Regional-scale assessment of energy potential from hydrokinetic turbines used in irrigation channels

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Abstract: The development of small hydropower plants can still make a major breakthrough in green energy production, especially if considering non-conventional sources. In this work, we focus on water current hydrokinetic turbines (WCT) technology, which can be used to generate power using only the kinetic energy of the water, with very little hydraulic head. So far, no particular attention to this kind of turbines existed in Italy: although this technology is mainly developed for tidal currents and large rivers, it can be also applied to medium and small channels. The aim of the work is to assess the applicability of this technology in the wide network of irrigation canals of the Piemonte region (Northwestern Italy). In order to define a large-scale mapping of the energy potential production a database of the regional irrigation canals has been analysed. The applicability of WCT systems with different technical characteristics has been considered in those canals where the expected energy production appears adequate without interference with the usual irrigation procedures. The obtained results are promising and suggest that further developments in turbines technological research can help in making available economically feasible systems for widespread applications.

Keywords: Renewable energy, mono-dimensional in-stream hydrokinetic turbines, regional-scale assessment, irrigation channels, master plan

1. Introduction

Development of renewal energy production in areas where natural resources are already heavily exploited seems to leave relatively small chances to further expansion of the hydropower production. In fact, local and national regulations on instream-flow for ecosystem preservation provide consistent limits to possible development of new hydro power projects based on river discharge diversion. Even then, however, water flowing in pipes and canals still preserve a very interesting power production potential, being not subjected to the above-mentioned limitations.

The purpose of the present study is to develop a methodology aimed at quantifying the hydropower potential of a wide network of irrigation canals, located in the Piemonte region (North-west of Italy). At an initial stage of the analysis, evaluation of the power potential has been referred to a number of simplifying hypotheses, to reach an approximated regional-scale assessment. In all cases, only production from Water Current hydrokinetic Turbines (WCT) installed along the irrigation canals have been considered. The proposed approach is based on a systematic analysis of flow conditions in all stretches of the canal networks, with the aim of providing a provisional master plan of mini-hydro potential over the region. These analyses can be also used to establish whether the power plant installation may be economically sustainable. Considering the assumptions made in this approach, results of this study are to be considered as bootstrap test on this kind of hydro power potential. The aim is also to promote more in-depth wide-area data gathering about canals geometries and associated discharges, that can give additional impulse to the development of this zero-impact power production technology.

2. Hydrokinetic turbines

Hydro energy production by in–stream hydrokinetic turbines is an environmentally friendly green energy technology that in terms of power generation can be classified as mini-hydro (SHP). WCT technology, considered in this study, can be widely used in those streams that have a principal use different from the energy production, like an irrigation network. This technology is also characterized by low initial investment and no environmental impact, and can benefit of simplified bureaucratic procedures and supports for renewable energy sources.

2.1 Description

WCT are systems that convert hydro kinetic energy from flowing water into electricity [1]. WCT's geometry is generally quite close to classical water turbines characterized by a rotor assembly, like underwater windmills or water wheels. Differently from systems that convert the available head into energy, WCTs harness the kinetic energy of the flowing water. These kind of turbines can work in-stream, just completely or partially submerged into the water flow. Additional structural works, like water catchments or penstocks, are then not required in order to regulate the flow.

The most widely diffused technology that can be used in irrigation canals is the mono-dimensional Non-Tidal River (NTR) device. The mono-dimensional NTR devices (e.g. figure 1) can be classified, from the structural point of view, in *paddlewheel*, *cross-axis turbine*, and *axial flow turbine*. Paddlewheel are characterized by flexible rotor blades, mounted on an axis which rotates, providing a turbine effect. The flexible rotor blades are arranged along the rotor axle in staggered rows. The effect creates a very high level of torque at the axle. Cross-axis turbines are characterized by the axis perpendicular to the flow direction; the axis can be horizontal or vertical. Axial flow turbine are, instead, characterized by axis parallel to the flow directions.

Figure 1. Cross-axis turbine (ENERCAT).

