Optimal Design and Techno-Economic Analysis of a Hybrid System to Supply a Remote Fishpond with Electricity and Heat

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***Abstract*—This paper deals with the design of a hybrid system for the generation of electricity and heat that will supply a remote fishpond in eastern Serbia. The proposed hybrid system consists of a micro-hydro power plant (MHPP), a photovoltaic (PV) generator, a combined heat and power (CHP) unit with one diesel generator, batteries, a converter, a thermal load controller (TLC), and a boiler. A comprehensive techno-economic analysis is performed in the HOMER Pro software, which evaluated and compared 12 possible configurations with different combinations of system components. The results show that the optimal system has the lowest total net present cost (NPC) and the lowest levelized cost of energy (COE) amounting to 284421.0 $ and 0.178 $/kWh, respectively. Compared to a diesel/batteries/converter/boiler hybrid system, the proposed system produces 65.4 % less greenhouse gas (GHG) emissions, while the shares of electricity, heat, and renewable energy generation are increased by 31.1 %, 5.0 %, and 51.2 %, respectively. It is shown that covering the demand for heat by regenerating the waste heat from the diesel generator and excess electricity from renewables contributes to reducing the total cost of the system and the GHG emissions. This finding finally emphasised the necessity of applying TLCs in off-grid hybrid systems.**

***Index Terms*—Excess electricity; Fishpond; Hybrid system; Optimisation; Techno-economic analysis; Thermal load controller (TLC).**

I. INTRODUCTION

The depletion of fossil and nuclear fuel resources and the concern for the environment have led the world's attention to alternative technologies for electricity generation [1]. Among renewable energy sources (RES), during the last decade, hydropower and solar energy had the fastest growing trends, mainly due to favourable political incentive measures, significant technological progress, and their high availability [2]. In addition to meeting the global goals to reduce greenhouse gas (GHG) emissions [3] and the dependance of humans on fossil fuels, the use of RES is also suitable for powering isolated sites, whose connection to the power grid is unprofitable or physically impossible. Due to the inaccessibility of certain isolated sites, powering them can be very difficult or too expensive. One of such sites is the Jablanica trout pond, which was built next to the Radovanska Reka mountain river in eastern Serbia [4] and which is taken here as a case study.

In the literature, there are a large number of papers dealing with the optimisation and techno-economic analysis of the feasibility of hybrid systems for supplying electricity to consumers using the HOMER Pro software. In [5], an optimal design of a hybrid system with a photovoltaic (PV) generator of 1 kW, 8 batteries of 200 Ah, and an inverter of 0.2 kW was proposed for the aeration of a fishpond in Sleman Regency of Yogyakarta. The techno-economic analysis performed by the authors in [4] showed that by modifying the performance parameters of a propeller S-turbine, it is possible to minimise total net present cost (NPC), levelized cost of energy (COE), and GHG emissions, and to maximise total annual electricity generation. To supply electricity to a rural area in India, an off-grid solar/wind/biogas/biomass/fuel cell (FC)/battery hybrid system was considered in [6]. The hybrid system proposed by the authors in [6] was identified as the cheapest and most reliable solution having a total NPC and levelized COE of 890013.0 $ and 0.214 $/kWh, respectively.

In [7], a techno-economic feasibility of an off-grid hybrid system was carried out to supply electricity to a remote area in Bangladesh. This hybrid system, consisting of a 9 kW biogas generator, 10 kW PV generator, 2 diesel generators (10 kW each), 72 batteries (390 Ah each), and 15 kW inverters, was found to have a total NPC of 612280.0 $ and levelized COE of 0.28 $/kWh with a renewable fraction (RF) of 60 % [7]. Performance evaluation of a feasible off-grid PV/wind/diesel/battery hybrid system for a large resort centre in the South China Sea, Malaysia, was studied in [8].

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For this hybrid system, optimisation resulted in a total NPC, levelized COE, and RF of 17.15 M$, 0.279 $/kWh, and 41.6 %, respectively. The feasibility of different configurations of a PV/wind/diesel/battery hybrid system for telecommunication applications in different cities of Punjab, India, taking into account the techno-economic aspects, was analysed in [9]. Depending on the system configuration, in this specific case, the levelized COE ranged from 0.162 $/kWh to 0.210 $/kWh. In [10], a hybrid system consisting of 100 % RES was designed and simulated in order to supply some off-grid areas in Rwanda with electricity.

The techno-economic feasibility analysis of four off-grid systems for the island of Pratas in Taiwan was carried out in [11]. According to the results of this analysis, the lowest COE of 0.3569 $/kWh was obtained for a PV/diesel hybrid system configuration having a total PV system capacity of 200 kWp, the RF of 15.3 %, and excess electricity fraction of 2.6 %. In addition, the authors of the study in [12] optimised the size of the Barishal and Chattogram hybrid microgrids in Bangladesh, consisting of a wind turbine, an energy storage unit, a PV generator, a diesel generator, and a load profile of 27.31 kW for five load dispatch strategies. A hybrid system consisting of two wind turbines, an 80 kW PV generator, 72 batteries, and a 70 kW converter, that can meet the energy needs of a five-story residential building in Tehran, was analysed in [13]. An optimal configuration of a RES-based hybrid system with a wind turbine and a PV generator to fulfill the electricity demand of a medium-sized workshop in an industrial area in Ardabil, Iran, was studied in [14]. It was proven in [14] that the industrial area has enough potential to generate electricity from wind and solar energy, and that the wind generator provides more electricity than the PV generator due to the climatic conditions in Ardabil.

In [15], an optimal design of a PV/micro-hydro/diesel/battery hybrid system was investigated to supply electricity to a rural community of Nigeria under tropical climate conditions. Four different configurations were considered in [15] and the most economically feasible one was selected. That configuration, consisting of a 50 kW PV generator, a 94.1 kW hydro system with nominal battery capacity of 111 kWh, a 100 kW diesel generator, and a 50 kW power converter, had the lowest total NPC of 963431.0 $ and the lowest levelized COE of 0.112 $/kWh [15]. Three different hybrid systems with different capacity shortage values were optimised separately by HOMER and a differential evolution algorithm in [16]. The differential evolution algorithm was much faster than HOMER and generated almost the same results as HOMER [16]. In [17], the feasibility of PV/battery/FC and PV/battery hybrid systems for an indigenous residence in East Malaysia was analysed using HOMER. The optimisation results showed that the PV/battery hybrid system is economically and environmentally friendly with a total NPC of 335297.0 $, a levelized COE of 0.323 $/kWh, an excess electricity generation of 35.5 %, and no GHG emissions [17].

Several studies have considered the supply of electricity and heat to consumers, including the generation of excess electricity using thermal load controllers (TLCs). In [18], a hybrid power system, including a PV generator, an energy storage system (ESS), a FC, a natural gas (NG) boiler, a TLC, and a converter, was optimised to meet the demand of an electric vehicle. The total NPC and levelized COE of this hybrid power system were obtained at 230223.0 $ and 0.0409 $/kWh [18], respectively. According to [18], ESS played a key role in the supply of electric vehicle consumption at night, while TLC converted excess electricity generation from the PV generator to heat and contributed to the reduction of GHG emissions. A hybrid system, consisting of a PV generator, a wind turbine, a diesel generator, an ESS, a converter, an electrolyzer, and a hydrogen tank, was created and optimised to provide uninterrupted power and meet different load demands of different communities in a village in India [19]. The given hybrid system had a minimal total NPC of 7.01 M$, a levelized COE of 0.244 $/kWh, and an RF of 84.1 %. Techno-economic analysis of a RES-based hybrid system was conducted in [20] to co-supply electricity, heat, and hydrogen to five different major cities in Iran (Bandar Abbas, Shiraz, Tabriz, Tehran, and Yazd). According to the work in [20], recovering extra electricity can improve the RF by up to 35 % and reduce levelized COE and exhausted CO_2 by 7.1 % and 10.6 %, respectively.

