Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 62 (2014) 512 – 521
Energy Procedia

6th International Conference on Sustainability in Energy and Buildings, SEB-14

Technical and Economic Perspective for Repowering of Micro Hydro Power Plants: a Case Study of an Early XX Century Power Plant

A. Gagliano[a], G. M. Tina[b], F. Nocera[a] , F. Patania[a]

[a]*University of Catania, DII, viale Andrea Doria 6, Catania 95125, Italy*
[b]*University of Catania, DIEEI, viale Andrea Doria 6, Catania 95125, Italy*

Abstract

Nowadays many countries have dramatically cut the incentives for solar photovoltaic and wind farms; consequently many new investors and entrepreneurs pay more attention to small and mini hydro power plants. Hydropower currently respect to other renewable sources has not negligible benefits as lower cost of installation to equal installed capacity, higher reliability, higher energy production and more intensity and consistency over time. Many aspects as well as the sensibility to environmental issues related to civil works and the introduction of incentives for the production of renewable energy from small plants (< 1 MW) drive the attention to small Hydro Power Plants (HPPs). The thousands of historic mills, water wheels, inoperative hydropower stations or unrealized potential offer an interesting opportunity for small and micro hydropower generation.
This article evaluates technical and economic feasibility of the repowering of one of the oldest Sicilian hydro power plant currently abandoned and disused. The reactivation of the Catarrate hydropower plant allows producing energy from renewable source contributing to the energy independence of the local community, with an energy yearly production of about 220 MW. Moreover, this study demonstrates the attractiveness of small hydropower as a local investment vehicle and at same time an occasion to preserve the historical industrial heritage of disused hydro plants.

Selection and peer-review under responsibility of KES International
Keywords: micro-hydro power, renewable energy, repowering, economic analysis

1. Introduction

Hydroelectricity is one of the most mature forms of renewable energy, providing more than 16% of the world's electricity consumption from both large and small power plants [1].

* Corresponding author. Tel.: + 39-320-433-2228; fax: +39-095-738-2496.
E-mail address: agagliano@dii.unict.it

Selection and peer-review under responsibility of KES International
doi:10.1016/j.egypro.2014.12.413

The hydropower plants can be classified in function of different parameters [2],[3]:

• head: low (less than 50 m); medium (between 50 and 250 m); high (greater than 250 m);

• exploitation and storage: with daily (or seasonal) flow regulation (reservoir type); without flow regulation (run-of-the-river type);

• conveyance system: pressurized (penstock); mixed circuit (canal and penstock);

• powerhouse site: dam or diversion scheme;

• energy conversion mode: turbining or reversible pumping-turbining;

• type of turbines: impulse, reaction and reversible;

• installed power: pico ($P_t < 5$ kW; micro ($5 \leq P_t < 100$ kW); small ($100 \leq P_t < 1$MW); medium ($1 \leq P_t < 10$ MW).

Hydroelectric facilities are typically older and operate with a mismatched assortment of hardware and controls, which are not optimized to work as a unified system. The median age of hydroelectric capacities in Europe is 41 years. This and barriers to new builds explain why electric utilities in Europe tend to focus on the repowering of existing plants with modern turbines and equipment rather than greenfield projects. Many aspects as well as the sensibility to environmental issues related to civil works and the introduction of incentives for the production of renewable energy from small plants (< 1 MW) drive the attention to small HPPs (S-HPPs). Moreover, the dramatically cut off the incentives for solar and wind farms might attract many new investors and entrepreneurs to pay more attention to small hydro. With approximately 13 GW [3], small hydro represents a significant renewable energy resource. The renewed interest for HPPs is witnessed by several projects co-financed by the European Commission under the Intelligent Energy Europe programme, i.e the Renewable Energy Sources Transforming Our Regions (RESTOR) Hydro, or Hydro Data Initiative (HYDI), which provides statistics and information on energy, market and policy data covering the entire Hydropower sector in EU-27 Member States. Access to the database is free of charge. Several studies demonstrate that the potential for future S-HPPs development, both in terms of upgrading the oldest existing plants and building new sites [3],[4],[5]. The annual electricity production exploitable through the reinstalling or upgrading existing underdeveloped plants was estimated in of about 4500 GWh [6]. The aim of this study is twofold: firstly the assessment of the economic perspectives of mini-hydro in Italy is performed (section 2), therefore the perspectives of the repowering of an old micro hydropower plant located in the territory of Petralia Sottana (Sicily) is presented (section 3,4 and 5), finally some conclusions are drawn..

