Zema D.A., Nicotra A., Tamburino V., Zimbone S.M. 2016. A simple method to evaluate the technical and economic feasibility of micro hydro power plants in existing irrigation systems. Renewable Energy (Elsevier) 85, 498-506,

which has been published in final doi

10.1016/j.renene.2015.06.066

(https://www.sciencedirect.com/science/article/pii/S0960148115300896)

A simple method to evaluate the technical and economic feasibility of micro hydro power plants in existing irrigation systems

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Abstract

A simple method is proposed to site turbines and choose their power output, evaluate costs and incomes and provide useful indications for Micro Hydro Power (MHP) plant design in existing irrigation systems. This method, based on simple models available in literature and requiring a reduced number of input parameters easy to survey in preliminary design stages, has been applied and verified in an existing irrigation system located in Calabria (Italy).

The results have highlighted that in the case study the smallest profitable turbine would produce 5 kW. A lower number of plants (with higher output) would produce no particular monetary savings compared to a greater number of smaller turbines. Furthermore, neither was the option of increasing pipeline diameter found to provide savings.

In general, an appreciable potential from MHP operation has been shown in existing irrigation systems, providing a return on investment higher than that provided by the Italian financial market.

Finally, MHP profitability noticeably increases with total annual operation time, being on average 55% higher in a wet year (eight months of electrical production/four month of irrigation) compared to a dry year (six months of electrical production/six months of irrigation).

Key words: Water User Association; micro hydro power plant; optimal discharge; collective irrigation system; annual operation time; hydroelectric energy.

ABBREVIATIONS

A = internal pipeline area [m^2]
AC = Annual Costs [€]
C_{CEME} = Civil and Electro-Mechanical Equipment Costs [€]
C_{DE} = Depreciation of Equipment Costs [€]
C_{ED} = Engineering and Design Costs [€]
$CNPV$ = Cumulated Net Present Value [€]
C_{OM} = Operating and Maintenance Costs [€]
C_p = unit pipeline cost [€ m^{-1}]
C_{PTL} = Power Transmission Line Costs [€]
C_{RR} = Replacement and Renovation Costs [€]
C_{SA} = Supervision and Administration Costs [€]
C_{TD} = Transport and Disposal Costs [€]
D = pipeline diameter [m]
DN = commercial pipeline diameter [mm]
E = total annual energy yield [kWh $year^{-1}$]
FC = Financial Charges [€]
g = gravity acceleration [9.806 m s^{-2}]
H_j = hydraulic head in node “j” [m]
I = annual income [€ $year^{-1}$]
IC = Investment Costs [€]
J = hydraulic gradient [m km^{-1}]
J_{en} = hydraulic gradient calculated for $Q = Q_{en}$ [m km^{-1}]
L = pipeline length [km]
MHP = Micro Hydro Power
NPV = Net Present Value [€]
p = hydrostatic pressure [Pa]
P_E = energy price [€ kWh^{-1}]
p_{max} = maximum tolerable pressure of a pipeline [Pa]
P_n = net electrical power of the turbine [kW]
$P_n^{(irr)}$ = surplus of net electrical power during irrigation period [kW]
Q = water discharge [m^3 s^{-1}]
Q_{en} = water discharge in irrigation period destined to electrical production [m^3 s^{-1}]
Q_{av} = available water discharge in the supplying water course [m^3 s^{-1}]
$Q_{i,in}$, $Q_{k,out}$ = input and output water discharges in network nodes “i” and “k” [m^3 s^{-1}]
Q_m = minimum water discharge in the supplying water course required for environmental conservation or downstream uses [m^3 s^{-1}]
Q_{max} = maximum water discharge [m^3 s^{-1}]
$Q_s = Q_{av} – Q_m$ = water discharge supplying the turbine [m^3 s^{-1}]
R_{irr} = total precipitation during irrigation period [mm]
ROI = Return On Investment [%]
R_{out} = total precipitation out of irrigation period [mm]
RP = Residual Price at the end of the plant life [€]
RUE = average Return per Unit of produced Energy [€ kWh^{-1}]
SHP = Small Hydro Power
T = Taxes on Income [€]
T_a = annual operation time [h]
WUA = Water User Association
γ = water specific weight [9806 N m^{-3}]
ΔH = gross hydraulic head [m]

ΔH_n = net hydraulic head [m]
ΔY = total hydraulic losses (distributed and concentrated) [m]
η = turbine efficiency [-]
λ = pipe roughness coefficient [$m^{(p-3l)}$ s^l]
ξ_k = coefficient of the local hydraulic head loss "k" [-]

1. INTRODUCTION

Hydroelectric power is by far the most mature renewable energy used for electricity generation, being totally inexhaustible and carbon-free (Dragu et al., 2001; Kaldellis et al., 2005; Paish, 2002; Abbasi and Abbasi, 2011). Furthermore, today, installation of hydroelectric power turbines allows additional economic resources for users thanks to the subsidies granted by the national energy policies for decreasing CO_2 emissions.
SHP plants (i.e. with a nominal power lower than 10 MW, Dragu et al., 2001; Paish, 2002) have found special importance due to their low installation and management costs, short construction time, robust technology and reliability (Dragu et al., 2001; Paish, 2002; Hosseini et al., 2005). The adoption of SHP plants has been recommended in rural or marginal areas, because they do not require major construction works (which may involve environmental impacts), can be operated entirely by remote control with few operating personnel and enhance rural electrification (Dragu et al., 2001; Paish, 2002).
The availability of geodetic heads in existing water systems suggests the possibility of integrating SHP plants at sustainable installation, operation and maintenance costs. This is the case of the existing irrigation systems of many WUA, where water availability out of the irrigation season may allow electrical energy production by turbines, in order to exploit potential energy and integrate the income of the associated users.
Siting of SHP plants, calculation of the installation capacity (in particular the optimal designed discharge, Hosseini et al., 2005), hydraulic adjustments and income/cost estimation (to assess whether, where and how to proceed with plant installation) are important factors, in order to assure the feasibility of electrical energy production; these factors become crucial, especially if one considers that an SHP plant requires a high initial investment (Dragu et al., 2001). It is therefore important to evaluate whether the project is worth pursuing, and if so, to plan the subsequent budget (Aggidis et al., 2010). Thus, suitable technical and economic methods are needed for SHP plant design. The existing literature describes the methods to evaluate the best plant configuration to adopt from the technical and economic points of view. For example, Voros et al. (2000) developed an appropriate empirical model describing hydroturbine efficiency and the design problem was formulated as a mathematical programming problem. The study by Karlis et al. (2000) presents a computer program for categorized and systematic analysis, in order to specify the parameters that are crucial to the financial investment viability of a potential SHP system project together with pertinent non-financial attributes and socio-economic impacts. A paper by Montanari (2003) proposes a scientific method for planning a SHP plant, based on the formalization of the economic profitability indicators of the investment in probabilistic terms and on its linkage to the characteristic parameters of the distribution functions, which define the flow regime of the course of water.
However, these methods are mainly relevant for SHP integration in common water systems (e.g. aqueducts for civil and industrial uses). Moreover, these methods seem to be more useful for detailed installation projects rather than for a preliminary feasibility assessment, because the proposed methods require a large number of input variables, whose determination could be difficult and time consuming at the preliminary design stage.
Simpler and quicker procedures, easy to implement by means of a low number of easy-to-survey input parameters, may be a useful tool in deciding whether or not the SHP plant is viable; thus, they may be a support for stakeholders, decision makers and designers to help identify the most suitable