2.2 Energetical Theory

The macro scale evaluation of the intrinsic potential of the irrigation canals can take advantage of the River In-Stream Energy Conversion (RISEC) theory. It starts from the hypothesis that the electricity is produced by converting the kinetic energy of the water flowing in a stream or in a canal. This method is also discussed by [2], [3]. The power of a water flux is expressed as

$$P = 0.5 \rho A v^3 \tag{1}$$

where A is the hydraulic cross-section, ρ is the density of the flowing fluid, and v is the flux velocity.

If the value of flow velocity is not directly available, it can be evaluated through the continuity equation

$$v = \frac{Q}{A} \tag{2}$$

that requires the discharge Q to be known. A more sophisticated approach is through the Chezy formula:

$$Q = A \frac{1}{n} R^{1/6} \sqrt{Ri} \tag{3}$$

with A the hydraulic cross-section, n is the Manning's roughness coefficient, R is the hydraulic radius and i is the slope of the canal bed (under steady-state conditions, this hypothesis can be accepted for low value of the canals bed slope [5]). Equation (3) can be easily used for simple geometrical sections, as those of irrigation canals, however it is strictly dependent to the roughness that need to be estimated and can significantly affects the accuracy of the computed water surface level. In general it should be calibrated whenever water surface level information is available. In the present study, as a first approximation, n could be assumed equivalent to 0.03, since this value can be suitable for concrete-bed canals [6].

3. Power evaluation

Since the irrigation canals network is a manmade opera, it might be thought that find the data necessary for the energetic analysis could be easier than, for instance, in the case of same analysis conducted for rivers. The canals were build for irrigation purpose and the monitoring and control activity are related to this aim, so very often there are not available information for our purposes.

However, the method hereafter described, is based on a macro-scale analysis of the irrigation network and is based on some simple assumption that do not require detailed information about the canals. We will show how using the information collected into a databases created by the local government is possible to make a quick and economical estimation of the hydroelectric potential of the irrigation canals network aimed at mapping the potential power to create a master plan. It is anyway important to highlight that for more detailed analysis, preparatory to building project, the databases data are not sufficient and further field investigations would be necessary.

3.1 Case Study: The irrigation network of the Piemonte region

In the Piemonte region (Northwestern Italy), the irrigation canals network is managed by the Consortium for Irrigation. A major re-organization of the irrigation and drainage activity has been done due to the enforcement of the regional law L.R.21/99 "Norme in materia di bonifica e irrigazione" [7]. In particular this organization has been divided into smaller areas hierarchically controlled by small local consortia, and the previous 800 independent irrigation consortia were substituted by 36 wider organizations. After that, the first task was to collect, organize, control, and elaborate the data related to the irrigation canals characteristics, with the aim of creating shareable GIS maps. In order to create these maps, the data of the irrigation canals network of Piemonte region were collected and an informatics database has been created. All these information are merged into the Drainage and Irrigation Informatics System (SIBI).

3.2 The SIBI database

The SIBI database contains data and geographic information concerning irrigation, with the purpose to provide a set of basic information for the water management for irrigating use. It contains more than 8,500 km of irrigation infrastructures (penstocks and canals) on an irrigable area of more than 450,000 ha.

The SIBI uses both geographic and alphanumeric information. By the geographic information the irrigation infrastructures and the irrigation area are identified and the surveyed infrastructure can be georeferenced. The alphanumeric information, instead, collects the technical characteristics of the irrigation canals. The SIBI is then a useful tool to get information about the geographical description (see figure 2) as well as technical references to describe the canals network defining the size, type, coatings, and the water demand.