The capacity to meet the simultaneous demands for electricity and heat from an off-grid community with different configurations of hybrid power was examined in [21]. The configurations, which include PV generators, wind turbines, micro gas turbines, and Li-ion batteries, were studied in [21] using different load dispatch strategies, namely load following and cyclic charging. The feasibility of integrating RES-based hybrid power system with a reverse osmosis desalination plant to provide electricity, heat, and water was analysed for the New Capital International Airport in Egypt [22]. Among the 14 configurations considered in [22], the configuration comprising one 66.33 kW PV generator, 14 wind turbines, each with 10 kW power, one 50 kW diesel generator, one 150 kW combined heat and power (CHP) microturbine generator, 50 batteries packs, one 150 kW TLC, one 64 kW bidirectional converter, and one boiler was considered as optimal. The results revealed that this optimal configuration has the least total NPC and levelized COE by 1.54 M$ and 0.089 $/kWh [22], respectively. The inclusion of 150 kW TLC succeeded in decreasing total NPC, levelized COE, GHG emissions, and batteries by 52 %, 56.4 %, 36.5 %, and 90 %, respectively; and improving RF by 11.2 % [22]. A CHP microgrid for a remote community in Newfoundland in Canada was designed and analysed in [23]. An earth-air heat exchanger coupled with a hybrid renewable power system that includes wind, solar, and hydrogen energy was analysed in [24] in the aspects of reliability and sustainability. The authors of the study in [24] demonstrated that adding geothermal energy to the hybrid renewable power system can lead to an improvement of approximately 5.5 % of RF, as well as a decrease in GHG emissions and diesel consumption of almost 48 %.

This paper deals with the design of a hybrid system to supply electricity and heat to the Jablanica trout pond, an off-grid site in the territory of the municipality of Boljevac, in eastern Serbia. The configuration of this hybrid system differs from other types of hybrid system in the literature because it is designed to power an isolated trout pond and because it includes a micro-hydro power plant (MHPP). The MHPP is located next to the settling basin for fishpond water and uses overflowing water from the settling basin. The Jablanica trout pond was chosen as a case study because it is powered by such a hybrid system, as well as because of its importance for healthy food production and the growing demand for trout, carp, and other species of fish.

Specifically, the main objectives of this paper are as follows:

1. Changing the offer of fish species from Jablanica fishpond according to market requirements, assuming that, along with trout, carp will also be grown, for which warmer water is needed;
2. Using regenerated waste heat and excess electricity generation to warm water in feeding and spawning basins where carp will be grown;
3. Optimisation and techno-economic analysis of a hybrid power system consisting of different combinations of the following components: MHPP, PV generator, CHP unit with one diesel generator, batteries, converter, TLC, and boiler;
4. Selecting the best hybrid system configuration based on financial, reliability, sustainability, and technical perspectives.

In this paper, HOMER Pro software is used to simulate the operation of the considered off-grid hybrid power system and to verify the technical and economic criteria for the integration of that hybrid system. The main objective here is to maximise energy generation (electricity and heat) together with RF, as well as to minimise GHG emissions, total NPC, and levelized COE.

II. Description of the Trout Pond of Jablanica and Data on Resources

The Jablanica trout pond is located in eastern Serbia, 13 km from the village of the same name, in the municipality of Boljevac, surrounded by forest and overlooking the mountain of Rtanj. This fishpond is one of the largest trout ponds in Serbia and has all the necessary characteristics suitable for the life and growth of trout species. In particular, the microclimate conditions are suitable, the fishpond is surrounded by hills that protect it from the wind, the water is clear and does not freeze in winter, the water temperature is at a stable level throughout the year, the water saturation with dissolved oxygen is almost 100 %, and the chemical composition and quality of water are appropriate. Such characteristics of the water catchment make the fishpond an ideal environment for trout breeding.

The altitude of the Jablanica trout pond is 820 m, while the geographical coordinates are 43°53'47.47" north latitude and 21°47'11.55" east longitude. Figure 1(a) shows the exact location of this fishpond in Google maps. In the immediate vicinity of the fishpond (at 150 m) there is the source of the Radovanska Reka river from which the fishpond is supplied with water. In addition to the settling basin, this fishpond contains 15 feeding and six spawning basins for trout. The total volume of concrete ponds for trout fattening is 4500 m^3. The ponds represent an imitation of a river bed with a constant flow of fresh water from the entrance to the exit, the so-called race track, in which fish constantly swim against the direction of the water flow. The actual appearance of these ponds is shown in Fig. 1(b).

In addition to trout, it is planned to breed carp in five closed ponds. Carp are one of the most popular fish in the world. Carp species have been grown in ponds with warmer water; they are very adaptable and resistant to changes in the environment. The water temperature, which ranges from 20 °C to 27 °C, plays a significant role in the chemical and biological processes related to the breeding of carp. At lower temperatures, carp do not achieve optimal growth, whereas at temperatures that are too high, especially in the presence of organic matter and ammonia, various carp diseases occur. These are the reasons why the water temperature in the ponds should be maintained within the given range, and this is done by warming the water using a boiler, a diesel generator, and TLC.

In addition, some studies in [25]–[27] showed that in this area of eastern Serbia, hydropower and solar energy represent energy sources suitable for off-grid hybrid power systems. Water at the outlet from the settling basin is used to generate electricity in the MHPP. Namely, after 15 ponds used for fish breeding, strung together in a cascade of five levels, the water is collected in a larger basin from where it is directed through a measuring channel into the river. Figure 2 shows the histogram of the monthly average stream flow for the river of Radovanska Reka, obtained on the basis of multiyear measurements.

The stream flow decreases during the period spring to summer (from May to October) due to a large number of dry days and increases during the period autumn to winter (from November to April) due to significant rainfalls and snowfalls. Accordingly, the lowest monthly average stream flow of 90 l/s occurs in October, and the highest monthly average stream flow of 845 l/s occurs in April. The annual average stream flow is 328.04 l/s, while the annual average residual stream flow is 32.80 l/s.

The monthly average values of solar irradiation and the clearness index for the area of Boljevac are shown in Fig. 3. Solar irradiation data corresponding to the latitude and longitude of the municipality of Boljevac (where the trout pond of Jablanica is located) are taken from NASA Surface Meteorology and Solar Energy [28]. According to Fig. 3, solar irradiation has a high level in July, while a low level of irradiation occurs in December. Additionally, the annual average value of solar irradiation is 3.62 $kWh/m^2/d$, and the clearness index is 0.486.

(a)

(b)

Fig. 1. Location of the Jablanica trout pond (a) on Google maps and (b) its actual appearance.

