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OPTIMIZED DESIGN OF A HYDRO-SOLAR OFF-GRID ELECTRICITY GENERATION SYSTEM

BY

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Abstract. Hydropower is known as an inexpensive renewable energy source. Production costs of electricity increase only as the hydro power potential decreases. This work focuses on studying the benefits of implementing a pico-hydro turbine in a hybrid off-grid electricity generation unit, working at a power of up to 3 kW. Numerical simulations performed with the software HOMER, in a case study which is characterized by extreme operating conditions, highlight the importance of using a water turbine when possible. A location defined by a very low hydraulic potential and a solar potential specific to the southern Romania is considered. Four microgrid configurations are analyzed: hydro-diesel, hydro-solar-diesel, solar-diesel, diesel-only. The results highlight that, in the studied case, the use of all available renewable resources, including hydro, can be the best solution, both from a financial and a technical point of view. Furthermore, a high fraction of energy delivered to the load that originated from renewable power leads to low emissions in the first recommended case.

Keywords: hybrid micro grid; renewable energy; hydro resource; solar resource; HOMER software.

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1. Introduction

A study conducted by International Energy Agency, based on data collected during 15 years from 140 countries, estimates that new access to electricity generation from renewable sources will reach 60% by 2040 (IEA, 2017). The study specifies that, in the future, almost half of these new electricity production units will be stand alone, mini grid systems located in rural areas.

A report conducted by International Renewable Energy Agency points out that off grid renewable solutions increased from 2 GW installed capacity in 2008 to 6.5 GW in 2017, providing electricity to 120 million people in 2016 (IRENA, 2018). Most standalone systems are located in East Africa and South Asia, where the temperature and the high sunshine duration recommend solar PV as the best solution.

In Europe, renewable sources are diversified and, in addition to solar energy, the renewable on-site resources might include hydro, wind, biomass. According to Article 2(2) of the Energy Performance of Buildings Directive (Directive 2010/31/EU - EPBD) on nearly zero energy buildings, "the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (European Commission, 2016).

According to article 15(4) of the Regulation 2018/1999 of the European Parliament and of the Council that came into force on 24 December 2018 (European Commission, 2018), "Member States shall introduce appropriate measures in their building regulations and codes in order to increase the share of all kinds of energy from renewable sources in the building sector". The use of multiple renewable sources in the same micro grid energy system denotes a hybrid architecture. The scientific literature proposes and analyzes different design configurations to be used in off grid renewable energy systems, such as hydro-solar (Jure and Glasnovic, 2010; Ismail *et al.*, 2013) and hydro-wind (Jaramillo *et al.*, 2004; Bakos, 2002; Prabhakar and Ragavan, 2013).

In this paper, the design of an off-grid electricity generation system, that supplies a residential building, is studied by using the HOMER software (HOMER Energy, 2019). The building is located near a small hydro resource and different micro-grid configurations that contain hydro or/and solar resources are analyzed, in order to identify the best architecture. The operating conditions for the pico-turbine are extreme: very low head ($H < 2$ m), very low flow rates (20 l/s $< Q <$ 300 l/s) and periods without useful hydraulic potential because the season is very dry. Based on the net present costs and on the reduced emissions criteria, the results of this study point out how important is to implement water pico-turbines in hybrid systems, even though hydraulic parameters are out of the range where classic turbines are recommended.

2. Methodology

Hydropower is the world's largest source of renewable electrical power that generated 4185 TWh of clean energy in 2017, representing 16.4% of the total electricity production, while wind power produced 5.6%, biomass 2.2% and solar PV 1.9% (IHA, 2018). In Europe, sites that had large or medium hydropower potential are already homes of hydroelectric power plants. There is enough room for small hydropower plants, but new investments in the sector must follow strict environmental rules, imposed by the Water Framework Directive (WFD). One implementation problem refers to the measures required to keep in the river the "amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon", the so-called ecological flow (EC, 2015). In Romania, the legislation specifies restrictions concerning the amount of water flow rates that can be considered for hydropower purposes and the monthly average water flow rates available to be used by water turbines must be calculated according to it (OUG 78/2017).