technical and economic solution for each specific case. Moreover, this simplification is particularly suitable for design of SHP plants in existing irrigation systems. Here, the existing availability of irrigation water (outside the dry-season irrigation period) makes in-depth hydrological evaluations for hydroelectric production redundant (e.g. duration curves, peak flows).
This paper proposes a simple method to site turbines and choose their power output, evaluate costs and incomes and provide useful indications for Micro Hydro Power plant design (i.e. with a nominal power lower than 1 MW, Dragu et al., 2001) in existing irrigation systems. This method is based on simple models available in the literature and requires a reduced number of input parameters easy to survey in preliminary design stages. It has been verified through an application in an existing irrigation system of a WUA located in Calabria (Italy), in order to compare three alternative MHP installation schemes.

2. METHOD

The method proposed is schematized by the flow chart reported in Figure 1.

Figure 1

2.1 Mapping of water network

Based on reliable maps (at least 1:2000), combined with quick field surveys and analysis of the available hydraulic schemes, the water network layout can be built, identifying supply and distribution lines (pipeline length, material and diameter) and nodes (geographic coordinates of supplies, confluences, reservoirs, discharge points, etc.). Pipelines should be sorted by hierarchy (supply, distribution lines, etc.). The difference in height in the nodes can be taken as the gross hydraulic heads.

2.2 Analysis of water network adjustments

Some adjustments in the existing water network could be examined to exploit as much as possible the available potential energy and/or to reduce installation costs (Figure 1). Such adjustments can be classified as follows:

- replacing turbines of small size (thus obtaining economies of scale);
- discarding turbines of the smallest sizes;
- if necessary increasing discharges and sections of supplying lines.

Replacing small turbines can be done:

- by diverting the total water discharge towards the highest hydraulic head in pipeline branches, thus maximizing energy yield;
- by installing by-passes under pressure in correspondence to surge tanks in consecutive pipelines, in order to avoid energy losses.

These adjustments require the verification of whether the new $p < p_{max}$ of the existing pipeline. Otherwise, where $p > p_{max}$, a new pipeline with higher strength must be installed.

2.3 Hydraulic calculations

The proposed adjustments require water network verification: to this aim, the *n* equations of mass balance (1) (as many as the number of the network nodes) and *m* motion equations (2) (as many as the number of the network pipelines) must be satisfied:

$$\begin{cases} \sum_{i=1}^{r} Q_{i,in} - \sum_{j=1}^{s} Q_{k,out} = 0 & (1) \\ \Delta H = H_j - H_{j-1} & (2) \end{cases}$$

r and *s* being the number of input and output pipelines in the network nodes.

Hydraulic calculations provide P_n achievable by the plant and the corresponding Q^*, that is the value of Q which maximizes the function (3):

$$P_n = \eta\gamma Q \Delta H_n = \eta\gamma Q(\Delta H - \Delta Y) = \eta\gamma Q\left(\Delta H - JL - \sum_{k=1}^{t} \xi_k \frac{Q^2}{2gA^2}\right) \quad (3)$$

t being the number of the concentrated hydraulic losses.

If J is calculated by a common monomial equation, as:

$$J = \lambda Q^l D^{-p} \quad (4)$$

where λ, l and p are the coefficients of the adopted formula, the equation (3) becomes:

$$P_n = \eta\gamma Q\left(\Delta H - \lambda Q^l D^{-p} L - \sum_{k=1}^{t} \xi_k \frac{Q^2}{2gA^2}\right) \quad (5)$$

In hydroelectric plants integrated in common water systems (e.g. aqueducts for civil and industrial uses), the variable hydrological regime of the supplying water course makes Q variable throughout the year and thus η. However, in preliminary sizing of the turbines to be installed in existing irrigation systems, a constant value of η can be assumed, because Q corresponds to the constant value which is drawn for irrigation purposes in the dry season and it is equal to the calculated Q of the supplying pipeline.

With $L/D > 1000$, local hydraulic head losses can be ignored and therefore Q^* is:

$$Q^* = \left(\frac{\Delta H D^p}{(1+l)\lambda L}\right)^{1/l} \quad (6)$$

Q^* maximizes the energy production of each line; the set of Q which maximizes the energy production in the whole system, satisfying the node balance in equation (1), has to be found by a “trial and error” computational procedure. A timesaving procedure could be adopted taking into account the ΔH of each line and their profitability (for example nominal power over 5 kW).

In addition to P_n achievable outside the irrigation period, when Q delivered to users in the irrigation period is lower than Q_{max} of the existing pipeline, it is possible to exploit the surplus of discharge Q_{en} (= Q_{max} - Q) for electrical energy production. $P_n^{(irr)}$ during the irrigation period is expressed by the following equation:

$$P_n^{(irr)} = \eta\gamma Q_{en} \Delta H_n = \eta\gamma Q_{en}(\Delta H - J_{en} L) \quad (7)$$

In irrigation systems with rotational delivery schedule the discharge flowing in the water network is always equal to Q_{max}, because the water volumes are usually delivered only by adjusting irrigation duration instead of discharge Q. In on-demand irrigation systems, Q delivered to farmers may be sometimes, but rarely, lower than Q_{max}; therefore, the turbine efficiency η is in general variable.

Discarding pipelines with P_n lower than a certain threshold is generally advisable, because of their low economic viability.
The option of increasing D in supplying lines, in order to reduce ΔY and/or increase Q, requires replacement (in the case of pipelines in poor condition) or installation of a new conduit in parallel. This alternative would allow the exploitation of surplus power, due to increased Q and/or ΔH_n for electrical energy production, outside the irrigation period and to produce additional electrical energy also during the irrigation period, due to reduced head losses.