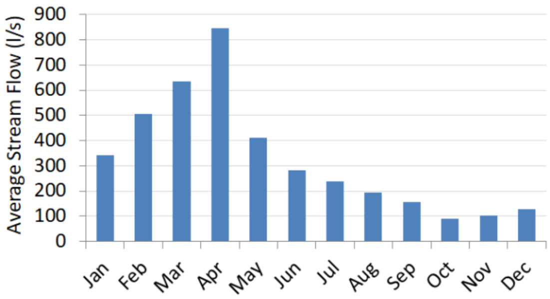


Fig. 2. Histogram of the monthly average stream flow for the river Radovanska Reka.

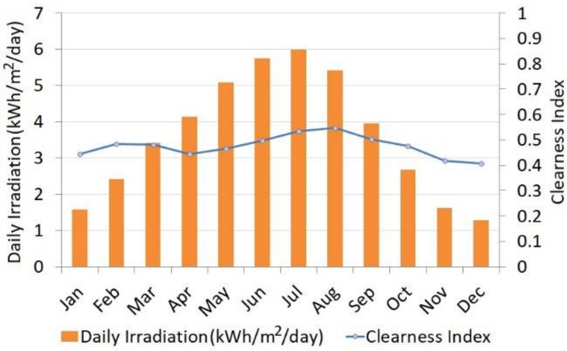


Fig. 3. Monthly average values of solar irradiation and the clearness index for the area of Boljevac.

The climate of the municipality of Boljevac has the characteristics of a moderately continental climate. The air temperature data corresponding to the latitude and longitude of the municipality of Boljevac are also taken from NASA Surface Meteorology and Solar Energy [28]. The monthly average values of air temperature for the area of Boljevac are shown in Fig. 4. Cold days with a monthly average air temperature ranging from -2.19 °C to 9.51 °C have been experienced during autumn and winter, with the lowest air temperature in January. Warm days with a monthly average air temperature ranging from 10.55 °C to 21.97 °C have been experienced during spring and summer, with the highest air temperature in August. The annual average air temperature is 9.88 °C.

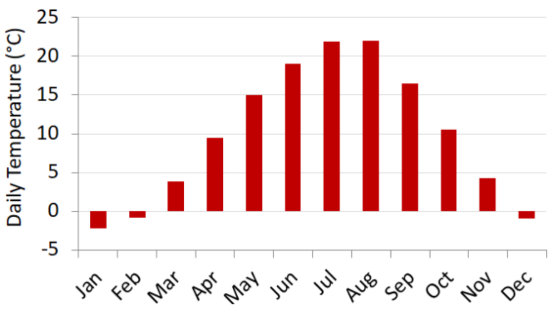


Fig. 4. Monthly average values of air temperature for the area of Boljevac.

III. MATHEMATICAL MODELLING OF COMPONENTS AND COSTS FOR THE PROPOSED HYBRID SYSTEM

In this section, the mathematical formulations used to model the components of the proposed hybrid system are presented. The formulas used to model the MHPP, PV generator, CHP unit with one diesel generator, batteries, converter, and boiler are taken from the works in [29], [30] and are represented in Table I.

TABLE I. MODELS OF THE COMPONENTS USED FOR THE PROPOSED HYBRID POWER SYSTEM.

MHPP
$P_{hyd} = \eta_{hyd} \times \rho_{water} \times g \times h_{net} \times Q_{turbine}/1000$, where P_{hyd} is the power output of the MHPP (kW), η_{hyd} is the efficiency of the MHPP (%), ρ_{water} is the density of the water (1000 kg/m^3), g is the acceleration due to gravity (9.81 m/s^2), h_{net} is the effective head (m), and $Q_{turbine}$ is the flow rate through the MHPP (m^3/s).
PV generator
$P_{PV} = Y_{PV} \times f_{PV} \times (\bar{G}_T/\bar{G}_{T,STC}) \times [1 + \alpha_p \times (T_c - T_{c,STC})]$, where P_{PV} is the power output of the PV generator (kW), Y_{PV} is the rated capacity of the PV generator, meaning its power output under the standard test conditions (STC) (kW), f_{PV} is the PV derating factor (%), $\bar{G}_T$ is the solar irradiance in the current time step (kW/m^2), $\bar{G}_{T,STC}$ is the solar irradiance at the STC (1 kW/m^2), α_p is the power temperature coefficient (%/°C), T_c is the temperature of the PV cell in the current time step (°C), and $T_{c,STC}$ is the temperature of the PV cell under the STC (25 °C).
CHP unit with one diesel generator
$F = F_0 \times Y_{gen} + F_1 \times P_{gen}$, where F is the fuel consumption rate (l/h), F_0 is the fuel curve intercept coefficient (l/h/kW), F_1 is the slope of the fuel curve (l/h/kW), Y_{gen} is the rated capacity of the generator (kW), and P_{gen} is the generator's output in the current time step (kW).
$c_{gen,fixed} = c_{om,gen} + (c_{rep,gen}/R_{gen}) + F_0 \times Y_{gen} \times c_{fuel,eff}$, where $c_{gen,fixed}$ is the fixed COE ($) of the generator, $c_{om,gen}$ is the operating and maintenance (O&M) cost ($/h), $c_{rep,gen}$ is the cost of replacing ($), R_{gen} is the generator lifetime (h), F_0 is the fuel curve intercept coefficient (l/h/kW), Y_{gen} is the rated capacity of the generator (kW), and $c_{fuel,eff}$ is the effective price of fuel ($/l).
ESS (batteries)
$c_{bw} = c_{rep,batt}/(N_{batt} \times Q_{lifetime,I} \times sqrt(\eta_{rt}))$, where c_{bw} is the battery wear cost depending on the cost of cycling energy through the battery bank ($), $C_{rep,batt}$ are the costs of replacing the battery bank ($), N_{batt} is the number of batteries in the battery bank, $Q_{lifetime,i}$ is the lifetime throughput of a single battery (kWh), and η_{rt} is the efficiency of the battery round trip (fractional).
Converter
$P_0(t) = P_i(t) \times \eta_{inv}$, where $P_0(t)$ is the output power of the converter (kW), $P_i(t)$ is the power input to the converter (kW), and η_{inv} is the utilisation rate of the converter.
Boiler
$c_{boiler} = (3.6 \times (c_{fuel} + c_{boiler,emission}))/(\eta_{boiler} \times LHV_{fuel})$, where c_{boiler} is the marginal cost of the boiler ($/kWh), c_{fuel} is the cost of fuel ($/l), $c_{boiler,emission}$ is the cost penalty associated with emissions from the boiler ($/kg), η_{boiler} is the boiler efficiency, and LHV_{fuel} is the lower heating value of the boiler fuel (MJ/kg).
Excess electricity fraction
$f_{excess} = E_{excess}/E_{prod}$, where f_{excess} is the excess electricity fraction, is the ratio of total excess electricity to total electricity generation (%), E_{excess} is the total excess electricity (kWh/year), and E_{prod} is the total electricity generation (kWh/year).
Renewable fraction
$f_{ren} = 1 - ((E_{prod} - E_{ren}) + (H_{prod} - H_{ren}))/(E_{served} + H_{served})$, where f_{ren} is the renewable fraction of the energy delivered from RES (%),

E_{prod} is the total electricity generation (kWh), E_{ren} is the renewable electricity generation (kWh), H_{prod} is the total heat production (kWh), H_{ren} is the renewable heat production (kWh), E_{served} is the total electrical load served (kWh/year), and H_{served} is the total thermal load served (kWh/year).
Economic modeling
$C_{NPC,tot} = C_{ann,tot}/CRF(i, R_{proj})$, where $C_{NPC,tot}$ is the total NPC ($), $C_{ann,tot}$ is the total annualized cost ($/year), CRF is a function returning the capital recovery factor, i is the annual real interest rate (discount rate) (%), and R_{proj} is the project lifetime (year).
$CRF(i, N) = [i \times (1 + i)^N]/[(1 + i)^N - 1]$, where i is the annual real interest rate (%), and N is the number of years.
$COE = (C_{ann,tot} - c_{boiler} \times E_{ther})/(E_{prim,AC} + E_{prim,DC} + E_{def} + E_{grid,sales})$, where COE is the levelized COE ($/kWh), $C_{ann,tot}$ is the total annualized cost of the system ($/year), c_{boiler} is the marginal cost of the boiler ($/kWh), E_{ther} is the total thermal load served (kWh/year), $E_{prim,AC}$ is the AC primary load served (kWh/year), $E_{prim,DC}$ is the primary DC load served (kWh/year), E_{def} is the deferrable load served (kWh/year), and $E_{grid,sales}$ is the energy sold to the grid (kWh/year).