In the following, a comprehensive case is studied to understand whether very little hydro energy potential is worthy to be used in a hybrid micro grid that supplies a remote building with electricity. The methodology is based on the numerical analysis that the HOMER software can perform. HOMER, the abbreviation of "Hybrid Optimization Model for Multiple Energy Resources", is a software originally developed at the National Renewable Energy Laboratory, U.S.A, that provides tools for optimizing microgrid design in all sectors, so that engineering and economics work side by side.

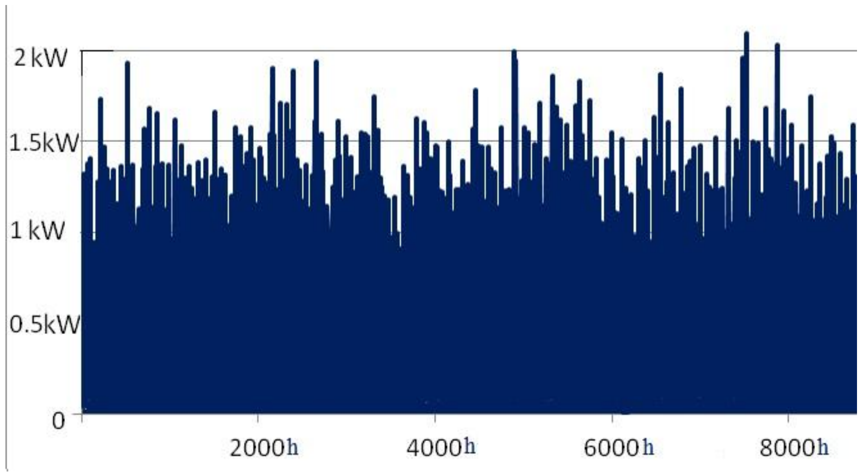

Fig. 1 − Electrical load versus time during one year (8760 h).

The residential building studied in this paper is situated in Romania, on Desnățui river, near Drăgoaia village (latitude 44°13.8 N, longitude 23°30.8 E).

The diagram of the electrical load versus time, over a period of one year, is presented in Fig. 1.

Renewable resources data to be used are presented in Table 1: multiannual monthly average flow values calculated based on measured data collected during 1965-2009 (Ciuinel and Onţel, 2012) on Drăgoaia hydro-measuring station (column 2); monthly average flow values available for hydro power purposes, calculated by subtracting from the multiannual monthly average flow value the ecological flow and the flow to be used by the nearby communities (column 3); solar clearness index (column 4); solar daily radiation (column 5). The data on solar energy are from NASA Surface meteorology and Solar Energy database (HOMER Energy, 2019).

Table 1

Input Resource Data

Month	Multiannual monthly average flow [l/s]	Available monthly average flow [l/s]	Solar clearness Index	Solar daily radiation [kWh/m^2/day]
January	430	223	0.438	1.540
February	940	605	0.481	2.380
March	1020	665	0.490	3.460
April	450	238	0.475	4.410
May	400	200	0.501	5.460
June	270	103	0.526	6.100
July	340	155	0.555	6.230
August	210	58	0.560	5.530
September	160	20	0.515	4.020
October	350	163	0.456	2.540
November	350	163	0.412	1.580
December	420	215	0.398	1.230

The micro-grid configuration to be analyzed and optimized with HOMER software contains the following components: the electrical system of the building having the average daily energy consumption E_{day}=11.26 kWh/day, the annual energy consumption E_{year}=4019 kWh/year, and the peak load P_{max}=2.09 kW; a Banki water pico-turbine for very low heads, H<2 m, with the flow rate Q=100…300 l/s and the nominal power output P=1.92 kW; a PV system, equipped with inverters and MPPT (Maximum Power Point Tracker), which can use up to 12 photovoltaic panels of 0.26 kW each, providing the overall maximum power output of P_{max}=3.12 kW; a diesel generator, with a power output of P=4.2 kW; batteries with the nominal capacity E=0.96 kWh and 40 Ah; a converter with the nominal capacity P=3 kW; a load following controller. The excess energy can be used by a pump that fills with water a reservoir.