2. Economic perspective of mini-hydro power plants in Italy

Italy is one of the leading countries in Europe referring to hydroelectric power generation, where many historic mills, water wheels, inoperative hydropower stations, weirs and other lateral structures in rivers, which constitute an unrealized potential for small and micro hydropower generation exist. The exploitation of water energy through hydraulic wheels occurred between XII and XIII centuries, while of the invention of water turbine (1827) led to development and spread of modern hydro power stations in Europe. The first run-of-river water hydropower, called “Tusciano”, was built in Italy in the late nineteenth century (1890). At that time, the hydro source was the most favorable energy source and it was called "white coal". Until the 60s, electric energy demand was almost entirely satisfied by hydraulic energy resource, certainly the most efficient of the renewable sources. For example, the annual electric production in Italy in 1960 was of around 56 TWh, of which 82% hydroelectric. Many small HPPs were abandoned and disarmed during the nationalization of the electric energy (1962) and many of them could be reactivated today in Italy.

Nowadays S-HPP contributed to about 5% of the electricity generated by hydropower (41.8 TWh) and to about 2.5% of the total electricity generation from renewable sorces [7].

Available statistics show that in 2012, there were 1,886 small hydro plants achieved with an overall installed capacity of 590 MW (figure 1). HPPs grew at an annual average rate of 1.3% but the installed capacity increased only by 0.7% per year. Small and medium size HPPs (<1 MW and 1-10 MW) have higher rate of expansion, while the number of larger HPP remains almost constant [7].

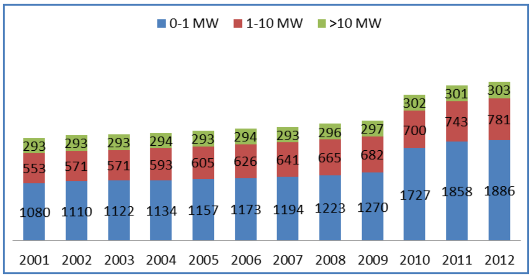

Fig. 1. Hydroelectric plants in Italy from 2001 to 2012.

The slow but steady growth of small hydropower has been driven by tariff schemes, incentive and regulatory favorable to the so-called "distributed generation", in which you can recognize indisputable social and environmental benefits. Tangible examples among others are measures to simplify authoritative procedures (Italian law, D.Lgs. 387/2003); guaranteed minimum prices (decree of Authority, AEEG 280/07) which guarantee a minimum return, regardless of the performance of the electricity market. In the next future are expected the realization especially of small and mini hydropower plants, in line with what happened in the last few years. A recent survey estimates a ‘reasonable’ potential for further development equal to 1 GW [8]. Moreover, Hydro plants are characterized by lower investment costs per kW and by larger productivity compared to competing renewable sources. Table 1 shows costs and some financial data for Small Hydro plant [9].

Table 1. Economics data for small hydro power plants.

	Low head	High head
Average investment cost (€/kW)	4500	3800
Average cost per kWh produced (€)	0.15	0.076
Average O&M cost (as % of total investment cost)	1 to 4	1 to 3
Average lifetime of the mechanical equipment (number of years)	30	30
Average civil works cost (as a % of total investment cost)	50 to 60	40 to 50
Internal Rate of Return IRR (average in %)	10 to 15	15 to 20