Since the considered hybrid system also contains the TLC, it is necessary to know the models for estimating excess electricity and renewable fractions of the total energy generation. Additionally, Table I also contains the formulas necessary to model the total NPC and levelized COE.

IV. Configuration of the Proposed Hybrid System and Input Data

This section presents the input data, costs, and specifications of the individual components that are necessary for the HOMER Pro software. Two load dispatch strategies are considered when examining the techno-economic performance of the proposed hybrid system and finding the optimal solution by combining different sizes of components, namely load following and cyclic charging. On the one hand, under the cyclic charging strategy, the diesel generator operates at its maximum power output to supply the primary load, while the excess energy is used to charge the batteries. On the other hand, under the load-following strategy, the diesel generator has sufficient generating capacity available to meet the load needs, while the batteries are charged from RES. The project lifetime should be 25 years with an annual real interest rate of 5.88 %.

Figure 5 shows the schematic of the proposed hybrid system for the Jablanica trout pond. To perform simulations and conduct a techno-economic analysis of the proposed hybrid system, it is necessary to define typical daily load profiles that the system needs to cover. In addition, data on RES (MHPP and PV generator) and data on the components of the proposed hybrid system are required, namely CHP unit with one diesel generator, converters, batteries, boiler, and TLC.

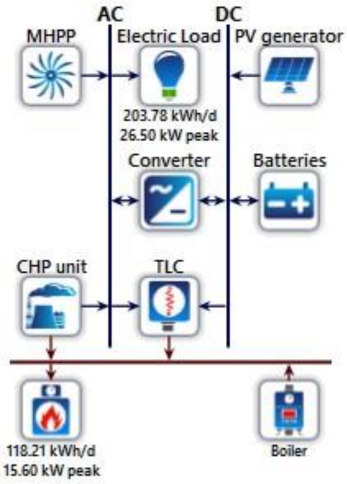


Fig. 5. Schematic of the hybrid system proposed for the Jablanica trout pond.

A. *Daily Load Profile*

The electricity obtained from the hybrid system supplies the office building with the following appliances: freezer, refrigerator, electric oven/stove, water heaters, television, computer, washing machine, iron, hair dryer, vacuum cleaner, air conditioner, boiler heating system (for heating the building), indoor lighting with 18 bulbs and outdoor lighting with 15 LED bulbs. In addition, the following devices that are necessary for the operation of the trout pond also consume a lot of electricity:

1. A cooling chamber to cool the fish while waiting for delivery (from the water temperature of the pond of 12 °C to 6 °C in the chamber, where the fish only cools but does not freeze);
2. Water spray devices that generate oxygen;
3. The ice machine that makes the ice on which the fish is transported (e.g., for a quantity of 1 t of fish, the ice machine should be turned on five hours before the ice has formed);
4. Water pump for the ice machine;
5. Lighting and video surveillance in the hatchery for fish breeding.

The necessary data on the given appliances and devices are given in Table II, while the typical daily load profiles of the Jablanica fishpond for the summer and winter periods are shown in Fig. 6.

TABLE II. MONTHLY ELECTRICITY DEMAND OF THE JABLANICATROUT POND.

Device	Power (W)	Pieces (units)	Period of operation (h/day)		Electricity (Wh/day)	
			Summer (Apr-Oct)	Winter (Nov-Mar)	Summer (Apr-Oct)	Winter (Nov-Mar)
Freezer	300	1	14	14	4200	4200
Refrigerator	200	1	14	14	2800	2800
Electric oven/stove	1000	1	2	2	2000	2000
Water heaters	2000	1	3	3	6000	6000
Television and computer	300	1	5	5	1500	1500
Washing machine	2000	1	2	2	4000	4000
Iron	400	1	2	2	800	800
Hair dryer	1500	1	1	1	1500	1500
Vacuum cleaner	300	1	1	1	300	300

Device	Power (W)	Pieces (units)	Period of operation (h/day)		Electricity (Wh/day)	
			Summer (Apr-Oct)	Winter (Nov-Mar)	Summer (Apr-Oct)	Winter (Nov-Mar)
Air conditioner	2500	1	5	-	12500	-
Boiler heating system	16000	1	-	3	-	48000
Indoor lighting	100	18	10	15	18000	27000
Outdoor LED lighting	40	15	10	15	6000	9000
Cooling chamber	10000	1	2	2	20000	20000
Oxygenator	500	6	24	24	72000	72000
Ice machine	2000	1	5	5	10000	10000
Water pump for the ice machine	500	1	5	5	2500	2500
Lighting and video surveillance	500	1	24	24	12000	12000
Total					176100	223600

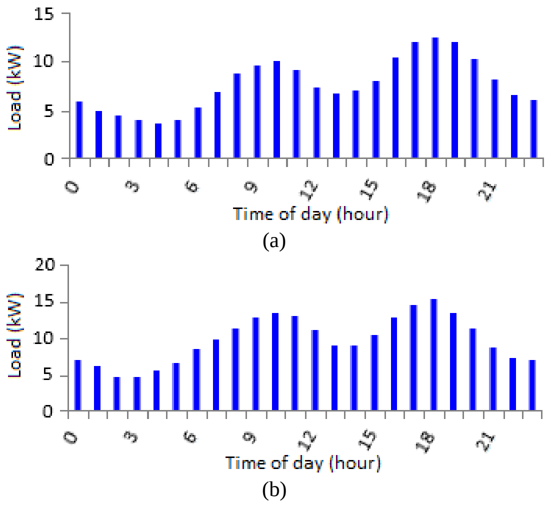


Fig. 6. Typical daily electrical load profiles of the Jablanica fishpond for the (a) summer and (b) winter periods.

According to Fig. 6 and other data generated by the HOMER Pro software, the annual daily average electricity consumption is 203.78 kWh, the peak power is 26.5 kW, and the load factor is 0.32.

The heat produced by the proposed hybrid system will be used to warm the water in five concrete ponds intended for the breeding of carp. These ponds have a total volume of 843.75 m^3 of water that will be warmed by the boiler, the CHP unit with a diesel generator, and a TLC, and the water temperature will be maintained at 27 °C. Figure 7 shows typical daily thermal load profiles of the Jablanica fishpond for the summer and winter periods.

