UNIVERSITÀ POLITECNICA DELLE MARCHE

Engineering Faculty
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HYDROELECTRIC POWER GENERATION IN WATER SUPPLY SYSTEMS: APPLICATION TO SOME STUDY SITES IN THE ABRUZZI REGION

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ABSTRACT

The purpose of the following thesis is to give a complete description of the mini-hydro sector. The total exploitation of the sites, where the large hydroelectric basins are installed, has increased the interest for this sector, which allows one to obtain simple and functional solutions for the production of electricity.

The first chapter gives a general overview of the situation of renewable sources in Italy. Statistical data relating to the current situation in Italy of renewable energy plants are analyzed, focusing mainly on hydroelectricity, and also focusing on the part relating to incentive methods and tariffs.

The second chapter instead analyzes the state of the art about hydroelectric technology, evaluating the different types of hydroelectric plants and the main hydraulic machines used.

The next chapters examine the case study of the “Acquedotto del Verde”", for which it has been made a design and economic analysis, for the installation of 2 mini hydroelectric power plants that use the water supply system for the production of electricity, and a cross-correction study with the aim of building a model that allows one to understand how the trend of the spring influences the flow of the aqueduct.

CONTENTS

1 GENERAL INTRODUCTION

Through the centuries, scientific discoveries and technological innovations have allowed humanity to progress in every sector, thanks to scientific and technological research.

A fundamental role in the development of society was played by electricity, a high-level energy source that is easily adaptable to all human activities. The advantages of electricity have meant that it enters everyday life in an ever-deeper way.

Over time, dependence on electricity has become increasingly indispensable, up to the present day, when most human activities could not exist or would be limited without the availability of this type of energy.

The use of electricity has brought to a series of problems related to the pollution associated with its production. The levels of pollution reached due to human activities in general, and to the production of electricity in particular, are critical to the point of becoming dangerous.
In 2018, global carbon dioxide emissions related to energy production increased by 1.7 %, reaching an all-time high of 33.1 Gt of CO2. This is what emerges from data from the International Energy Agency (IEA), which attribute 85% of the increase in emissions to the USA, China and India

The repercussions on human health and the environment of this pollution have led to the birth of numerous protocols used to regulate the countries that joined them, the limitation of emissions of pollutants deriving from the use of fossil fuels and the increase in the production of energy from renewable sources.

The "*Protocollo di Kyoto*" is the first international agreement that contains the commitments of industrialized countries to reduce the emissions of certain greenhouse gases responsible for global warming. It was adopted in Kyoto, Japan on 11 December 1997 and came into effect on 16 February 2005.

The Kyoto Protocol concerns the emissions of six greenhouse gases: carbon dioxide (CO2); methane (CH4); nitrous oxide (N2O); hydrofluorocarbons (HFCs); perfluorocarbons (PFCs); sulfur hexafluoro (SF6).

The main feature of the Kyoto Protocol is that it establishes binding and quantified targets for the limitation and reduction of greenhouse gases for 37 industrialized countries and the European Community.

Hence the intrinsic need for sustainable energy development is recognized: implementing clean electricity production, without polluting or in any case limiting emissions of harmful substances.

1.1 RENEWABLE SOURCES REGULATION AND INCENTIVES

On 17 January 2009 the “climate - energy” package was approved by the European Parliament. The purpose of this package is the achievement of the objectives set for 2020, objectives on which the Heads of State of the various European countries had previously agreed in 2007 with the famous 20-20-20 package, so called because it provides for the reduction of greenhouse gas emissions by 20%, an increase of 20% in the share of energy produced from renewable sources and a reduction in energy consumption by 20%, by 2020.

The approval of the agreement led to the adoption of some legislative proposals including *Directive 2009/28 /EC*, known as the "Directive on the promotion and use of energy from renewable sources". In fact, this directive sets the specific objectives of each country in terms of the percentage of energy from renewable sources. The targets set are binding and each individual State must undertake energy policies adequate to achieve the limits set. Each Member State must adopt a national action plan through which it sets the share of energy from renewable sources consumed in the transport, electricity and heating and cooling sectors in 2020, while also taking into account the effects of other policy measures relating to energy efficiency on final energy consumption.

The plans also provide for the incentive method for each individual source and therefore the tariffs divided into categories of energy production, plus it also provides for incentives for access to the national electricity grid of energy produced from renewable sources. In fact, the Directive explicitly requires that priority access be given to the network, to electricity produced from renewable sources.

On 13 November 2018, the European Parliament voted the *Directive 2018/2001* (also called the RED II Directive - Renewable Energy Directive) on the promotion of the use of energy from renewable sources, published in the Official Journal of the EU on 11 December 2018.

This Directive, which must be implemented by the Member States by 30 June 2021, aims to accelerate the transition from fossil sources to other sources of energy and sets, by 2030, a precise target in terms of renewable energy, which must reach at least 32% of the total energy consumption.

On 20 January 2020 in Italy, the Ministry of Economic Development published the text "*Integrated National Plan for Energy and Climate (PNIEC)*", which includes the innovations contained in the Decree Law on Climate and also those on investments for the Green New Deal provided for in the 2020 Budget Law.

With the *"Integrated National Plan for Energy and Climate"*, the national targets for 2030 on energy efficiency, renewable sources and the reduction of CO_2 emissions are established.

"Italy's objective - declares the Minister of Economic Development Stefano Patuanelli - is to contribute decisively to the realization of an important change in the energy and environmental policy of the European Union, through the identification of shared measures that are in able to accompany the transition underway in the productive world towards the Green New Deal".