2.1. Incentive policies for mini-hydro

A feed-in tariff (FIT) is one policy option used to encourage the deployment of renewable energy by making it a more secure long-term investment. Under a feed-in tariff, renewable energy producers are guaranteed a connection to the electric grid and a payment rate set above market price by the government. Historically, Italy has the highest incentives in Europe for renewables production (for example, the unit incentives for photovoltaic production were about double those of Germany). The 2008 Budget Law (244/2007), updated by law 99/2009, introduced a 15 years feed-in tariff (omni-comprehensive tariff) for RES-E plants as alternative to Tradable Green Certificates (TGCs). The “omni-comprehensive tariff includes both the price of the energy sold to the system and the incentive of the power stations. It can be applied to plants that have been operative since December 31st 2007, with a nominal power capacity less than 1 MW (except for photovoltaic). Table 2 shows the tariff level (€/MWh) and duration of support for different technologies.

Table 2. Tariff level (€/MWh) and duration of support for different technologies

	Small hydro	Wind	Biomass	Biogas	PV	Geothermal
fixed	220 15 years	220 15 years	280 15 years	280 15 years		200 15 years
premium					353 ÷480 20 years	

In 2012 the Omni – comprehensive tariff included 851 GWh with an expense of 187 M€ [7]. Figure 3 reports the level of remuneration in the different EU countries applying feed-in tariffs for electricity from small-scale hydro power plants. An alternative support for the RES-E is ensured by simplifying the conditions of market access, through the provision of some specific services, (e.g. net metering).

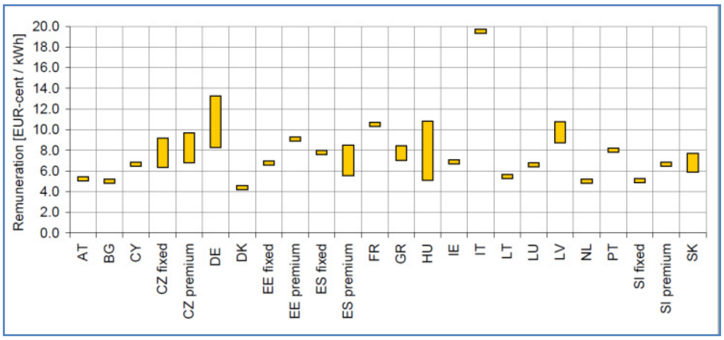

Fig. 2. Bandwidth of remuneration from FIT for small-scale hydropower in Europe [10]

For small plant owners, two simplified mechanisms are available: Net metering and purchase & resale arrangements ("ritiro dedicato" or RID). The GSE has offered simplified purchase & resale arrangements to small producers since 2008. An agreement is entered between the producer and GSE, whereby GSE purchases and resells the electricity to be fed into the grid at the zonal price or at a minimum guaranteed price; on behalf of the producer, transfers the fees for the use of the grid (dispatch and transmission fees) to distributors and to the Transmission System Operator. The guaranteed minimum prices are updated annually by AEEG. At the end of each year, GSE makes adjustments for plants in respect of which the revenue associated with the hourly zonal prices proves to be higher than the one resulting from the application of the minimum guaranteed prices. The simplified purchase & resale arrangements are not compatible with net metering and the all-inclusive feed-in tariff.

Table 3 – Summary of the available tariffs for small hydro power plants in Italy

Time	Incentive	Energy value
First 15 years	Omni – comprehensive tariff	Omni – comprehensive tariff
After	No incentive	Self-consumption and Free market[1], "dedicated withdrawals"; Net metering

[1]The energy exceeding the self-consumption needs issold on the free market.

Currently, the political address is that incentives need to be brought in line with European levels to keep energy bills down, given the burden they place on businesses and households. In this context, several policies and regulatory framework have been assumed to decrease the FIT for RES. Since 1 January 2014, the dedicated withdrawal has been heavily modified (reduced) with the stated aim of reducing the impact of component A3 tariff on electricity bills. According to the "guaranteed minimum prices" only the first 1,500,000 kWh are appraised (2,000,000 kWh for hydro and biogas from biomass). The energy produced in excess of 1,500,000 kWh (2,000,000 kWh), is paid according to the market price of a quarter of an hour. The annual change in prices is indexed according to the ISTAT consumer price index (FOI 2013), unless the hydroelectric who from 2014 will not enjoy of increases. The reduction of the minimum prices affects all sources; it is lesser for the mini-hydro and biomass plants, while for the solar minimum guaranteed price has halved, from 80.6 to 37.8 €/MWh.