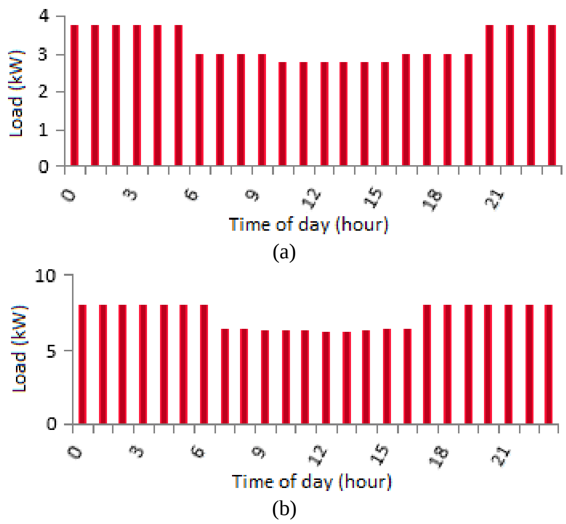


Fig. 7. Typical daily thermal load profiles of the Jablanica fishpond for the (a) summer and (b) winter periods.

According to Fig. 7 and other data obtained by the HOMER Pro software, the annual daily average consumption of heat is 118.21 kWh, the peak power is 15.6 kW, and the load factor is 0.32.

In reality, the sizes and shapes of the daily electrical and thermal load profiles vary from day to day. By including hourly and daily data variations, the daily load profiles change in size and shape, so the profiles become more realistic. Figure 8 shows the annual electrical and thermal load diagrams with daily and hourly variations generated for 15 % day-to-day variability and 20 % time-step-to-time-step variability.

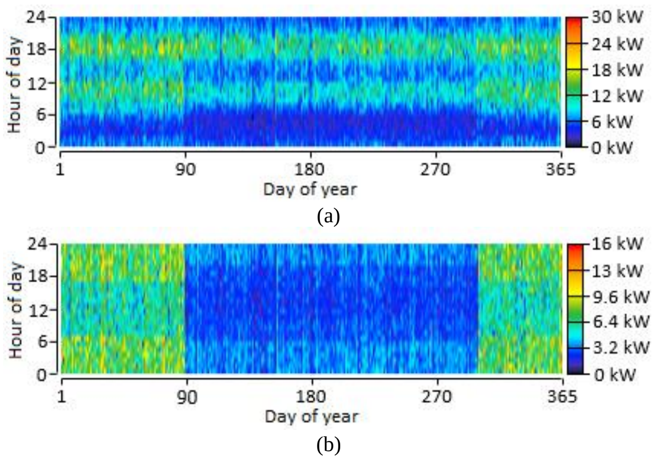


Fig. 8. A representation of the hourly and daily variations in the annual (a) electrical and (b) thermal load diagrams.

B. MHPP

For its operation, the MHPP uses water from the settling basin that holds water all the time and that receives water from the river of Radovanska Reka, whose histogram of the monthly average stream flow is shown in Fig. 2. The water is then directed to the propeller S-turbine using an 8 m-long pipe with a diameter of 0.5 m. The S-turbine propeller was first designed and constructed with fixed propeller blades, but for the purposes of the research conducted in [4] and [31], it was optimised for operation with flow rates in the range of 90 l/s to 350 l/s. This hydro-turbine has a net head of 2.9 m and an efficiency of 85.37 %. With these parameters, the rated power of 8.5 kW was obtained for the MHPP. The costs of investment and replacement of the MHPP are the same and equal to 1000 $/kW [32]. The annual O&M costs amount to 2.5 % of the investment costs. The lifetime of MHPP is 25 years.

C. PV Generator

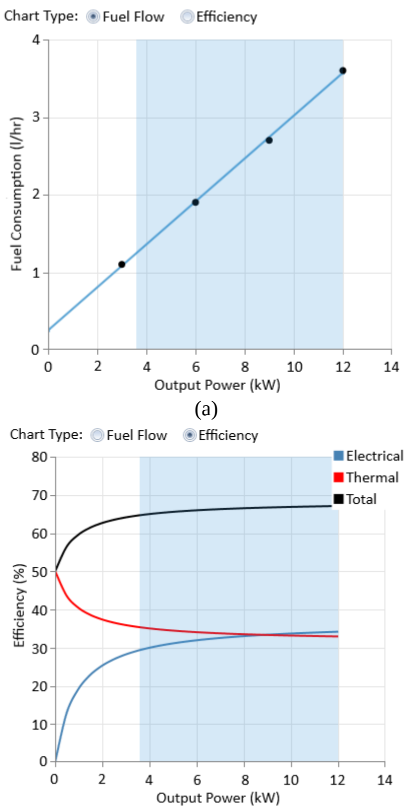
For the purposes of the HOMER Pro simulations, polycrystalline PV panels of brand-type SHARP with a rated power of 250 W were chosen [33]. Other data on the PV generator consisting of these PV panels are: lifetime 25 years, loss factor 88 %, efficiency at the STC 13 %, power temperature coefficient –0.485 %/°C, nominal cell operating temperature (NOCT) 47.50 °C, angle of inclination 40 °, and azimuth 0 °. The costs of investment and replacement of the PV panels are 544 $/kW and 544 $/kW (1 $ was equal to 0.9159 € on August 16, 2023 [34]), respectively. In addition, the corresponding annual O&M costs are 5 $/year. The power of the PV panels in the HOMER Pro simulations ranged from 0 kW to 620 kW.

D. *CHP Unit with One Diesel Generator*

A 12 kW three-phase diesel generator of Yamaha brand type [35] is used. According to the works in [36], [37], the price of diesel fuel in Serbia on August 16, 2023, was 1.705 $/l. This price is assumed in the HOMER Pro simulations. The fuel consumption and efficiency curves of the considered CHP unit with the diesel generator are shown in Figs. 9(a) and 9(b), respectively.

According to these two fuel curves, the associated intercept coefficient and slope are 0.0208 l/h/kW (rated) and 0.2767 l/h/kW (output), respectively. The lifetime of this CHP unit according to the technical characteristics of the generator should be 15 thousand hours. The costs of investment, replacement, and annual O&M are equal to 3710 $, 1500 $, and 0.025 $/h, respectively.

Other properties of diesel fuel are as follows: lower calorific value 43.2 MJ/kg, density 820 kg/m^3, carbon content 88 %, and sulfur content 0.33 %.



(a)

(b)

Fig. 9. Performance of the CHP unit with the diesel generator: (a) fuel consumption, (b) efficiency curves.

E. *Bateries*

A Trojan brand type kinetic battery model [38] was chosen for the ESS. The batteries are designed for cyclic operation at 12 V, with a capacity of 115 Ah (1.39 kWh), a lifetime throughput of 1212 kWh, an initial state of charge of 100 %, and a minimum state of charge of 20 %. The lifetime of these batteries is 10 years. The investments and replacement costs for these batteries are the same and equal to 235 $/kW, and their annual O&M costs are 5 $/year. The number of batteries in the HOMER Pro simulations ranged from 0 to 1650.

F. *Converter*

A converter is a device that converts direct current (DC) electricity into alternating current (AC) electricity and vice versa. The selected converter is of the Occren NB brand type and has a rated power of 1 kW [39]. The Occren NB converter converts a DC voltage of 24 V or AC voltage of 220 V ± 36 % and 50 Hz ± 10 Hz into AC voltage of 220 V ± 6 % and 50 Hz ± 0.5 Hz [39]. The efficiency of this converter is 95 %, and its lifetime is 15 years. The costs of investment and replacement are the same and equal to 235 $/kW, while the annual O&M costs are 5 $/year. The powers of this converter in the HOMER Pro simulations ranged from 0 kW to 125 kW.