2.4 Hydrologic evaluations

The option of increasing the diameter of supplying pipelines must take into account water availability. This can be carried out by the quick procedure proposed below, postponing more detailed hydrological calculations, if necessary, to later design steps. This procedure is advisable when runoff data are not available (as in many water courses of Southern Italy) and therefore the historical precipitation series (easily available) must be used.
Q_{av} can be estimated multiplying Q_{max} of the existing pipeline, usually diverted during the irrigation period, by a coefficient k, assuming a constant runoff coefficient (that is the ratio between runoff and rainfall) throughout the year, k could be estimated as the ratio between R_{out} and R_{irr}, as shown by the equation:

$$k = \frac{R_{out}}{R_{irr}} = \frac{Q_{av}}{Q_{\max}} \tag{8}$$

The increase of D in the existing network has to be evaluated only when k is lower than a certain threshold (e.g. k is in the range 2.4-4.4 in southern Italy, Caloiero et al., 2011; Vijaya Kumar et al., 2013); if higher, it is advisable to evaluate also a new water scheme purposely designed for hydroelectric uses. The minimum Q_m must be subtracted from Q_{av}, in order to estimate Q_s (thus $Q_s = Q_{av} - Q_m = kQ_{max} - Q_m$).
The unit cost of the pipeline depends C_p on its diameter according to the following monomial equation:

$$C_p = \alpha D^{\nu} \tag{9}$$

α and ν being two constants (depending on the material type of pipeline), whose values have to be estimated by a power regression based on available pairs of C_p and D. For the Italian market the exponent ν is in the range 1.0-1.5 (Milano, 1996).
The optimum DN should maximize the ratio between energy production and the total costs of the SHP turbine and new pipeline (this latter depending on D). Therefore, one should evaluate different DN - assumed for as many values of k in equation (8) - for the new pipeline, yielding $Q^* \cong Q_s$ in equation (6).
When the pipeline diameter is increased and in the case $Q_s < Q^*$, depending on variations of flow rates in the supplying water courses, the turbine would work at an efficiency η lower than the optimum value. In subsequent design steps (that is in the final working plan) the analysis of duration curve of the supplying water course for a significant observation period allows the estimation of Q_s and the number of days in which $Q_s < Q^*$: thus an evaluation of reduction of energy production compared to the expected value and the consequent lower income and profit can be quantified.
However, it is possible to adopt a high-flexibility turbine for which the hypothesis of a constant η could be a realistic assumption, as for example cross-flow (used with low to medium heads) or

Pelton (in the case of high heads) turbines, where η is higher than 0.75-0.80 for values of the ratio Q/Q^* in the range 0.1-1.0 (Paish, 2002).

2.5 Economic evaluations

Based on the calculated P_n produced by the water network, the economic evaluation of the incomes and costs will provide the viability of the MHP system.

2.5.1 Income

I of the MHP system derives, according to the equation:

$$I = P_E E = P_E P_n T_a \tag{10}$$

When a surplus of discharge (Q_{en}) is available in the irrigation period, the income produced by exploiting $P_n^{(irr)}$ should be estimated. However, this surplus can be ignored in preliminary economic evaluations and postponed to subsequent design steps, because it is significant only few hours a day or few days a month (i.e. when there is no water demand for irrigation) and not easily predictable *a priori*.

2.5.2 Costs

The economic analysis methods are proposed according to the guidelines reported by Hosseini et al. (2005).
IC are the sum of C_{CEME} (turbines, generators, control systems as well as civil works for adapting the existing small dams and building the equipment housing, etc.), C_{PTL}, C_{ED} and C_{SA} (purchase of land, management, inspection and supervision costs).
For the determination of the cost of the electro-mechanical equipment, there are graphs which can approximately calculate those costs, but these graphs have not recently been updated. Furthermore, manufacturers of turbines and alternators do not supply any information about cost, since every installation is different and complex (Ogayar and Vidal, 2009). In a simpler but reliable way, C_{CEME} can be calculated as a function of hydraulic characteristics of the hydro site such as ΔH and Q or ΔH and P_n, as reported in many studies (Gordon and Penman, 1979; Papantonis, 2001; Aggidis et al., 2010). In this method the equation reported by Papantonis (2001), who estimated the costs of different components of the hydro plant based on the European data available at that time, has been adopted:

$$C_{CEME} = \sum_{i=1}^{N} \beta P_{n,i}^{0.7} \Delta H_i^{-0.35} \tag{11}$$

N being the number of the plants in the network system.
However, Papantonis' estimates have to be used with care as they are based on out-of-date prices and the cost of electro-mechanical equipment has decreased due to the increase in number of small scale hydro power developments since his formula was developed (Aggidis et al., 2010). Thus, the value of the coefficient β (equal to 20570 € $kW^{-0.7}$ $m^{0.35}$ in the original form of the Papantonis' equation) has to be calibrated to present conditions through a comparison with the market values of electromechanical equipments and civil works.

Equation (11) highlights how unit C_{CEME} (that is cost per plant power unit) decreases when P_n and ΔH increase; therefore, it is evident that unifying hydraulic heads, increasing ΔH and P_n, allows economies of scale.
C_{PTL}, C_{ED} and C_{SA} can be assumed approximately as a fraction of C_{CEME}; Kaldellis et al. (2005) and Hosseini et al. (2005) report a range from 4 to 8%.
AC are the sum of C_{DE} (equal to the annual plant amortisation), C_{OM} (including labour, insurance, tax, duties, landscape and consumable materials), C_{RR} (the costs of renovation and reconstruction of equipment at year 25), *FC* (the passive interest rate on the borrowed capital), *T*, *RP* and C_{TD}.
C_{DE} can be an approximation assumed as the ratio between the investment costs and the plant lifespan, while C_{OM} are a percentage (2%) of the annual share of *IC* (Hosseini et al., 2005).
Due to the nature of the SHP plants, C_{RR} at year 25 are approximately equal to the total value of equipment at time of purchase (Hosseini et al., 2005); for plant lifespan shorter than 25 years, these costs can be assumed null. This assumption complies with findings by Kaldellis et al. (2005), who reported that the impact of different residual value is important for the first decade of operation and it is negligible after this period, especially after the 15th year of operation.
In Italian market conditions *RP* can be considered to balance C_{TD}.

2.5.3 Return

NPV, that is the net cash flow of the i^{th} year (equal to the difference between income and costs for each year actualised at the first year of the investment by the future inflation rate), and *CNPV* for the overall plant lifespan are evaluated; finally, *ROI*, given by the ratio between the *CNPV* and the *IC* and averaged on the plant lifespan, is calculated.

3. STUDY CASE: THE *SPILINGA-RICADI* WATER SYSTEM

3.1 Study area

The *Spilinga-Ricadi* irrigation system, located in the territory of Vibo Valentia (Calabria, Southern Italy, Figure 2) and managed by the Water User Association *Consorzio di Bonifica Tirreno Vibonese*, delivers and distributes irrigation water to farms which mainly cultivate citrus groves.
In the irrigation system, high river discharge occurs outside of the irrigation season (from May to September). The WUA wants to exploit the production capacity of the existing geodetic heads through an MHP system.

Figure 2

3.2 Methodology implementation

3.2.1 Mapping of water network

The water network (Figure 2), installed in the 1980s and 90s, consists of eight pipelines (P_1 to P_8), with water discharges from 34 to 119 l s^{-1}, fed by three small river dams (S_1, S_2 and S_3) and three surge tanks (R_1, R_2 and R_3), regulating the discharge and disconnecting the network. The pipeline network is made of HDPE (10.5 km) and steel (3.3 km).
The map and longitudinal profile of the water network have been schematized by a 1:2000 map, drawn from the last available aerial view (2010). Field surveys, operated on a longitudinal 100-m step, and the analysis of water network design have provided the material and the diameter (from 125 to 315 mm) of the existing pipelines.