The annual change in prices is indexed according to the ISTAT consumer price index (FOI 2013), unless the hydroelectric who from 2014 will not enjoy of increases. The reduction of the minimum prices affects all sources is less it is lesser for the mini-hydro and biomass plants, while for the solar minimum guaranteed price has halved, from 80.6 to 37.8 €/MWh. After FIT incentives scheme, Italy's renewable energy market will be based on promotional schemes like net-metering in combination with tax rebates and increasingly on power purchase agreements (PPAs). Regarding the latter, the hopes of the domestic renewables industry lie on a pending deliberation by Italian Authority (AEEG). Among other things, the deliberation is meant to regulate Efficient User Systems (SEU), where producers of electricity from renewable sources are directly connected with the end customer.

3. The Madonie's hydro power plants at the early 1900.

In the central part of Sicily (Italy) there is the "Madonie" mountain chain, where the use of water to provide motive power has ancient origin as evidenced by numerous ruins of water mills and hydraulic machines (gualchiere) still visible today. Since early 1900 in that area a cascade network was built of four HPPs that exploit the local hydro energy resources. These power plants were distributed along the torrent "Mandarini"or Imera Meridionale. Table 4 shows the main characteristic of such hydro plants [11].

Table 4 – hydro plants cascade network

Hydro plant name	Cataratte	Paratore	Pagliaio	Castellana Sicula	Pucci&Calascibetta
Turbine type	Pelton	Pelton	Francis	Pelton	water mill
Rated power	193 kVA	170 kVA	135 kVA	180 kVA	-

The aim of this paper is the evaluation of the feasibility and affordability of the refurbishment and modernization of the hydro power plant "Catarrate" located near Petralia Sottana town. Figure 3 shows some photos regarding the area where it is located, as well as the cabin construction and the electromechanical equipment. The source Catarratte, site at 1175 m.a.s.l. on the Mount San Salvatore, is perennial and has an average flow of about 40.5 l/s. The construction works of the hydroelectric plant started in 1907, as discovered in the archive of Petralia Sottana. The plant has changed over time and has had upgrades, revisions, technological adjustments to achieve a more rational exploitation of hydropower. The electrical energy produced by the plant was used to supply electricity for public lighting of Petralia Sottana as well as the electricity demand for private users. The yearly energy production plant was found out through archive researches and interviews to people, who have worked in the plant until its closure.

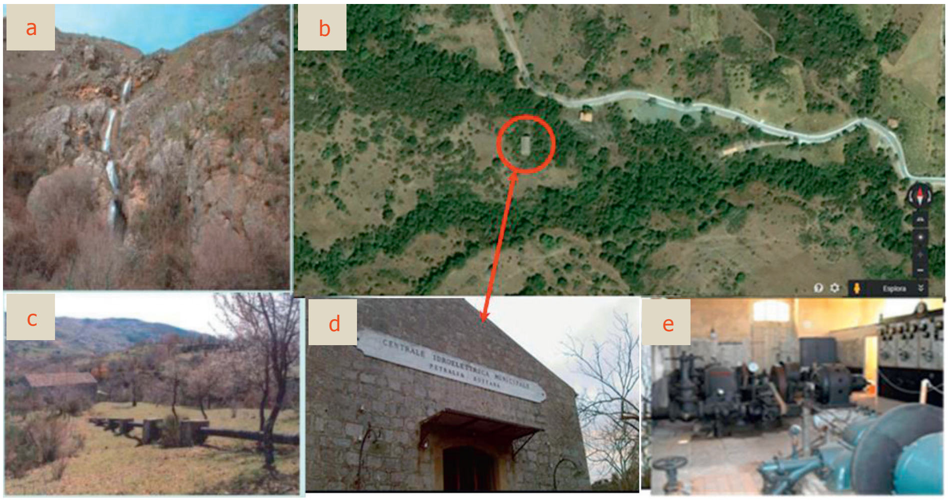

Fig. 3. “Catarrate’s HPP: spring (a), HPP placement (b), penstock (c), cabin (d), mechanical equipment (e)