G. *Thermal Load Controller and Boiler*

TLC is an electric heater that converts excess electricity from RES for the needs of powering the thermal load. TLC provides the primary heat production, while the remaining heat is obtained from the diesel boiler. For this case study, a TLC connected to AC and DC buses was chosen. The investment and replacement costs of TLC are the same and amount to 54 $/kW [21], while its lifetime is 20 years. HOMER Pro software assumes that such a boiler to heat water is an integral part of the building and therefore does not require any costs. The efficiency of the boiler is 85 %.

V. RESULTS AND DISCUSSION

Considerable time (expressed in hours) was spent on simulations with the optimal configuration of the hybrid system considered in the HOMER Pro software. All possible combinations of components with different input parameters were simulated and the optimisation results were sorted by the total NPC values, in sequence from the lowest to the highest value. A computer with the following specifications was used to perform the simulations: Intel Core i3 processor, 4 GB RAM memory, and 64 bit operating system.

Table III shows the configurations of the hybrid system considered obtained by optimisation according to the total NPC. The configurations in Table III consist of MHPP, PV generator, CHP unit with diesel generator, batteries, converter, TLC, and boiler. In this table, the following data are also given: total NPC, levelized COE, RF in percentage, excess electricity generation from RES in percentage, total electricity generation, and total heat production. In all the system configurations considered, the cyclic charging strategy was chosen.

TABLE III. HYBRID SYSTEM CONFIGURATIONS OPTIMISED ACCORDING TO THE TOTAL NPC.

Rank	MHPP (kW)	PVs (kW)	CHP unit (kW)	Batteries (Number)	Converter (kW)	TLC (kW)	COE ($/kWh)	NPC ($)	RF (%)	EE* (%)	Electricity (kWh/ year)	Heat (kWh/ year)
1	8.5	40.4	12	109	12.8	39	0.178	284421	51.2	29	109899	70849
2	8.5	36.5	12	107	12.7	-	0.199	305176	43	25.9	105380	48127
3	8.5	-	12	43	9.11	8	0.248	352398	19.1	3.38	77993	58081
4	8.5	-	12	43	9.11	-	0.254	357566	17.3	3.09	77835	57773
5	-	56.8	12	35	18.3	49	0.297	399380	19.1	36	119927	93196
6	-	94	12	381	31.2	-	0.317	418783	54.1	35.8	131937	45962
7	8.5	167	-	766	26.8	208	0.362	461173	73.6	69.1	258172	43407
8	8.5	147	-	812	36.5	-	0.382	480238	63.3	65.8	232856	43147
9	-	164	-	773	26.9	195	0.398	496008	70.2	60.8	216426	166599
10	-	157	-	790	36.2	-	0.409	507024	63.3	59.1	207560	43147
11	-	-	12	95	10.4	2	0.467	562853	0	0.188	75690	67324
12	-	-	12	95	10.4	-	0.468	562959	0	0.188	75690	67324

*Note: * - EE stands for excess electricity generation.*

Figure 10 presents a summary of the costs for the individual components of the optimal hybrid system over its projected lifetime. Figure 11 shows the monthly average energy production for the individual components of the optimal hybrid system, namely electricity generation by the MHPP, PV generator and diesel generator, as well as heat production by the TLC, CHP unit, and boiler.

From Table III it can be seen that the optimal hybrid system consists of 8.5 kW MHPP, 40.4 kW PV generator, 12 kW CHP unit with diesel generator, 109 batteries, 12.8 kW converter, and 39 kW TLC. The optimal hybrid system has the lowest total NPC and the lowest levelized COE amounting to 284421.0 $ and 0.178 $/kWh, respectively; as well as a high RF of 51.2 % and an excess electricity generation of 29 % (a part of the total electricity generated). With a high RF, there is a greater number of operating hours throughout the year. This is also accompanied by higher electricity generation and higher heat production, which in this particular case amount to 109899.0 kWh/year and 70849.0 kWh/year, respectively.

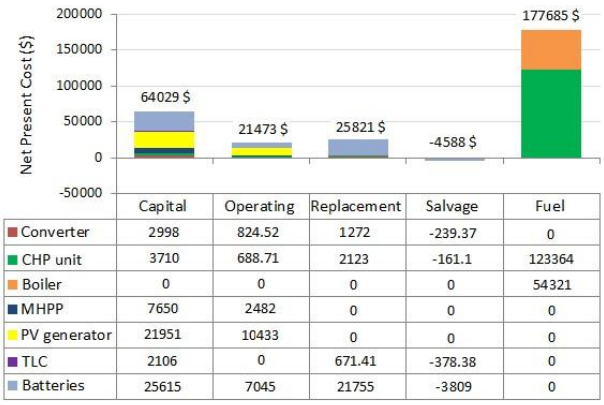


Fig. 10. Summary of the costs for the individual components of the optimal hybrid system configuration over the projected lifetime.

The second-ranked configuration is identical to the first one, but without TLC, which is why the power of the PV generator and converter, as well as the number of batteries, are reduced. In this case, RF and excess electricity generation are lower than those of the first-ranked configuration. In this regard, electricity generation and heat production are also lower, while the total NPC and the levelized COE are higher. It can also be noted that the seventh-ranked configuration has the highest RF value of 73.6 % and the highest excess electricity value of 69.1 %, and that the levelized COE is higher by 0.184 $/kWh than the one corresponding to Rank 1. However, the power of the PV generator for this rank is 167 kW, which is almost four times more than that of Rank 1. In addition, the number of batteries and the power of the converter are larger, so the total NPC is higher by 176752.0 $ compared to that of Rank 1. Rank 11 and 12 configurations consist of the CHP unit with the diesel generator, batteries, converter and boiler, with and without TLC, and have significantly higher GHG emissions than Rank 1 configuration. This can be seen in Table IV. Moreover, the total NPC and levelized COE are much higher than those of the best case. Therefore, the Rank 1 configuration can be considered as the best off-grid hybrid system to supply electricity and heat to the considered fishpond.

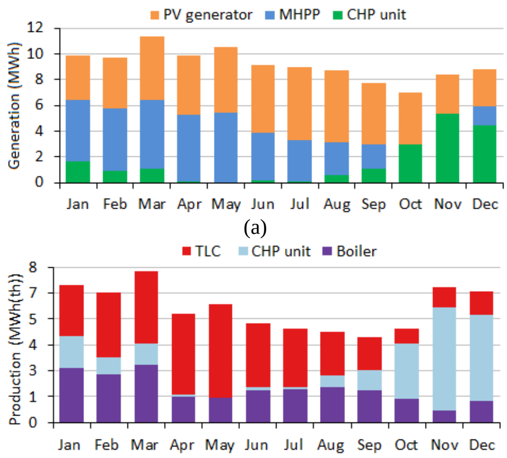


Fig. 11. Monthly average energy production for the individual components of the optimal hybrid system: (a) electricity generation, (b) heat production.

TABLE IV. GHG EMISSIONS FROM THE HYBRID SYSTEM CONFIGURATIONS CONSIDERED.