The financial data used in the simulations are as follows: discount rate 8%; inflation rate 3.8%; project lifetime: 30 years.

Once input data are implemented, HOMER attempts to simulate viable systems for all possible combinations of the equipment that has been considered. The main objective is to identify feasible micro-grid architectures at the lowest net present cost. A number of 4568 solutions were simulated, from which 780 were not feasible due to the capacity shortage constraint and 754 had to be omitted due to other technical issues. From the total, the software recommends 8 solutions. Since renewable resources may not be available full-time and shortage of electrical energy is not acceptable, 4 design solutions that did not contain storage batteries had to be eliminated. As a result, only 4 micro grid design solutions where chosen to be robust. Details on the components of highly recommended architectures are presented in Table 2 as scenarios 1 to 4. In the following, the scenarios will be used for financial and technical analyses, performed by numerical simulations.

Table 2
Simulation Scenarios of Recommended Solutions

Micro-grid architecture (installed power)	Sc. 1 (H+G)	Sc. 2 (H+S+G)	Sc. 3 (S+G)	Sc. 4 (G)
Solar Panels 0.26 kW, [pcs]	0	2	10	0
Banki turbine 1.92 kW, [pcs]	1	1	1	0
Diesel generator 4.2 kW, [pcs]	1	1	1	1
Battery 0.96 kW, [pcs]	1	1	3	2
Inverter capacity, [kW]	1.55	1.56	0.996	0.75

The first architecture, denoted as simulation scenario 1 (H+G), considers the Banki turbine and the diesel generator. The second simulation scenario (H+S+G) is based on the Banki turbine, a solar system with 2 solar panels having a power capacity of 0.26 kW each and a back-up diesel generator. The third micro-grid architecture, denoted as simulation scenario 3 (S+G), contains a solar system with 10 solar panels and the diesel generator. The last solution, simulation scenario 4, uses only the generator that runs on diesel to produce electricity and stores the excess in batteries. The later scenario is necessary in this work to underline the technical benefits of using renewable sources and to understand whether the high capital costs needed to purchase them pay off.

In all scenarios, the type of converter, the load following controller and the type of batteries are the same. To match the demand to the supplied energy of the microgrid, the necessary number of batteries and the capacity of the inverter were calculated with HOMER.

3. Numerical Results

Financial results that include net present costs, initial capital costs, operating costs, replacement costs and the levelized cost of energy, obtained by HOMER software, are presented in Table 3.

Table 3
Financial Results of Simulation Scenarios

Simulation results	Sc. 1 (H+G)	Sc. 2 (H+S+G)	Sc. 3 (S+G)	Sc. 4 (G)
Net present cost, [$]	26132	26860	53496	71558
Operating cost, [$/year]	977	955	2350	3826
Initial capital, [$]	9319	10427	13095	5775
Replacement, [$]	5732	6066	12523	16758
Levelized cost of energy, [$/kWh]	0.37	0.38	0.757	1.01

The best financial results are obtained for scenario 1, when the electricity is produced only from hydro resources and with the diesel back-up generator. Scenario 4 without renewable resources leads to the lowest initial capital cost and the highest operating cost. The levelized cost of energy of 1.01 $/kWh represents 272% compared to the rate obtained in scenario 1.

Table 4 presents the technical results of the simulation scenarios. It contains data on the renewable energy fraction and on the rate of electrical energy production from each source. The fraction of renewable energy was calculated by dividing the energy produced from renewable sources by the total energy delivered to the consumer through the micro grid.