3.2.2 Analysis of water network adjustments and design of the investigated MHP schemes

On the basis of the proposed methodology, three possible MHP schemes have been identified and analyzed (Figure 2 and Table 1).

Table 1

In a first alternative (scheme n. 1), with only minor water network adjustments, seven turbines have been considered, each one located in a network pipeline, with a total P_n of 106.7 kW. In this scheme no turbine is installed in the pipeline P_8, because its P_n would be lower than 5 kW and thus would not be economically viable.
In a second scheme some hydraulic heads have been incorporated; in more detail:

- ΔH of the pipeline P_5 has been increased by removing the old pipeline path along a valley bottom (thus the pipeline length is reduced from 3.0 to 2.8 km);
- ΔH of the pipeline P_8 has been joined to ΔH in the consecutive pipeline P_4;
- Q of the pipelines P_2 and P_6 has been diverted to P_3 and P_4 and the turbines T_3 and T_5 have been removed;
- two pressured by-passes have replaced the surge tanks R_2 and R_3 and the turbines T_4 and T_6 have been replaced by the larger T_{10}, and T_2 by T_9.

Therefore, the scheme n. 2 consists of four larger turbines instead of the seven smaller MHP turbines of the scheme n. 1 with a total P_n of 101 kW; this value is close to P_n of the scheme 1.
The last scheme (n. 3) has the same turbine number and layout as the scheme n. 2, but in a supplying line (P_5) a new 500-mm steel pipeline has been installed alongside the existing one in order to reduce ΔY and increase Q.
D of the new pipeline has been sized according to equation (6) with $Q^* \cong Q_s$.

3.2.3 Hydraulic calculations

In our calculations, the value of 0.85 has been taken for the turbine η in equation (5). It has been derived from the optimal values suggested by Dragu et al. (2001) and Paish (2002), considering that:

- in existing pipelines during the operation period the SHP plant is sized for and supplied by a constant Q^* (and the turbine can be chosen at the optimal η);
- in the pipeline P_5 of the scheme n. 3 (where the diameter has been increased), a high-efficiency turbine has been adopted (see section 2.4).

Hazen-Williams' equation has been chosen as monomial formula (4) for calculating J. Being L/D > 1000, concentrated head losses have been ignored; thus, $\Delta H_n = \Delta H - JL$.
All ΔH are over 50 metres (Table 2); therefore the plants can be classified as medium- to high-head, according to Smalls Hydro Association classification (ESHA, 2004), even though these ranges are not rigid, but are merely means of categorizing sites: it means that the physical size of turbines required for a profitable energy yield can be even lower than 5 kW (Abbasi and Abbasi, 2011). As mentioned above, after a preliminary application of the methodology this value has been taken as a threshold, in order to identify the smallest turbine P_n providing an annual medium profit higher than 6% (equal to the current return of Italian bonds) over a 25-year period.

3.2.4 Hydrologic evaluations

A coefficient k equal to 4.0 has been calculated, utilising the rainfall data of the last 90 years collected at the meteorological station of Mileto (within the watershed feeding the supplying river dams). Q_s has been calculated according to the Italian law (L.D. 152/2006), which provides the method to estimate Q_m. The optimal DN of the new pipeline has been calculated as 500 mm.

3.2.5 Economic evaluations

Based on duration of irrigation periods surveyed over the past 20 years, T_a has fixed to be about 5040 hours, equal to 24 hours per day in the seven months out of a 5-month irrigation period. Exploitation of energy surplus in the irrigation period has not been precautionarily estimated.

The economic viability of the investment has been evaluated considering a plant lifespan of 25 years (Hosseini *et al*., 2005). For P_E the values of 0.22 € kWh^{-1} for the first 20 years (comprising the unit subsidies provided by the Italian government, according the actual M.D. 6/7/2012) and of 0.07 € kWh^{-1} (with no public subsidies) for the remaining five years of the plant life have been assumed.

For estimating C_{CEME} of turbines with electrical power smaller than 100 kW, the value of the coefficient β has been calibrated for Italian market conditions. To this end, the market values of electromechanical equipment and the costs of the civil works have been surveyed for different size of turbines (below 100 kW) and compared with the output of (11), based on data collected for MHP plants recently installed in southern Italy; a value of 25635 € $kW^{-0.7}$ $m^{0.35}$ has been calculated and adopted for β (Figure 3).

For the largest turbine (T_8, with P_n = 250 kW) in the pipeline P_5 (scheme n. 3), the market price has been taken (about 310 k€). The cost of pipeline replacement has been estimated on the basis of an analytical computation of the civil works (700 k€).

A percentage of 5% of C_{CEME} has been assumed for C_{PTL}, C_{ED} and of 4% for C_{SA}.

The adopted inflation rate (2.5%) has been forecast on the basis of the average values over the last five years.

The managers of WUA *Consorzio di Bonifica Tirreno Vibonese* have planned that 20% of IC is provided by its own funds, while the remaining 80% is provided by a 15-year loan. Therefore, the annual FC costs have been estimated considering an interest rate on the borrowed capital equal to 6% (current average value for the Italian investment market). Costs for T have been calculated by the law-defined tax-coefficient of 33% of the difference between the income and the sum of C_{DE} and AC, if positive; otherwise, T has been assumed as zero.

Finally, the average RUE (the ratio between the $CNPV$ and the total energy yield) for the three investigated MHP schemes has been calculated separately for years 1 to 20 and years 21 to 25 by subtracting C_{DE} and AC from the annual I.

3.3 Results and discussions

3.3.1 Hydraulic aspects

Hydraulic calculations have provided Q up to 68% (scheme n. 1) lower than Q^* (Table 2), due to the mass balance in each network node; total P_n is up to 68% (scheme n. 1) less compared to the theoretical value calculated by input of Q^*. In the MHP systems, ΔH_n is conditioned by the small D of the network pipelines (rarely over 200 mm) and the age of the steel pipelines (about 30 years, with increased internal roughness), which determines noticeable unit energy losses (shown by J).

On the basis of the hydraulic calculations (carried out to maximise the total electrical yield of each scheme), Q^* is in the range 19 to 67 L s^{-1}; P_n varies from 6.1 to 36.3 kW for the scheme n. 1 and

12.7 to 36.6 for the scheme n. 2. Therefore, total P_n of the schemes n. 1 and 2 is 106.7 and 101 kW respectively, which gives E of 537.8 and 509 MWh respectively. In scheme n. 3 the turbine T_8, placed in pipeline P_5 with the new *DN* with a 5-fold Q, produces a 8-fold P_n (243.7 kW versus 31.9 kW) compared to T_1 in scheme n. 2 (Table 2). E of scheme n. 3 is only about three times higher compared to the scheme n. 2 (1577 against 509 MWh respectively).