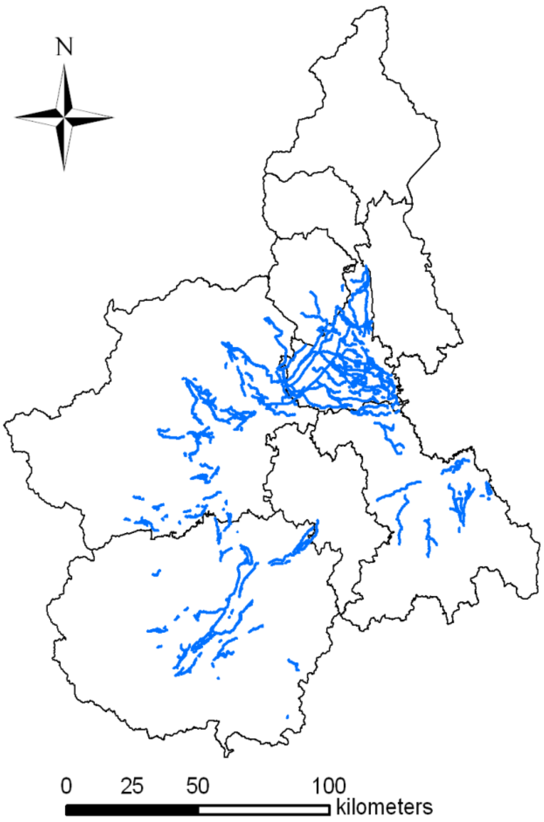

Figure 2. Irrigation network of Regione Piemonte (canals with discharge greater than $1m^3/s$ and cross section greater than $5m^2$).

The irrigation canals data are available from the web-gis portal (http://www.sistemapiemonte.it/agricoltura/sibi_web/) and can be freely downloaded. We use this database for a quick evaluation of the energy potential of the irrigation canals network of the Piemonte region.

3.3 The Piemonte region canals in SIBI

In order to obtain useful information for the evaluation of the Piemonte region energy potential from kinetic turbine installed in irrigation canals, the data provided by the informatics system SIBI are used. Many long canals have been added in the database as a sequence of connected stretches. In the following, we will usually consider the single stretches as fundamental canal units used in the calculations. We will refer also to the canals for a comprehensive power evaluation.

The SIBI database provides information for 9,726 reaches; each one is univocally identified by a reference code. The first four digits of the code identify the agency that manage the reach; the following two digits link each part of the stretch to a specific irrigation scheme according to their geographical location, not according to its managing consortium. This part of the code is extremely important because it allows a rather quick and efficient identification. The last five digits identify the main canal that the reach belongs to, and the location of the reach along the main canal. The data can be look through only according to the irrigation canal network scheme. This means that parts of channel which belong to different consortium managers are grouped together by geographical location.

For every canal reach the following technical information are available: the reference code, the canal name, the irrigation scheme, the canal bed and right and left bank building material, the incoming and outgoing canal discharge, the incoming and outgoing section area and the reach length.

3.4 Data Analysis

Before starting power evaluation it is extremely important to evaluate the reliability and accuracy of the available data relative to each stretch. A preliminary data checking is performed according to the following criteria:

- stretches whose discharge is $Q < 1m^3/s$ or unknown are rejected;
- stretches whose beginning section area is unknown are rejected;
- stretches whose ending section area is unknown are rejected.

The preliminary analysis shows that only the 14% of the total number of stretches available in the database can be profitably used for power evaluation (i.e. all the basic information are supplied). This percentage seems very low, however, it is important to remind that the database has been built for a different primary use and contains also information about stretches not usable for energy production.

More specifically, the majority of the stretches are rejected because of the value of the discharge (only 15% of the 9,726 stretches have discharge greater than $1m^3/s$), while 1% is rejected because of lack of section area information. To conclude only 1,350 stretches out of 9,726 are eligible for further power evaluations.

3.5 Assumptions for the analysis

The study reported in this paper refers to a large-scale analysis of the hydropower potential available for the Piemonte region, located in Northwester Italy. The aim of the study is to define a simple but feasible procedure to analyze canal hydropower potential without resorting to any at-site survey. Nevertheless, this level of analysis is suitable to identify the stretches that could provide an appreciable energy production. Obviously, estimation of more precise and accurate values of the effective power can be done using more detailed at-site information.

In this study some simplifying hypotheses are assumed for the analysis. These assumptions are hereinafter summarized:

- The water concession discharge values are used, instead of the "effective" values, which should be derived from hydrological analysis [7].
- The geometric cross-section height instead of the water level is used to compute the section area. This simplifying assumption can be acceptable because, when irrigation canals are in service, water level is constantly fairly equal to the geometric height.
- If the discharge at the beginning section is different from the one of the outlet section, the average value is adopted.
- Only one cross section is considered for each stretch, i.e. for each stretch only one section is supposed to be suitable for the hydrokinetic plant installation. From the technical point of view, a limited number of turbines on a singular stretch is necessary in order to avoid sensible disturbance on the regular irrigation water flow. The effect of the turbine on the water level will not be explicitly calculated at this level of analysis.
- The entire cross-section is consider in the energy potential evaluation. This assumption is not feasible from a technical point of view, since only the amount of water that flows through the turbine can effectively produce energy. However, this hypothesis is necessary as, at this stage of the analysis, we do not account for a particular turbine geometry.
- The mechanical efficiency of the turbine is not considered.