Rank	Emissions (kg/year)					
	CO_2	CO	UHC	PM	SO_2	NO
1	21173	91.5	4.03	0.548	42.9	86.0
2	24348	94.4	4.16	0.566	49.4	88.7
3	36830	201	8.84	1.20	74.5	188
4	37468	199	8.79	1.20	75.8	187
5	37705	227	10.0	1.36	76.2	214
6	18335	39.0	1.72	0.234	37.3	36.7
7	9794	0	0	0	20.0	0
8	13649	0	0	0	27.9	0
9	11077	0	0	0	22.7	0
10	13649	0	0	0	27.9	0
11	60924	378	16.6	2.27	123	355
12	60926	378	16.6	2.27	123	355

The summary of the costs for the individual components of the optimal hybrid system, shown in Fig. 10, indicates that capital and fuel costs contribute the largest share in the total NPC. High capital costs occur because of the inclusion of the PV generator and batteries, while the fuel cost is attributed to the operating times of the CHP unit with the diesel generator and the boiler. Maintenance of the PV generator leads to high O&M costs of 10433 $, and there are also battery replacement costs of 21755 $. Since the lifetimes of the MHPP and PV generator are the same as the projected lifetime, these RES do not have replacement costs. In addition, the total costs related to the TLC are the lowest and amount to 2399.03 $, which is 0.85 % of the total NPC. The highest costs refer to the CHP unit with the diesel generator and amount to 129724.61 $, which constitutes 45.6 % of the total NPC.

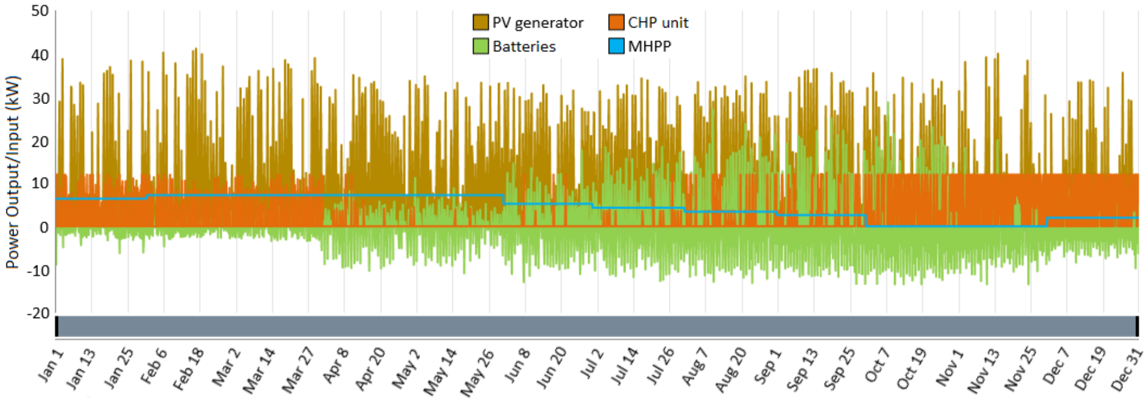
The next step is to accurately predict load demand and balance generation from different sources of electricity and heat. In this regard, the dispatch of power in a period of 365 days for power and thermal power flows is shown in Fig. 12. Figure 12 shows the simulation results related to the hourly operation of the following energy sources, namely the power outputs of the MHPP, PV generator, CHP unit with the diesel generator, TLC and boiler, and the power input of the ESS (i.e., batteries).

Based on Figs. 11(a) and 12(a), it follows that the main energy sources are the MHPP and the PV generator and the auxiliary CHP unit with the diesel generator and batteries. In this hybrid system, the majority of electricity should be generated by the PV generator (53197.0 kWh/year), followed by the MHPP (38399.0 kWh/year), and the CHP unit with the diesel generator (18304.0 kWh/year), which represent 48.4 %, 34.9 %, and 16.7 %, respectively, of the total electricity generation. Furthermore, it can be seen that the CHP unit with the diesel generator and batteries is activated when the demand cannot be met from the PV generator and the MHPP, specifically during the winter months when the solar irradiance is low and during the summer months when the stream flow is low. According to Fig. 12(a), the PV generator participates in electricity generation with a total of 4383 h of operation during the year and a maximum power output of 41.1 kW. In addition to this, the MHPP provides electricity throughout the year with a total of 7296 h of operation and a maximum power output of 7.23 kW, the CHP unit with the diesel generator provides electricity with a total of 2131 annual operating hours and a maximum power output of 12 kW, while the batteries operate with a maximum power input of 28.72 kW.

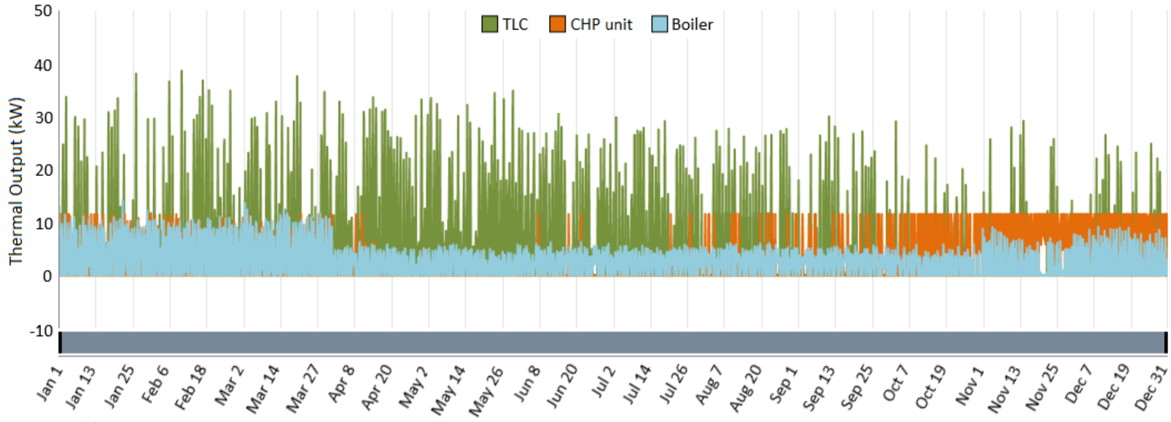
From Figs. 11(b) and 12(b) it can be seen that the peak production of heat occurs during the winter months and that the lowest production of heat occurs during the summer. In this sense, the most heat should be produced by TLC (31851.0 kWh/year), followed by boiler (20613.0 kWh/year) and CHP unit with diesel generator (18385.0 kWh/year), which account for 45.0 %, 29.1 %, and 25.9 %, respectively, of the total heat production. Specifically, Fig. 12(b) shows the contributions of the CHP unit with the diesel generator, boiler, and TLC to meeting the thermal load of the considered fishpond over a period of 365 days. The existence of TLC enables excess electricity generation to be converted into heat, so that there is very little or no unused electricity. For the TLC, boiler, and CHP unit with the diesel generator, the annual operating hours are 2982 h, 5189 h and 2131 h, respectively; while their maximum power outputs are 38.6 kW, 14.2 kW, and 11.6 kW, respectively.

Table IV lists GHG emissions, i.e., the concentrations of carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (UHC), particulate matter (PM), sulfur dioxide (SO_2), and nitrogen oxides (NO) released from each considered configuration. The release of GHG emissions and pollutants from the given hybrid power systems is attributed to the consumption of diesel fuel in the diesel generator and boiler. It can be seen in Table IV that the optimal hybrid system is environmentally friendly because it releases pollutants in the amount of 21398.0 kg/year and has a diesel fuel consumption of 8061.0 l/year. The seventh-ranked hybrid system has the lowest GHG emissions of 9814.0 kg/year and diesel fuel consumption of 3702.0 l/year, while the twelfth-ranked hybrid system has the highest GHG emissions of 61801.0 kg/year and diesel fuel consumption of 23272.0 l/year.