In 1932, the plant was equipped with an accumulation reservoir located immediately upstream of the penstock that drops the water to the turbines and it has function of flywheel, limiting the flow variations of the Cataratti source. Since 1958 the power station was equipped with a turbine type Calzoni Riva whose power rating is 77 kW, the flow rate and the Net Head Gross were, respectively, of 63 l/s and 150 m. The shaft from the turbine went up into the electric generator type Pellizzari with an active power of 85 kVA and 1500 rpm. The hydro plant remained operative beyond the 1963 (year of the Nationalization of electrical production), as the power plants owned by municipalities were protected. Thereafter in 1963, the energy production was used only for feed the public lighting and the power plant was operative only during night time. The hydro plant stopped the production of energy in May 1972 and was closed and disused definitely in November 1972. Many components of the disused hydro plant are in good state of conservation, especially the powerhouse, the turbines and some other equipment.

4. 1. Simulation tool

The technical and economic evaluation of mini hydro power plants is usually done through specific software. In this study a simulation tool, called “MadoWatt”, has been developed in Matlab environment. Figure 3 shows The modules discharge, turbine, energy, costs and financial analysis, constitute the simulation tool (Figure 4). Each module is divided into sub modules logically structured to lead the user to the final result. The module discharge allows determining the available flows esteemed, throughout the flow Duration curve (FDC), which is obtained plotting recorded values of flow during the year on number of days in which this value has been reached or overcome. The FDC coincides with the curve of flow rates used "cut" horizontally at the design flow rate and vertically at the minimum flow rate of the turbine. The module Turbine allows determining the technical parameters of the turbine in function of the head, discharge, rotational speed and cavitation’s’ problems. The suitability of the turbine is evaluated by calculating the revolutions per minute (rpm) of the Pelton turbine, which is the only typology, which can be chosen, since the architecture of the “old” hydro plant want to be maintained. If the rpm are less than 100 the MadoWatt indicates that the number of hydro jets are function of the diameter. The energy module calculates the energy delivered based on the adjusted available flow (adjusted flow-duration curve), the design flow, the residual flow, the load (load-duration curve), the gross head and the efficiencies/losses.

The costs module aims to estimate the cost required for the construction of the power plant in all its components. The financial analysis module calculates the Net Present Value (NPV).

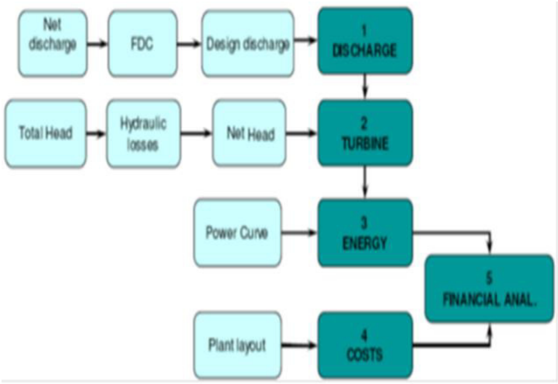

Fig. 4. Madowatt flow chart

The energy power P and the efficiency "η_t" of the turbine has been calculated with the follows equation [11]. The complete set of equations used can be found in reference [12].

$$P = \rho g H Q \eta_t \eta_g \left(1 - l_{trans}\right)\left(1 - l_{para}\right) \quad (1)$$

$$\eta_t = \left\{1 - \left[1.35 \cdot \left|\frac{Q_p - Q}{Q_p}\right|^6\right]\right\} \cdot \eta_p \quad (2)$$

ρ is the density of water, η_g is the generator efficiency, l_{trans} are the transformer losses and l_{para} are the parasitic electricity losses, Q_p (peak efficiency flow)= $0.663 \cdot Q_d$; η_p (Turbine peak efficiency) = $0.864 \cdot d^{0.04}$. The minimum flow rate is limited to 40% of the design flow rate in such manner to have an acceptable turbine efficiency, which is the lowest flow without an accumulation reservoir.