3.6 Equations for power calculation

Given the hypothesis of section 3.5, the method follows two main steps: the calculation of the mean section velocity by Eq.(2) or (3) and the subsequently power estimation by Eq.(1) for all the suitable stretches.

In this framework, the flow velocity can be computed with Eq.(2), i.e. considering a mean-section velocity value, inferred from the information available in the database. This approach is very simple but adequate for our aims. Differently, Eq.(3) can be profitably used when more detailed information are available (e.g. it is possible to estimate roughness coefficients). However, it should be used carefully, as wrong hypothesis may lead to misleading results [8]. More precise analysis based on hydraulic modelling can be performed, if necessary, considering that, for an irrigation network, a steady-state analysis is usually adequate since the discharge is regulated and stays almost constant in a certain timestep.

In this work, Eq.(3) is not used because it requires information not easily valuable without a field survey.

3.7 Distribution of potential power

In the previous sections, the potential power has been defined for each channel stretch. Here, we classify these results in order to obtain an overall view of the power production of the WCT potentially located in the Piemonte region. In particular, we analyze:

- The range of potential power; according to this it is possible to understand how the power is distributed in the irrigation network: a great amount of stretches with little power rather than a small number of canals with high degree of power production.
- The most suitable stretches and their location; this selection is useful for further more detailed analysis.

The most of the stretches (about the 90%) belongs to a lower potential classe (below 5 kW). These results are sumarized in Fig.3, that represents the cumulated power (ordinate axis) as a function of the stretch velocity (abscissa axis). It can be noted that a lot of points fall in the left part of the plot, that represents a large number of canals which produce a small increment in the cumulated power production (due to their low velocity). The total potential power of the below-5kW canals is about 40% of the total.

A further 10% of the total potential power is expected from a few stretches that presents velocity ranging from 3m/s to about 6.5m/s. The remaining 50% is produced by only 6 stretches whose velocity is about 5-6m/s.

These results confirm the hypothesis of a small geographically concentrated group of powerful stretches, which can cover a big part of the regional potential power by in-stream hydrokinetic turbines. This results can be adopted for further optimization purposes.

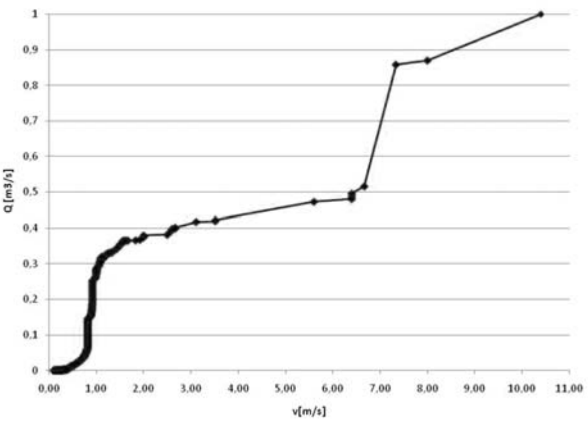

Figure 3. Cumulated potential power as a function of flow velocity.

The following step is then to identify the most powerful stretches and canals: 12 canals are identified for a total amount of 61 stretches. Two of them, the Scaricatore del Castello and the Cavour Canal, produce the 60% of the potential power.

Considering the Scaricatore del Castello canal, formed by 2 stretches, the high velocity is the key element, since it reaches values of the order of 8-9m/s. On the other hand, the Cavour Canal have a different behaviour: the energy out-put is high because of the great number of stretches (43) involved in the procedure (one turbine for each stretch is supposed to be installed). They are located along the canal starting from the town of Chivasso (on the river Po) down to the river Sesia. To sum up, while only two plants can be considered for the case of Scaricatore del Castello canal, a more complete and articulated scheme should be designed for the Cavour canal.

Extending the procedure to the whole set of suitable stretches, the total power output for the Piemonte region is 8,645kW. However, it is important to remember that irrigation activity spans for 5 to 6 months yearly, typically from March to September, affecting the effective energy production. Thus, the flow rate may change dramatically during wintertime, with effects on the average annual power out-put.

