, including carbon dioxide (CO2), methane (CH4), nitrous oxide (NOx), Sulphur dioxide (SO 2), and dust. The main energy generation types of impacts are indicated in Table 1.

The input data starts with the energy label information of the three fossil fuels that are commonly used in power generation: coal, natural gas, and oil. These values are determined for the annual energy savings (MWh/year) based on the emission factors for electricity produced in the traditional power plants, determined on the basis of the electricity supplier's label for the previous year.

Table 1
Main Energy Generation Impact Types and Their Actions on the Environment

Type of Impact		Action	Affecting
Exhaustion of natural resource reserves		Consumption of non-renewable resources	Natural resources reserves
GHG effect		Main emissions: CO_2, NO_x, CO	The thermal balance
Toxicity and ecotoxicity	Toxicity	Heat, chemicals and radioactive emissions	People, fauna, flora
	Acidification	Chemical emissions: SO_2, NO_2, HCl	Flora, fauna
	Eutrophication	Emissions of elements such as nitrogen, phosphorus in wastewater	Flora, fauna

The electricity label is established according to Order no. 69 of 2009 from Romanian regulations (Lazăr, 2018). The emissions for the three types of fuel used for the traditional power plants are given in Table 2.

Table 2
GHG Emissions Resulting from Electricity Generation based Fuel in Power Plants

Fuel	SO_2 [g/MWh]	NO_x [g/MWh]	Dust [g/MWh]	CO_2 [kg/MWh]	CH_4 [g/MWh]
Coal	2418	703.6	617.7	1145.2	77.5
Oil	849.0	872.0	16.0	608.0	22.7
Natural gas	-	0.71	0.014	401.2	0.28

Next, a deterministic mathematical model is proposed to evaluate GHG emissions, taking into account that SO_2 and NO_x emissions (with synergetic effects at regional scale), and dust or CO_2 emissions are the most common pollutants released by power plants (with global effects).

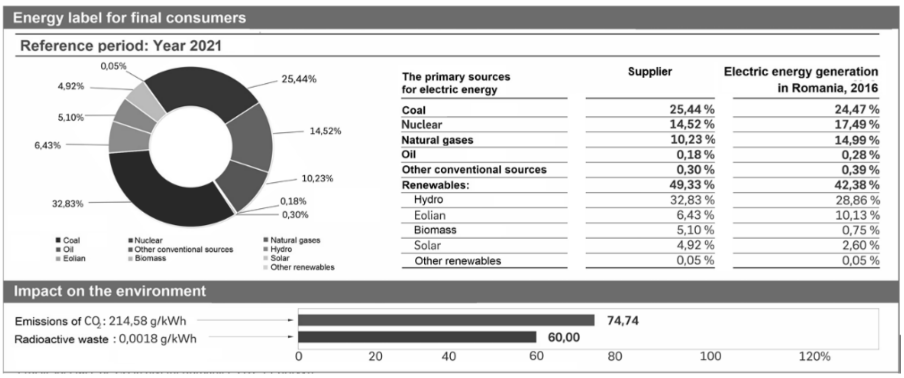

Fig. 1 – Energy label used for GHG emissions evaluation.

The goal of the electricity label is to provide the end-users with a high level of information by increasing market transparency, reducing the impact of the electricity sector on the environment by promoting renewable energy sources and clean technologies, and enacting specific EU legislation. A modified energy label was shown in Fig. 1 (Neagu and Grigoras, 2019).

The method used by the authors is based on the GHG emissions computed using a combination between the SO_2, NO_x, dust, CO_2 and CH_4 emissions from fuels combustion indicated in Table 1, and the percentage values of the energy produced using the classical fuels indicated by the supplier in the energy labels (Fig. 1). In this context, the GHG emissions (Ξ) value is a sum of specific emissions resulted from the combustion of the three fossil fuel (coal, oil and natural gas):

$$\Xi = \sum_{j=1}^{3} \xi_{ff,j} \tag{1}$$

or

$$\Xi = W_{es} \cdot \sum_{k=1}^{n} \sum_{j=1}^{3} F_j(k) \cdot \varepsilon(j) \cdot \Delta t \tag{2}$$

where: *ff* is a term for fossil fuel and ξ_{ff} represent the emissions resulted from the combustion of the three fossil fuels (coal, oil and natural gas).