4.1. Testing of MadoWatt

MadoWatt has been tested through the comparison between the energy production calculated by this simulation tool and the yearly energy production of the "Catarrate" hydro power plant in the year 1972. In 1972, the HPP worked only during night hours with the operating characteristics summarized in Table 5.

Table 5 – input data

Description	Symbol	Value	Unit
Gross head	H_d	155	[m]
Design Flow	Q_d	40	[l/s]
Pipeline Length; Manning's coefficient; Gaukler-Strickler's coefficient	L; N; K	700; 0.009; 111	[m]; -; -
Rate of gross head limit losses ; Concentrated losses		4; 0	[%]; [m]
Efficiency of Generator,; Frequency; Rotor speed	η_g	95; 50; 1500	[%];[Hz] ; [Rpm]

Figure 5a and 5b show respectively the minimum/maximum/average values of the flow rates "Q_s", the monthly "E_m" and daily "E_d" energy production. The simulations performed by MadoWatt estimate an annual electric energy production of 195.8 MWh. The comparison between the energy yearly production calculated trough MAdoWatt and the energy production obtained in the year 1972, shows a difference of just 2%. Consequently, it is possible to assert that the results of simulation can be considered sufficiently reliable.

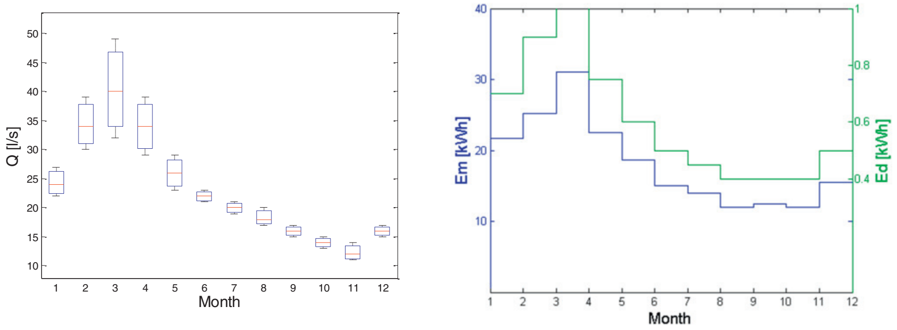

Fig 5. Operating data of HPP: (a) flow rates; (b) yearly energy production

5. Repowering of the disused plant

In order to refurbish the disused HPP it is necessary to consider the availability of the water of the Catarrate's spring. Nowadays the Catarrate's spring feed the public aqueduct of Petralia Sottana.

Thereby, a bypass valves and a control system should be installed to ensure the continuity of the water supply in the public aqueduct [2]. Considering the characteristics of the site a turbine Pelton "Ecowatt Series AS4" has been selected (figure 6) that has dimensions of 1050x1050x1450 mm. It is fitted with six nozzles controlled by flow regulation valves, which help the efficiency of the system. The runner is directly splined onto the generator shaft; all the main mechanical parts are in stainless steel.

As the Pelton turbine operates in the air, at atmospheric pressure, the reservoir that receives the turbine outlet must be guarantee a sufficient pressure, or, in alternative, a counter pressure Pelton turbine must be chosen to guarantee the required pressure.