In accordance with the energy resource and to the type of fuel, the emissions were also calculated and the obtained results are presented in Table 4.

Table 4
Technical Results of Simulation Scenarios

Simulation results	Sc. 1 (H+G)	Sc. 2 (H+S+G)	Sc. 3 (S+G)	Sc. 4 (G)
Renewable energy fraction, [%]	76.9	78.9	40.5	0
PV electricity production, [%]	0	4.37	49.6	0
Banki electricity production, [%]	93.0	89.5	0	0
Diesel electricity production, [%]	7	6.16	50.4	100
Total diesel fuel consumed, [l]	384	350	990	1857
Carbon Dioxide, [kg/year]	1005	917	2592	4863
Carbon Monoxide, [kg/year]	6.27	5.72	16.2	30.4
Unburned Hydrocarbons, [kg/year]	0.276	0.252	0.713	1.34
Particulate Matter, [kg/year]	0.0376	0.0343	0.097	0.182
Sulfur Dioxide, [kg/year]	2.46	2.24	6.35	11.9
Nitrogen Oxides, [kg/year]	5.9	5.38	15.2	28.5

4. Conclusions

The paper uses the HOMER software to identify the optimized solution to design a micro-grid system that can use hydro, solar and diesel fuel to generate electricity for a residential building located in a remote location, without connection to the electric grid. In accordance to the input data, the HOMER software proposed several design configurations and four of them were chosen to be highly recommended and further analyzed.

The first one, a hydro-diesel scheme was shown to generate the lowest net present cost, operating cost, and levelized cost of energy and emissions. The second configuration, namely the hydro-solar-diesel one, uses most of the renewable resources available on-site. The third configuration proposed uses only solar and diesel as source of energy.

Although in the studied location the hydro resource is too low to be used two months per year, the net present cost increases up to 204.7% when solar panels are used instead of the water turbine. Technical data confirms that scenarios based on the energy produced from hydro resources are the best; the fraction of renewable energy is the highest; the quantity of diesel fuel consumed is the lowest.

The forth configuration is the usual solution for remote locations, a diesel generator that requires very low initial capital investment. The study points out that this requires the highest operating, replacement and net present costs.

To conclude, offline micro grids based on renewable energy sources have the reputation to be very expensive, but the present study demonstrates that they can be the best solution from a financial, technical and environmental protection point of view, compared to the diesel generator-only solution.

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CONFIGURAREA OPTIMIZATĂ A UNUI SISTEM HIBRID HIDRO-SOLAR DE PRODUCERE A ENERGIEI ELECTRICE OFF-GRID

(Rezumat)

Hidroenergia este cunoscută ca fiind o sursă ieftină de energie regenerabilă. În cazul amenajărilor hidroenergetice, costurile de producție ale energiei electrice sunt invers proporționale cu puterea de producție. Lucrarea studiază beneficiile produse de implementarea unei pico turbine hidro într-o microrețea hibridă de putere de până la 3 kW, care alimentează o clădire rezidențială, neconectată la Sistemul Energetic Național. Simulările numerice efectuate cu software-ul HOMER, într-un caz în care condițiile de funcționare sunt extreme, subliniează importanța utilizării turbinelor hidraulice într-un sistem hibrid. Locația analizată în studiul de caz, dispune de energie solară specifică zonei de sud a României și de energie hidraulică caracterizată prin căderi și debite extrem de mici, de regulă, neexploatabile. Programul de calcul propune patru soluții, hidro-diesel, hidro-solar-diesel, solar-diesel, diesel pur. Rezultatele relevă că utilizarea resurselor regenerabile locale, inclusiv din surse hidro este cea mai bună soluție, atât d.p.d.v. tehnic cât și economic. În plus, microrețelele hibride, bazate preponderent pe resurse regenerabile, conduc la emisii reduse de noxe în mediul ambiant.