The Eq. (2) can be rewritten considering all considered fossil fuels as:

$$\begin{aligned} \xi_{ff.coal} &= W_{es} \cdot \sum_{k=1}^{n} F_{coal}(k) \cdot \varepsilon(coal) \cdot \Delta t \\ \xi_{ff.oil} &= W_{es} \cdot \sum_{k=1}^{n} F_{oil}(k) \cdot \varepsilon(oil) \cdot \Delta t \\ \xi_{ff.\mathrm{nat.gas}} &= W_{es} \cdot \sum_{k=1}^{n} F_{nat.gas}(k) \cdot \varepsilon(nat.gas) \cdot \Delta t \end{aligned} \tag{3}$$

where: Δt – the interval of simulation; W_{es} – the yearly energy savings; n – the number of GHG emissions sources (k is 5 because of SO_2, NO_x, dust, CO_2 and CH_4 are considered); ε – the percentage values of the three fossil fuel for each MWh/year generated in power plants.

4. Case Study

The proposed method was tested on the real operational system of 4.0 kWp at the Hospital in Răducăneni, Iaşi. In the first step, using the PVGIS web interface the yearly PVT system energy production was obtained, as is shown in Fig. 2.

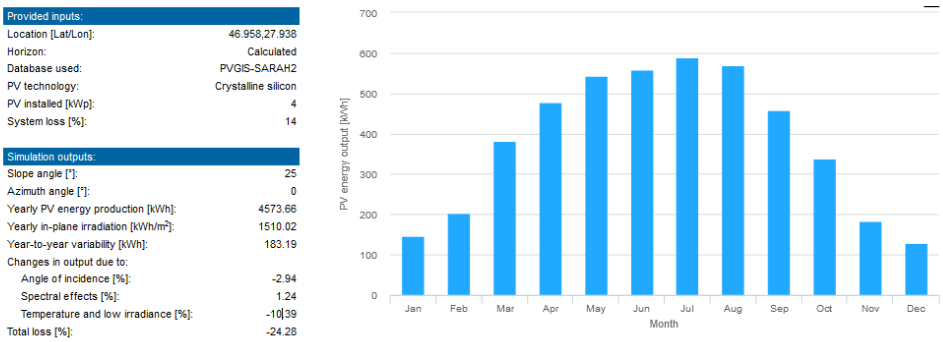

Fig. 2 – Estimates of solar electricity generation for the studied 4.0 kWp PVT.

Fig. 3 shows that the PVT will generate 4573.66 kWh electricity annually. The losses from temperature and low irradiance constitute 10.39%, which means a loss of 475 kWh/year, to be recovered by cooling the panels to 25°C. In this context, taking into account that the total energy demand of the Raducaneni Hospital in 2021 was 94.169 MWh, and by using the method based on the energy lebel proposed by the authors in section 3, the GHG emisions are assesed. Thus, in Tables 3 and 4 the results regarding the GHG emissions without PVT for the three conventional fuels (coal, oil and natural gases) are presented.

Table 3

Annual GHG Emissions for Electricity Demand of the Raducaneni Hospital in 2021

GHG emission type	SO_2 [kg]	NO_x [kg]	Dust [kg]	CO_2 [kg]	CH_4 [kg]
$\xi_{ff.coal}$	5792.70	1685.59	1479.80	2743.51	185.66
$\xi_{ff.oil}$	14.39	14.78	0.27	10.31	0.38
$\xi_{ff.nat.gas}$	-	0.68	0.01	386.50	0.27
Ξ	5807.10	1701.05	1480.08	3140.31	186.32

In accordance with Fig. 1, the energy supplied in 2021 was generated from fossil fuels as 25.44% coal, 10.23% natural gases, and 0.18% oil. The real value of CO_2 emisions for 2021 is 3.14 to.

As suggested in Fig. 2, the application of the PVT system will determine an equivalent electricity saving equal to the yearly PV energy production, namely 4.57 MWh. These values are considered to emphasize the advantages of the largely use of the small scale trigeneration systems. Using the proposed methodology, the obtained results are indicated in Table 4. The GHG emissions are reduced with 5% whitout considering the thermal level of the PVT. The obtained GHG emissions are indicated in Fig. 3.