Conclusions

The SIBI database, thanks to the information collected for the management of the irrigation activities (a total 9,376 stretches of canals are available), turns out to be a very useful data collection for in-stream hydrokinetic turbine power evaluation. With regards to the aims of this analysis, the database has been filtered in order to consider only the stretches with useful information; a total of 1,350 stretches have been considered, for which suitable values of discharge, cross-section area and mean velocity can be derived.

The total amount of the potential power production, is estimated to be greater than 8 MW. This value constitutes a good result considering the primary use of the canals. Furthermore installation of this kind of turbine do not need big investment, nor major civil works. In particular, analyses relative to the Piemonte region showed that a small number of stretches potentially produce a big amount of power, which is of particular interest in terms of economical and technical feasibility. A summary of the canals that mainly contribute to the potential power generation is reported in Tab.1.

A further useful result obtained from this analysis is the identification of the main characteristics that an ideal hydrokinetic turbine should have to be profitably installed in the irrigation network under study.

The objective is then to identify some turbines which are suitable for being installed in the area of interest, since commercial in-stream hydrokinetic turbines are characterized by specific ranges of geometrical dimensions and velocity of the flow. In this contest, the features of the channels involved are the references: cross section area and flow velocity.

From this point of view, three ideal turbines that could be optimized for the irrigation network of Piemonte region have been considered. These ideal turbines are thought to be used in three different conditions:

- Type I: large canals with low velocity;
- Type II: medium canals with medium velocity;
- Type III: small canals or spillways with high velocity.

The range of cross-section area and velocity for these types of ideal turbine are summarized in Tab.2.

The optimization of such kinds of turbines would lead to an optimal power production. In fact, in this case, most of the suitable stretches could be exploited. Figure 4 shows how the total potential power would be available considering the three types of optimal turbines. Figure 4 also shows that 95% of the total power output derived from 61 selected stretches (which means 8,314 kW), can be reached using only two type of ideal turbines, the first and the third one.

Summarizing, local communities and different groups of stakeholder will find useful this kind of suggestion, that requires low investments to be productive, contributing to small but significant entrepreneurship aimed to the increase of renewable energy production in wide areas.

Channel selection

Denomination	*Irrigation Consortium*	*Location*	*Number of stretches*	*Power production [%]*
Scaricatore del Castello	Coutenza Canali Cavour	Villareggia	2	41
Canale Cavour	Coutenza Canali Cavour	Il percorso	43	21
Naviletto della Mandria	Associazione di irrigazione Ovest Sesia	Moncrivello	1	1
Canale Prata	Consorzio irriguo e miglioramento fondiario acque del Torrente Pesio	Mondovì	1	16
Naviletto Termine Cavour	Associazione di irrigazione Ovest Sesia	San Germano	2	8
Canale Depretis o di Cigliano	Coutenza Canali Cavour	Gerbido	4	4
Canale di Mazzè	Consorzio dei Canali del Canaveseex Cosorzio canale di Caluso	Casale	1	2
Scaricatore Farini	Coutenza Canali Cavour	Saluggia	1	1
Scaricatore dei Travi	Coutenza Canali Cavour	Ivrea	1	1
Roggia Comunale Vero	Consorzio Irriguo Rogge tortonesi	Tortona	1	1
Roggia Comunale Marencano	Consorzio Irriguo Rogge tortonesi	Bosco Marengo	3	3
Canale sussidiario Farini	Coutenza Canali Cavour	Crescentino	1	1

Table 1. Selected stretches.

Ideal Turbines

Range	*Velocity [m/s]*	*Dimension [m^2]*
I	$0.5 < v < 2$	35
II	$2 < v < 5$	4
III	$v > 5$	0.4

Table 2.Ideal turbines.

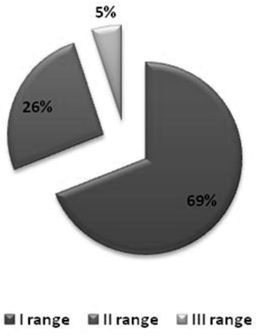

Figure 4 :Power out-put derivable using the three types of ideal turbines.

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