Table 3

3.3.2 Economic evaluations

As explained above, 5 kW has been identified as the smallest turbine P_n to provide an annual medium profit higher than 6% of the investment over a 25-year period. This is the reason why, as mentioned above, turbines with a P_n below this threshold have been excluded from this study.

IC for the installation of the MHP schemes n. 1, 2 and 3 are 275, 198 and 1249 k€ respectively; *AC* represents 6% of *IC*. After 20 years (with public subsidies) *CNPV* of 964, 985 and 2200 k€ are reached for the MHP schemes n. 1, 2 and 3 respectively (Table 3). If the MHP plant is exploited after the 20th year, the average *NPV* is 13% (scheme 3) to 20% (scheme 2) than in the first 20 years (Table 3).

Figure 4 highlights that the schemes n. 1 and 2 produce a profit (that is *CNPV* becomes positive) after four years from installation and scheme n. 3 after six years.

Figure 4

The comparison of schemes n. 1 and 2, yielding similar total energy and *CNPV* after 25 years (Table 3 and Figure 4), shows that a lower number of plants (with higher output) produces no particular monetary savings compared to a greater number of smaller turbines in the investigated case.

Figure 4 also highlights that the increase of *CNPV* in time (shown by the slopes of the three curves):

- is higher for scheme n. 3 compared to the other investigated schemes in relation to the higher P_n installed;
- is higher, as expected, in the first 20 years (with a higher P_E) than in the last five years of the plant lifespan (without public subsidies).

This is also shown by the average *RUE* during the first 20 years (0.07-0.09 € kWh^{-1}); these values are 4-7 times greater compared to the period (years 21-25) without national subsidies (0.01-0.02 € kWh^{-1}) (Table 4). This confirms that *RUE* depends noticeably on the national subsidies for renewable energy, particularly for MHP turbines of higher size (as for scheme n. 3).

Table 4

ROI of 14.0%, 19.9% and 7.0% (this latter negatively affected by civil works needed for pipeline replacement) have been achieved, which are in schemes n. 1 and 2 noticeably greater than the profitability of the capital provided by the WUA. In particular, in scheme n. 3, where the section of an existing pipeline (P_5) has been increased 2.5 times against an increase of the C_{CEME} by about 20 times, E of turbine T_8 increases only 8 times compared to scheme n. 2.

The method also allows the evaluation of the economic viability of the turbines with P_n slightly higher than 5 kW, whose profitability for the whole MHP scheme is marginal. For example, in scheme n. 1 the removal of the turbines T_1, T_3 and T_6 (with P_n of 9.0, 6.1 and 6.5 kW respectively) reduces *CNPV* from 964 to 798 k€ after 25 years, but increases the *ROI* from 14.0 to 16.4%.

Figure 5

Another factor which noticeably influences the economic viability of MHP systems is T_a. In our study it was preliminary supposed that the MHP turbines operate for at least seven months per year outside the 5-month irrigation period, which can be considered as a realistic value for the Mediterranean climatic conditions. Further simulations were carried out by hypothesizing a T_a of 4320 and 5760 hours per year (corresponding respectively to a 6-month or 4-month irrigation period, typical values for a dry or wet year). As shown in Figure 5, after 25 years from the investment, *CNPV* of the analyzed schemes increases appreciably with T_a. Moreover, the difference of *CNPV* between a wet year (T_a = 5760 hours, corresponding to an operating time of eight months) and a dry year (T_a = 4320 hours, irrigation season lasting six months) amounts to 55% on average for the three analyzed schemes.

4. CONCLUSIONS

A simple method is proposed for siting turbines, choosing their power output and evaluating costs and incomes for MHP plant design in existing irrigation systems. Furthermore, useful indications for MHP installation are also reported (e.g. joining small hydraulic heads in consecutive pipelines, by-passing surge tanks, increasing pipeline section). This method has been verified by evaluating the technical feasibility and the economic performance of three different MHP schemes in an irrigation system of a WUA in Calabria (Southern Italy).

In the analysed case study, the smallest turbine power providing a medium profit of at least 6% of the investment was shown to be 5 kW. A lower number of plants (with higher output) produces no particular monetary savings compared to a greater number of smaller turbines. Furthermore, increasing the diameter of a supplying line by a factor of 6.25 (from 200 to 500 mm) is not particularly advisable, because the pipeline replacement cost is not balanced by an increase of income from electrical energy production.

In general, it can be deduced that MHP installation in the existing irrigation systems provides a return higher than the current earning performance in the Italian investment market. The economic feasibility of MHP systems noticeably increases with the annual operation time: over 25 years the difference of *CNPV* between a wet and dry year amounts on average to 55% in the three analyzed schemes.

On the whole, the method proposed, easy to implement by means of a low number of easy-to-survey input parameters, may represent a useful support for stakeholders, decision makers and designers to identify the most suitable technical and economic solution for each specific case of small hydroelectric plant design.

REFERENCES

Abbasi T, Abbasi SA. Small hydro and the environmental implications of its extensive utilization. Renewable and Sustainable Energy Reviews 2011; 15: 2134-2143.

Aggidis GA, Luchinskaya E, Rothschild R, Howard DC. The costs of small-scale hydro power production: Impact on the development of existing potential. Renewable Energy 2010; 35: 2632-2638.

Caloiero T, Coscarelli R, Ferrari E, Mancini M. Precipitation change in Southern Italy linked to global scale oscillation indexes. Natural Hazards and Earth System Sciences 2011(11); 1683-1694.

Dragu C, Sels T, Belmans R. Small hydro power – state of the art and applications. International conference on power generation and sustainable development (AIM). Liège (Belgium), 8-9 October 2001; 265-270.

ESHA. 2004. Guide on How to Develop a Small Hydropower Plant. European Small Hydropower Association. Available at URL:

http://www.esha.be/fileadmin/esha_files/documents/publications/GUIDES/GUIDE_SHP/GUIDE_SHP_EN.pdf. Last access on 23th February 2015.

Gordon JL, Penman AC. Quick estimating techniques for small hydro potential. Journal of Water Power and Dam Construction 1979; 31: 46-55.

Hosseini SMH, Forouzbakhsh F, Rahimpoor M. Determination of the optimal installation capacity of small hydro-power plants through the use of technical, economic and reliability indices. Energy Policy 2005; 33: 1948-1956.

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.

Karlis AD, Papadopoulos DP. A systematic assessment of the technical feasibility and economic viability of small hydroelectric system installations (Technical note). Renewable Energy 2000; 20: 253-262.

Milano V. Acquedotti. Hoepli editor, Milano, Italy, pp. 643, 1996 (in Italian).

Montanari R. Criteria for the economic planning of a low power hydroelectric plant. Renewable Energy 2003; 28: 2129-2145.

Ogayar B, Vidal PG. Cost determination of the electro-mechanical equipment of a small hydro-power plant. Renewable Energy 2009; 34: 6-13.

Paish O. Small hydro power: technology and current status. Renewable and Sustainable Energy Reviews 2002; 6: 537-556.