Table 4
Annual GHG Emissions for Energy Savings of the Raducaneni Hospital in 2021

GHG emission type	SO_2 [kg]	NO_x [kg]	Dust [kg]	CO_2 [kg]	CH_4 [kg]
$\xi_{ff.coal}$	281.34	81.87	71.87	133.25	9.02
$\xi_{ff.oil}$	0.70	0.72	0.01	0.50	0.02
$\xi_{ff.nat.gas}$	0.00	0.03	0.00	18.77	0.01
Ξ	282.04	82.62	71.89	152.52	9.05

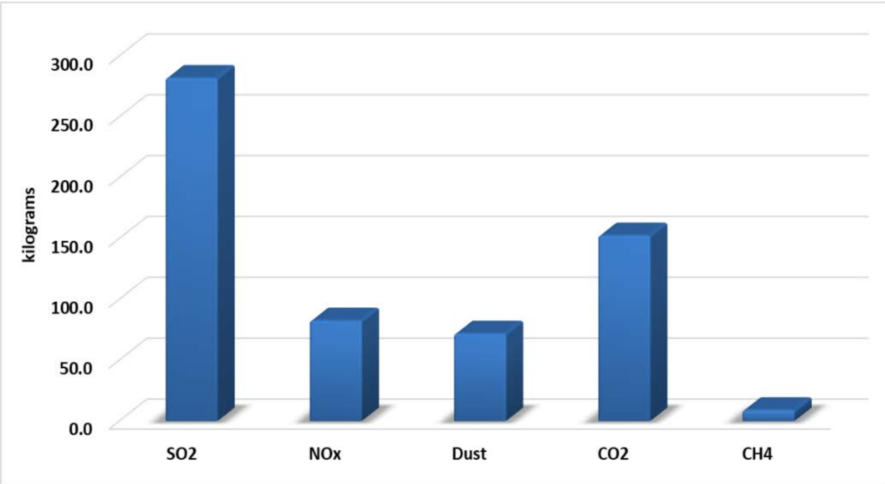

Fig. 3 – GHG Emissions for the Energy Savings with PVT.

The reduction in gas consumption is minimum 17 m^3 per day or 3.3 m^3/kWp of PVT panels, which means that 1 kWp of the Răducăneni system could reduce consumption by 5167 m^3 per year and reduce CO_2 emissions. Taking into account that the water heating at the Răducăneni is done with firewood, then the reduction will be 15810 kg/year or 22 m^3/year. The reduction of wood consumption is as important as the reduction of CO_2 emissions, because this will reduce the cutting of forests.

The above analyses indicate that the proposed PVT system is feasible and it can significantly improve the energy efficiencies of PVT systems. The technical aspects and cost-effectiveness profitability for photovoltaics and solar thermal collectors were presented in the previous paper (Tirsu *et al.*, 2021).

5. Conclusions

Because of the possibility of switching fuels and energy sources, energy-related GHG emissions are projected to expand more slowly than energy consumption in general and energy sector requirements in particular. This article investigates the capabilities of a real PVT system for a hospital. Primary energy savings can be realized by maximizing the use of PV for electricity, heating, and cooling (air conditioning). As a results, the proposed PVT as an efficiency measure could potentially reduce emissions by 152 $kgCO_2$ per year, in addition to the methane, nitrous oxide, sulphur dioxide, and dust. It is also important that the system operates automatically, requires minimal maintenance and is environmentally and human-friendly (no harmful gases, no noise).

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EVALUAREA PERFORMANȚELOR DE MEDIU PENTRU UN SISTEM DE TRIGENERARE DE MICĂ PUTERE

(Rezumat)

Clădirile moderne se supun unor standarde foarte ridicate și necesită sisteme de alimentare cu energie eficiente din cauza limitelor spațiului de montare pentru instalațiile regenerabile. Energia electrică și termică poate fi produsă simultan cu un sistem fotovoltaic-termic (PVT). În această lucrare sunt studiate capacitățile unui sistem PVT inovator pentru un spital. Colectoarele PVT servesc atât ca sursă de căldură, cât și ca radiator pentru o pompă de căldură reversibilă. Datorită consumului redus de energie electrică de la rețea pentru asigurarea confortului termic, eficiența generală a fost îmbunătățită prin utilizarea unei pompe de căldură reversibile apă-apă ca sursă de căldură și frig, în comparație cu un sistem convențional de răcire solară. Economiile de energie primară pot fi realizate prin utilizarea eficientă a energiei fotovoltaice pentru producerea de electricitate, încălzire și frig (aer condiționat). Lucrarea prezintă o metodologie originală pentru determinarea impactului asupra mediului prin exploatarea eficientă a sistemului de trigenerare. Studiul de caz arată că, în cazul unui PVT real de 4 kWp, economiile anuale de energie reduc emisiile de gaze cu efect de seră (GES) cu 281,8 kg/an pentru SO_2 și 152,4 pentru CO_2.