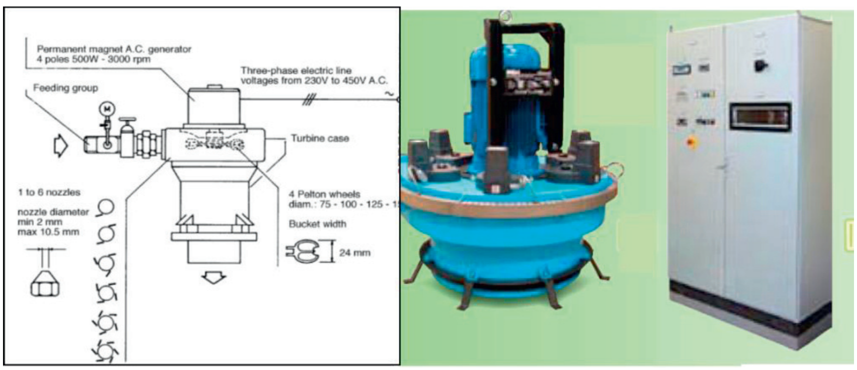

Fig. 6. Layout of the Turbine Ecowatt Series AS4; Turbine Generator Group and Electric Board Control.

Substantially, it will be necessary install a new drainage block, a cabin for the hydro-turbine generator group and an electric control board. In order to identify the most convenient plant scheme two systems configurations were evaluated: a) the turbine is placed after a reservoir, where the water is accumulated; b) the turbine is placed within the supply network.

5.1. Results of simulation

Simulations carried out allows obtaining the trend of the average daily flow rates, which is common for both the plant configurations. Fig. 7a shows: the FDC curve, the flow limits to maintain acceptable turbine efficiencies, the daily flow available with storage and the daily storage. Fig. 7b shows the energy production for the configuration whit the reservoir

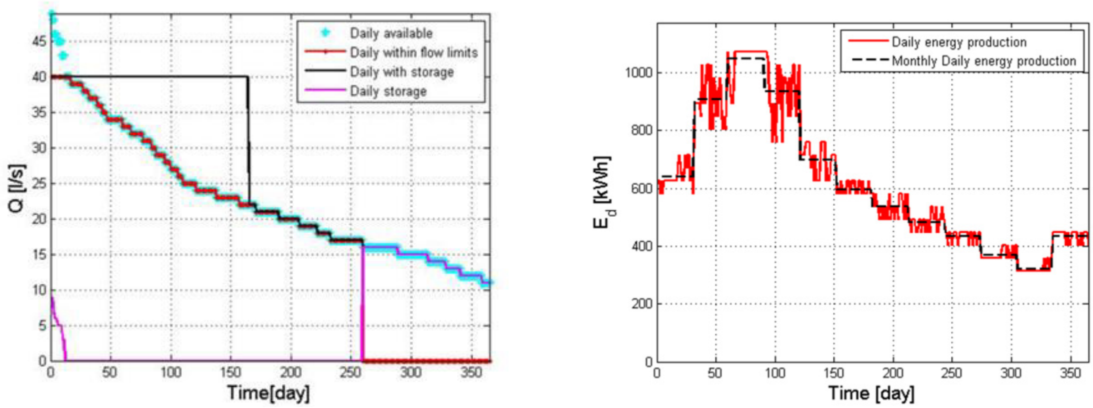

Fig. 7. Simulation results: (a) yearly FDC; (b) daily and monthly energy production

The two configuration give respectively the following electrical energy production: 223.74 MWh (with reservoir) and 187.67 MWh (without reservoir). The results of this study demonstrate that the repowering of the “Cataratte” hydroelectric plant allow producing renewable energy, otherwise wasted. Since the average electrical consumption of an Italian household is estimated at 3,500 kWh/year [13] the HPP satisfies the electricity needs of about 60 household with a Net GHG reduction of 102 ton CO_2/yr.

6. Financial Analysis

The capital cost of a micro-hydro project, include engineering, mechanical, electrical, site development, mark-ups and installation. The cost of installing HPPs varies from place to place. It depends on the existing infrastructures and the installation capacity. These costs have been overall estimated at approximately € 120,000, with a typical cost of €/kW 2,000 for this size of plant [14], [15]. The maintenance and operation (M&O) costs are similar to a pump, with an average of 5.000 €/year. It is assumed that the grid is able to absorb all the energy produced by the small hydro power plant. Cost and financial analysis are reported in table 6.