Papantonis D. Small hydro power stations. Athens: Simeon; 2001.

Vijaya Kumar P, Bindi M, Crisci A, Maracchi G. Detection of variations in precipitation at different time scales of twentieth century at three locations of Italy. Weather and Climate Extremes 2013(2); 27–15.

Voros NG, Kiranoudis CT, Maroulis ZB. Short-cut design of small hydroelectric plants. Renewable Energy 2000; 19: 545-563.

TABLES

Table 1 – Layout of turbines (T_i) for three MHP schemes in the *Spilinga-Ricadi* irrigation system.

<table>
<tr><th rowspan="2">Pipeline</th><th colspan="3">Scheme</th></tr>
<tr><th>1</th><th>2</th><th>3</th></tr>
<tr><td>P_1</td><td>T_4</td><td rowspan="2">T_{10}</td><td rowspan="2">T_{10}</td></tr>
<tr><td>P_7</td><td>T_6</td></tr>
<tr><td>P_5</td><td>T_1</td><td>T_8 (D = 200 mm)</td><td>T_8 (D = 500 mm)</td></tr>
<tr><td>P_8</td><td>-</td><td rowspan="2">T_9</td><td rowspan="2">T_9</td></tr>
<tr><td>P_4</td><td>T_2</td></tr>
<tr><td>P_2</td><td>T_3</td><td>-</td><td>-</td></tr>
<tr><td>P_3</td><td>T_7</td><td>T_7</td><td>T_7</td></tr>
<tr><td>P_6</td><td>T_5</td><td>-</td><td>-</td></tr>
</table>

Table 2 – Hydraulic parameters and P_n calculated for three MHP schemes in the *Spilinga-Ricadi* irrigation system.

MHP turbine	**Pipeline**	**ΔH [m]**	**L [m]**	**Q^* [L s^{-1}]**	**Q [L s^{-1}]**	**J [m^3 km^{-1}]**	**ΔY = JL [m]**	**ΔH_n [m]**	**P_n [kW]**
Scheme n. 1									
T_1	P_5	60.9	3043	27	27	7.01	21.3	39.5	9.0
T_2	P_4	118.5	1545	57	57	26.9	41.5	76.9	36.3
T_3	P_2	59.9	1363	33-67	14	0.22-4.14	4.0	56.0	6.5
T_4	P_1	81.7	1882	42	24	5.48	10.3	71.4	14.3
T_5	P_6	117.0	1941	50	16	2.52	5.0	112.1	14.7
T_6	P_7	80.0	1529	19-22	10([a])	4.14-5.61	7.4	72.6	6.1
T_7	P_3	82.4	1696	44	44	17.04	28.9	53.5	19.8
Total scheme n. 1		**600.4**	**12998**				**118.4**	**482.0**	**106.7**
Scheme n. 2									
T_7	P_3	82.4	1696	44	44	17.56	29.8	52.7	19.8
T_8	P_5	134.1	2800	44	44	16.79	47.0	87.1	31.9
T_9	P_4+P_8	178.7	2349	27-57	45	17.56-67.16	81.1	97.6	36.6
T_{10}	P_1+P_7	161.7	3411	22-42	10([a])	1.08-5.61	9.5	152.2	12.7
Total scheme n. 2		**556.9**	**10256**				**167.4**	**389.6**	**101.0**
Scheme n. 3									
T_7	P_3	82.4	1696	44	44	17.56	29.8	52.7	19.8
T_8	P_5	134.1	2800	57	230([a])	3.29	9.2	124.9	243.7
T_9	P_4+P_8	178.7	2349	27-57	45	17.56-67.16	81.1	97.6	36.6
T_{10}	P_1+P_7	161.7	3411	22-42	10([a])	1.08-5.61	9.5	152.2	12.7
Total scheme n. 3		**556.9**	**10256**				**129.6**	**427.4**	**312.8**

([a]) equal to Q_s.

Table 3 – *IC* and *AC* as well as average *NPV* and *CNPV* estimated for three MHP schemes in the *Spilinga-Ricadi* irrigation system.

MHP scheme	***IC* [k€]**	***AC* [k€]**	**Average *NPV* [k€]**		***CNPV* [k€]**	
			Years 1-20	**Years 21-25**	**Years 1-20**	**Years 21-25**
1	275	16.5	46.2	8.2	923	41.1
2	198	11.9	47.0	9.2	939	46.2
3	1249	74.9	106.5	13.8	2131	69.0

Table 4 – Total *E*, *CNPV* and *RUE* of three MHP schemes in the *Spilinga-Ricadi* irrigation system.

***MHP* scheme**	**Total *E* [MWh]**	***CNPV* [k€]**	***RUE* [€/kWh]**
Years 1-20			
1	10755	923	0.09
2	10181	939	0.09
3	31530	2131	0.07
Years 21-25			
1	2689	41	0.02
2	2545	46	0.02
3	7883	69	0.01
Years 1-25			
1	13444	964	0.07
2	12726	985	0.08
3	39413	2200	0.06

FIGURE CAPTIONS

Figure 1 - Flow chart of the method for assessing MHP feasibility in existing irrigation systems.

Figure 2 - Layout of three MHP schemes in the *Spilinga-Ricadi* irrigation system.

Figure 3 – Regression equation of C_{CEME} of SHP plants in the Italian market versus those estimated by equation (11) (β = 25635 € $kW^{-0.7}$ $m^{0.35}$).

Figure 4 – *CNPV* of three MHP schemes in the *Spilinga-Ricadi* irrigation system.

Figure 5 - *CNPV* after 25 years for different T_a for three MHP schemes in the *Spilinga-Ricadi* irrigation system.