Table IV also shows that the main pollutant of the atmospheric air at this location is CO_2, followed by CO and NO, while the share of PM in total GHG emissions is the smallest. In this case, too, one of the ways to reduce GHG emissions is the increased use of RES. The dependence of RF on GHG emissions is presented in Fig. 13. This dependence shows that with an increase in RF, GHG emissions fall, and vice versa. Based on Fig. 13, the seventh-ranked hybrid system has the highest RF and consequently the lowest GHG emissions, while the twelfth-ranked hybrid system has no RF and therefore has the highest GHG emissions.



(a)



(b)

Fig. 12. Power dispatch in a period of 365 days for (a) the power flow and (b) the thermal power flow.

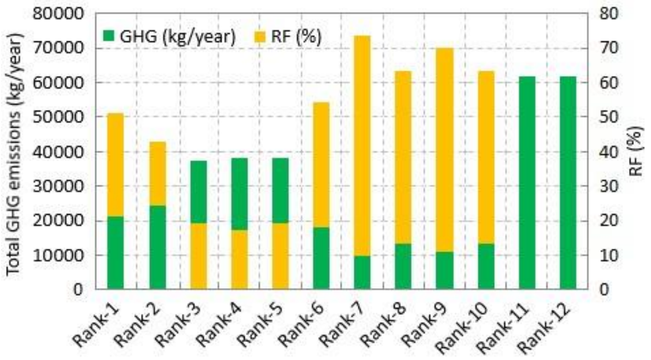


Fig. 13. Environmental performance of the hybrid system configurations considered.

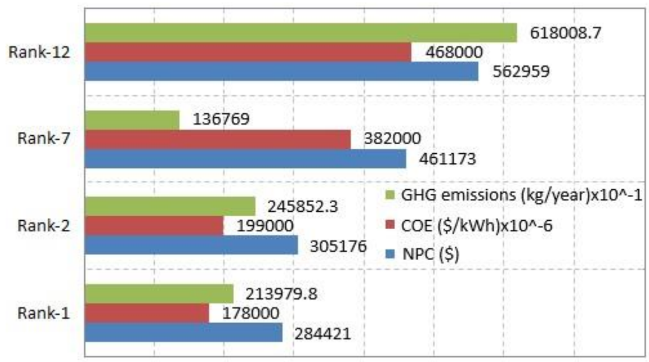


Fig. 14. A comparative presentation of the effects of RES and TLC on the system performance.

In order to investigate the effects of the RES and TLC on the optimal behaviour of the hybrid power system, various indicators were compared to each other. Thus, the optimal hybrid system is compared with the following three hybrid systems of similar configuration:

1. The twelfth-ranked hybrid system (base case), which does not include any RES and the TLC;
2. The seventh-ranked hybrid system, which does not include the CHP unit with the diesel generator;
3. The second-ranked hybrid system, which does not include the TLC.

According to Fig. 14 and Table III, compared to the second-ranked hybrid system, the use of TLC can reduce total NPC, levelized COE, and GHG emissions by 20755.0 $, 0.021 $/kWh, and 31872.5 kg/year, respectively. However, compared to the seventh-ranked hybrid system, where there is a very pronounced effect of the PV generator, the optimal hybrid system requires four times less power from the PV generator and approximately seven times smaller number of batteries. In this connection, it follows that the corresponding total NPC and levelized COE are lower by 38.3 % and 53.4 %, respectively; and that the corresponding GHG emissions are higher by 36.1 %. Furthermore, compared to the 12th-ranked hybrid system, the coupling of RES with the CHP unit, diesel generator, TLC, and boiler can have a very significant effect on saving the money invested and preserving the environment. According to this third comparison, the optimisation can reduce total NPC, levelized COE, and GHG emissions by 278538.0 $, 0.29 $/kWh, and 40402.9 kg/year, respectively.

Figure 15 shows the cumulative discount cash flow over the course of the project lifetime for the optimal hybrid system proposed and the base hybrid system (i.e., base case). According to this figure, the proposed system should return the invested money in only 1.8 years before it starts to make a profit. This confirms that the proposed optimal configuration could be, in principle, feasible.

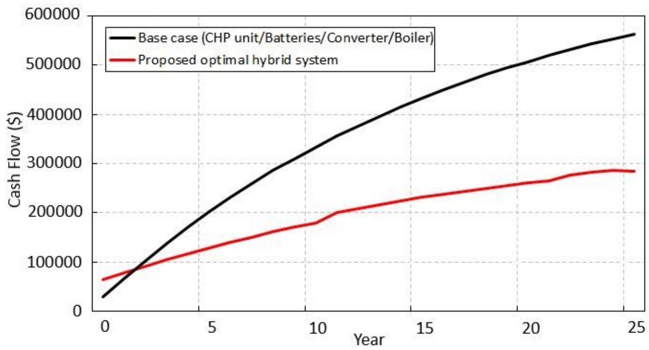


Fig. 15. Cumulative discounted cash flow over the course of the project lifetime.

VI. CONCLUSIONS

The optimisation and techno-economic analysis of the proposed off-grid hybrid system for the supply of electricity and heat to the Jablanica fishpond under the climatic conditions of eastern Serbia were carried out successfully. In addition, it was planned to grow carp in this fishpond in addition to trout, so the existing system should be integrated into the proposed one which uses water from the overflow of the settling basin, solar energy, the CHP unit, diesel fuel, batteries, TLC, converter, and boiler. Optimisation and techno-economic analysis of the proposed off-grid hybrid system were carried out using HOMER Pro software, and the following general conclusions can be drawn.

– Out of 12 possible configurations, the one consisting of 8.5 kW MHPP, 40.4 kW PV generator, 12 kW CHP unit with one diesel generator, 109 batteries, 12.8 kW converter, 39 kW TLC, and one boiler represents the optimal configuration for powering the considered fishpond with electricity and heat.

– Among all the configurations considered, the proposed hybrid system has the lowest total NPC of 284421.0 $ and the lowest levelized COE of 0.178 $/kWh.

– Compared to the base hybrid system consisting of a CHP unit with one diesel generator, batteries, converter, and boiler, the proposed hybrid system can reduce total NPC, levelized COE, and GHG emissions by 49.5 %, 62.0 %, and 65.4 %, respectively; and increase electricity generation, heat production, and RF by 31.1 %, 5.0 %, and 51.2 %, respectively.

– Integrating TLC into the hybrid system can reduce of total NPC, levelized COE, and GHG emissions by 6.8 %, 10.5 %, and 13.0 %, respectively. This also improves the RF by 8.2 %.

– A detailed analysis of the cumulative discounted cash flow showed that the proposed hybrid system is feasible because the investment can be recovered after only 1.8 years.

The results of this analysis determined that the fuel consumption rate and the effective price of fuel represent the main causes for the high total NPC and high GHG emissions for all considered hybrid systems. Specifically, for the proposed optimal hybrid system, it was obtained that only the fuel cost represents 62.5 % of the total NPC. In addition to RES integration, one of the ways to reduce total NPC and GHG emissions is to replace diesel fuel with fuels obtained from biomass. This can be considered as an idea for future research.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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