Table 6– Financial Analysis

Cost and prices	Total Cost of Plant	120.000 €
	Electricity Energy tariff kWh[€]	0,154 (Guaranteed minimum price)
	Energy cost escalation rate	4%
	Incentives time ; FIT	15 years; 0,22 €/kWh
Economic Parameters	Lifetime of turbine and Time of amortization	20 years
	Rate of management and maintenance; Inflation	4,0%; 2,5%
	Taxes on production; Discount Rate	12,5 %; 8,0%
Financial Results	Pre-tax internal rate of return (IRR)	36%
	Simple Payback; Year-to-positive cash flow	3.0; 3.2

	Net Present Value (NPV)	196.670,00 €
	Annual Life Cycle Savings; Benefit-Cost ratio	20.031,00 €; 2.50

The results of financial analysis demonstrate the economic viability of the HPP contradicting the established general opinion that hydropower plants are generally characterized as long-term investments.

7. Conclusions

The rehabilitation of disused micro hydro power plants to produce electricity is a topic of considerable interest today, not only for the benefit that it can draw the small community but also for the opportunity to further increase the electricity derived from renewable sources. Regarding environment, as the hydropower plant could be integrated to the existing infrastructure, the impacts are mainly due to its primary function. In particular, the refurbishment of the "Catarrate" Hydropower Plant highlights contribute to the energy independence of the local community, with an expected annual production of renewable energy of about 220 MWh not currently utilized, and, at same time, preserving the historical industrial heritage. Summarizing, several opportunities for the developments of small hydropower plants subsist in Italy, which if properly designed and realized should lead to considerable results in terms of both renewable energy production and profits.

References

[1] IEA, Key world energy statistics, https://www.iea.org/publications/freepublications/publication/kwes.pdf.
[2] Majumder M, Ghosh S, Decision Making Algorithms for Hydro-Power Plant Location. SpringerBriefs in Energy, 2013, DOI: 10.1007/978-981-4451-63-5_2,
[3] Energy recovery in existing infrastructures with small hydropower plants; http://www.esha.be/
[4] Patania F, Gagliano A, Nocera F, Pellegrino I. Clean energy saving: applied research into Etna's water supply systems in Catania". WIT Transactions on Ecology and the Environment 2007, 105: 35-42.
[5] Sherpa Project. Strategic study for the development of Small Hydro Power in the European Union. www.erec.org
[6] Inset ZM. Modern Trends in the Development of Small Hydro Power around the World and in Russia. Thermal Engineering 2010, 57(11): 953–960.
[7] GSE, Rapporto statistic 2012, http://www.gse.it/it/Statistiche
[8] Giudici G, Ghisla F, Ro Sottocornola R. The Potential for Mini-Hydro in Italy: The Case of the Refurbishment of Old Mills and Workshops, http://www.inshp.org/Img_Lib/UploadImg/201232712109370.pdf
[9] HDYI database, http://streammap.esha.be/25.0.html
[10] Klein A, Pfluger B, Held A, Ragwitz M, Resch G, Faber T. Evaluation of different feed-in tariff design options. http://www.renewwisconsin.org/policy/, 2008.
[11] Clean Energy Project Analysis - RETScreen International. www.retscreen.net
[12] Gagliano A, Patania F, Nocera F, Biundo G. "Micro hydroelectric power in Sicily: the energy production of early XIX sec. and the future opportunities. Presented at IREC, Sousse, 2012.
[13] Gagliano A, Patania F, Nocera F, Capizzi A, Galesi A. GIS-based decision support for solar photovoltaic planning in urban environment. Sustainability in Energy and Buildings, 2013, 865-874
[14] Kaldellis JK, Vlachou DS, Korbakis G.Techno-economic evaluation of small hydro power plants in Greece: a complete sensitivity analysis. Energy Policy 2005, 33: 1969–1985.
[15] Okot, DK. Review of small hydropower technology" Renewable and Sustainable Energy Reviews 2013, 26: 515-520