Figure 1

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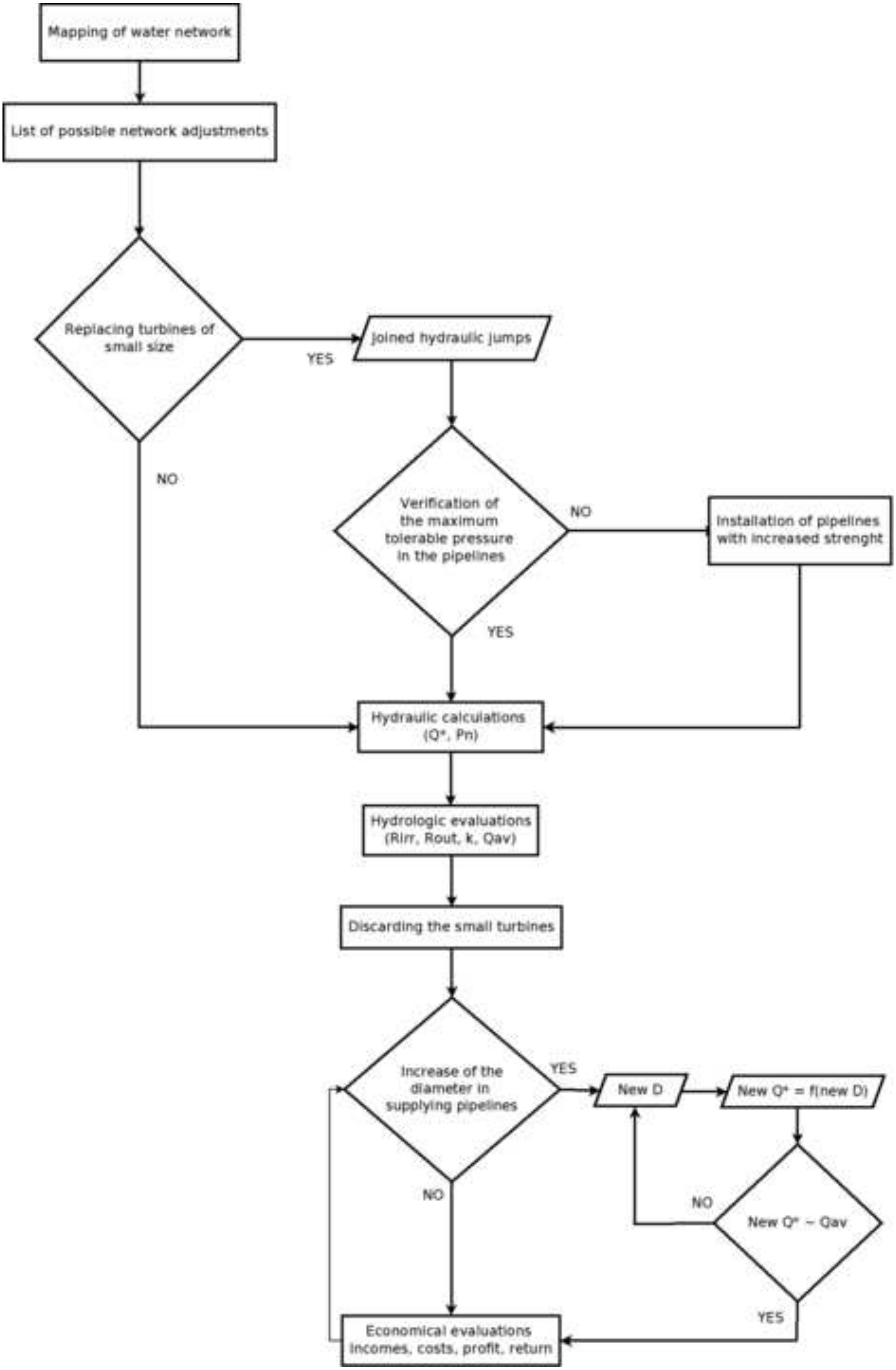

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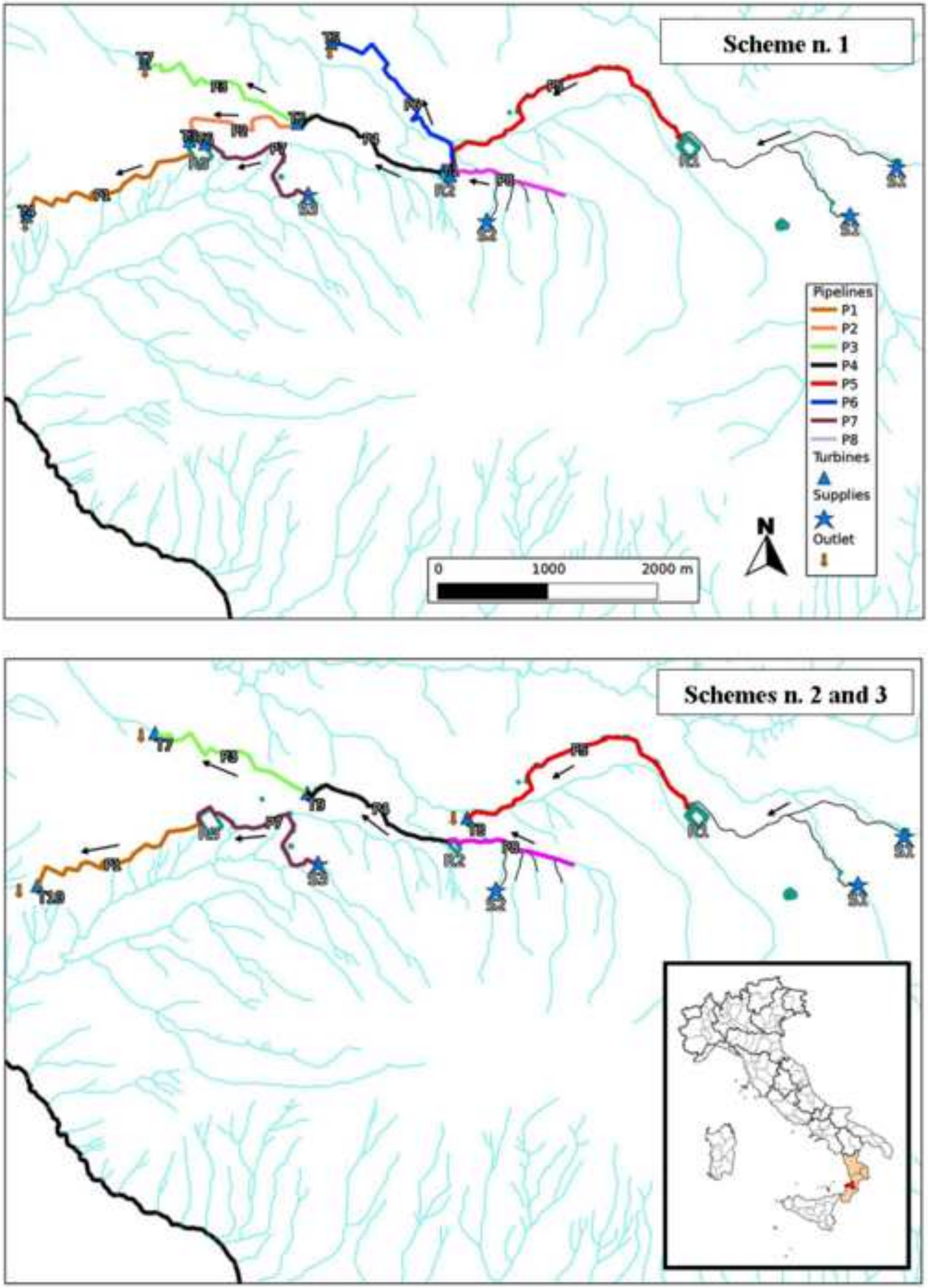

Figure 3

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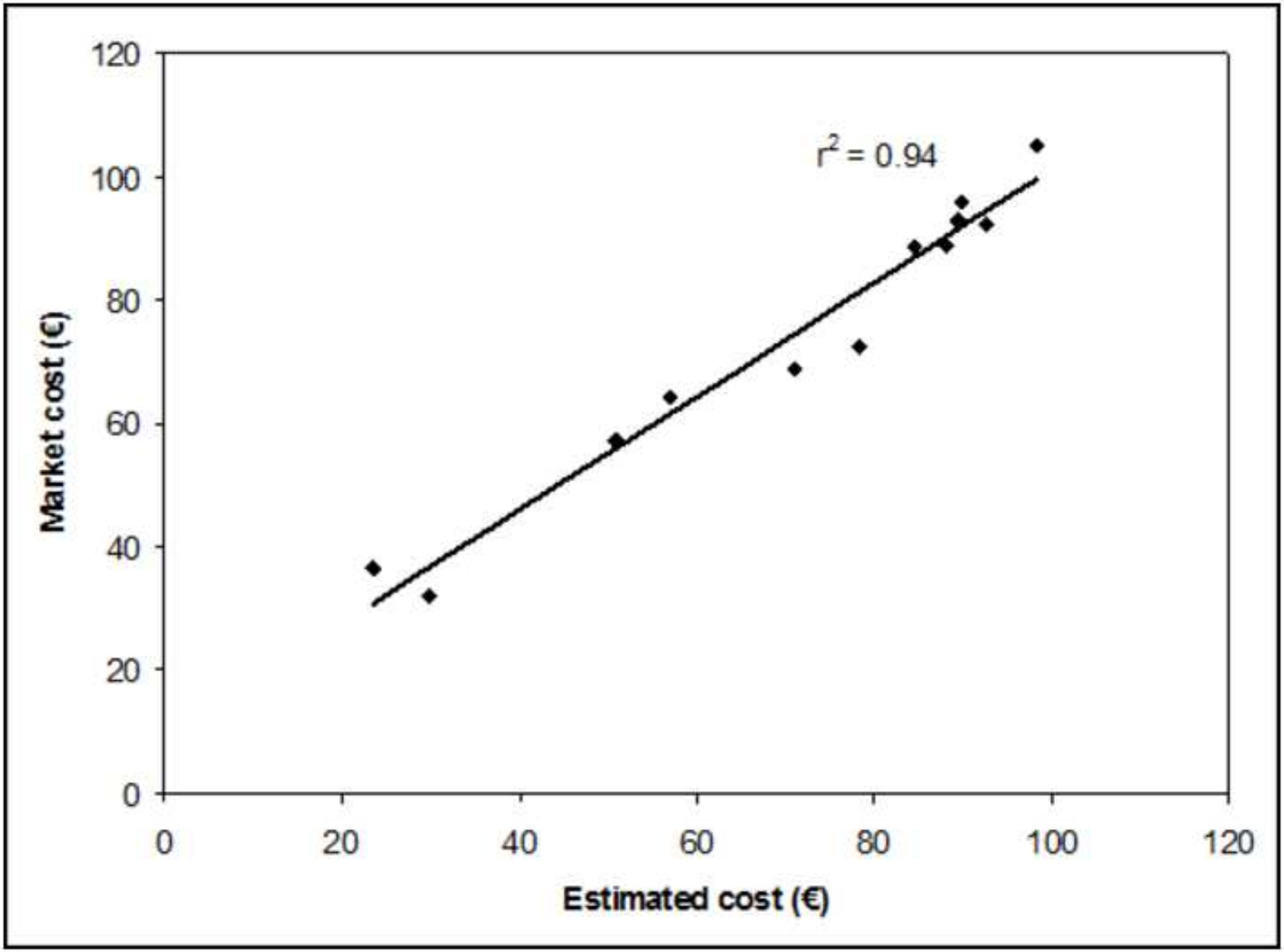

Figure 4
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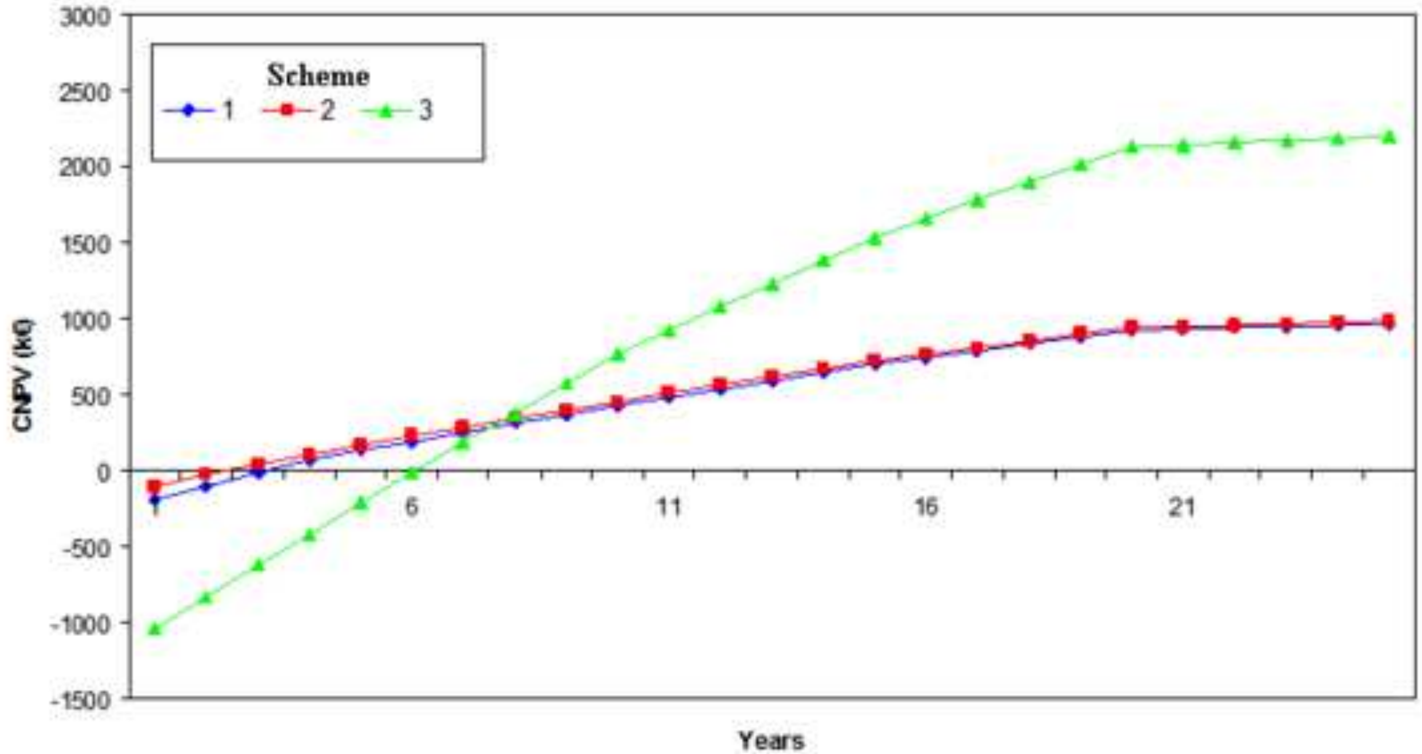

Figure 5

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