As regards public incentives for the installation of plants for the production of renewable energy, it is known that they are characterized by different mechanisms, which take into account, for example, the type of source, the size of the plant or the date of construction. They are divided into:

- *Conto Energia 2020*

  The "Conto Energia 2020" was introduced with the *Community Directive 2001/77/EC*, through the *Legislative Decree 387/2003*. Its goal is to improve the energy performance of buildings by installing photovoltaic systems. Those who produce electricity using solar energy receive a sum of money deriving from the electricity produced by their plant. The incentive, which the state provides is based on a period of twenty years. In 2020, the legislation is updated with the *Ministerial*

Decree of 4 July 2019, also known as the *FER Decree* (Renewable Energy Sources), which establishes that only plants whose components used are newly built and those whose nominal power is not less than 1 kW. An essential condition is that the photovoltaic systems installed are connected to the electricity grid or to small isolated networks.

- *Conto Termico 2020*

The "Conto Termico 2020" (whose fund is managed by the GSE, Energy Services Manager) allocates economic contributions for the improvement of energy efficiency through the production of thermal energy from renewable sources. It provides an economic bonus equal to 65% of the expense. Intended for improving the efficiency and energy saving of buildings and for the production of renewable energy. This bonus is valid for public administrations and private entities (businesses or residences).

- *FER Decree (Renewable Energy Sources)*

In force since 10 August 2019, the *FER Decree* (Renewable Energy Sources) provides for the requirements for access to incentive mechanisms for supporting the production of energy from renewable sources. In particular, it facilitates small energy production plants (up to 1MW of energy produced) such as photovoltaic, wind, hydroelectric and purification gas plants.

- *National Energy Efficiency Fund*

Tthe National Energy Efficiency Fund is regulated by the *Interministerial Decree of 22 December 2017*. It economically supports the energy efficiency interventions carried out by companies and by the Public Administration, on buildings, plants and production processes.

- *Former "Green Certificates" incentive*

Since 2016, the Green Certificates mechanism has been replaced by a new form of incentive. GRIN (Incentive Recognition Management) is the name of the new program that allows access to the new incentives provided for the D.M. 06/07/2012 for all IAFR qualified plants (Plants Powered by Renewable Sources), the IAFR is a certificate issued by the GSE (Energy Service Manager) which certifies the possession of the requirements to access State incentives.

1.1.1 INCENTIVES FOR HYDROELECTRIC ENERGY

The methods of incentivising electricity produced by hydroelectric plants connected to the electricity grid are established by the *Ministerial Decree of 4 July 2019*, also known as the *FER Decree* (Renewable Energy Sources). It regulates the incentive of all plants powered by renewable sources, with power not less than 1 kW.

The incentives have a duration equal to the useful life characteristic of the type of plant considered, and can be divided into:

- *All-inclusive rate*

  It consists of a single tariff, corresponding to the incentive and the electricity withdrawn by the GSE (Energy Services Manager, which deals with the withdrawal and payment of energy). It is defined as "all-inclusive" as its value includes both an incentive component and a component for enhancing the energy fed into the network.

- *Incentive*

  It is calculated as the difference between the tariff and the hourly price of energy, since the energy produced remains available to the operator.

In the Table 1, we can see the incentives for hydroelectric energy divided by type and generated power.

Table 1 - Incentives divided by type and generated power

Renewable Source	Type	Power [kW]	Plant useful life [years]	Incentive rate [€/MWh]
Hydropower	Flowing water (including installations on aqueducts)	$1 < P \leq 400$	20	115
		$400 < P < 1000$	25	110
		$P \geq 1000$	30	80
	Basin or Reservoir	$1 < P < 1000$	25	90
		$P \geq 1000$	30	80

1.1.2 HYDROELECTRIC ENERGY IN ITALY

According to data published by the Energy Services Manager, GSE, on the development of hydroelectric power in Italy, during 2018, production from hydroelectric sources amounted to 48.786 GWh, which corresponds to 42.6% of total production from renewable sources. 75% of the electricity generated by hydroelectric plants was produced by plants with a capacity greater than 10 MW, 19% by those with a capacity between 1 and 10 MW and the remaining 6% by small-sized plants (less than 1 MW).

In Table 2, the data corresponding to the number and gross efficient power of hydroelectric plants in Italy are shown.

The table shows that the most numerous class is the one with power less than or equal to 1 MW which accounts for approximately 72%. It is evident, however, that 81.3% of the national hydroelectric power is installed on 308 plants, so it can be said that few and large plants are the national hydroelectric assets.

The overall increase in terms of power in 2018 compared to 2017 was 72.7 MW, therefore with an increase of 0.4%.

The incidence of hydroelectric power installed on renewable plants in Italy is 34.8%.

Table 2 - Number and power efficient of hydroelectric plants in Italy "GSE – gestore servizi energetici"

	2017		2018		2018 / 2017 Variazione %	
Classi di potenza (MW)	**n°**	**MW**	**n°**	**MW**	**n°**	**MW**
P ≤ 1 MW	3.074	841,1	3.123	858,5	1,6	2,1
1 MW < P ≤ 10 MW	886	2.640,8	900	2.676,1	1,6	1,3
P > 10 MW	308	15.381,1	308	15.400,9	0,0	0,1
Totale	**4.268**	**18.862,9**	**4.331**	**18.935,5**	**1,5**	**0,4**

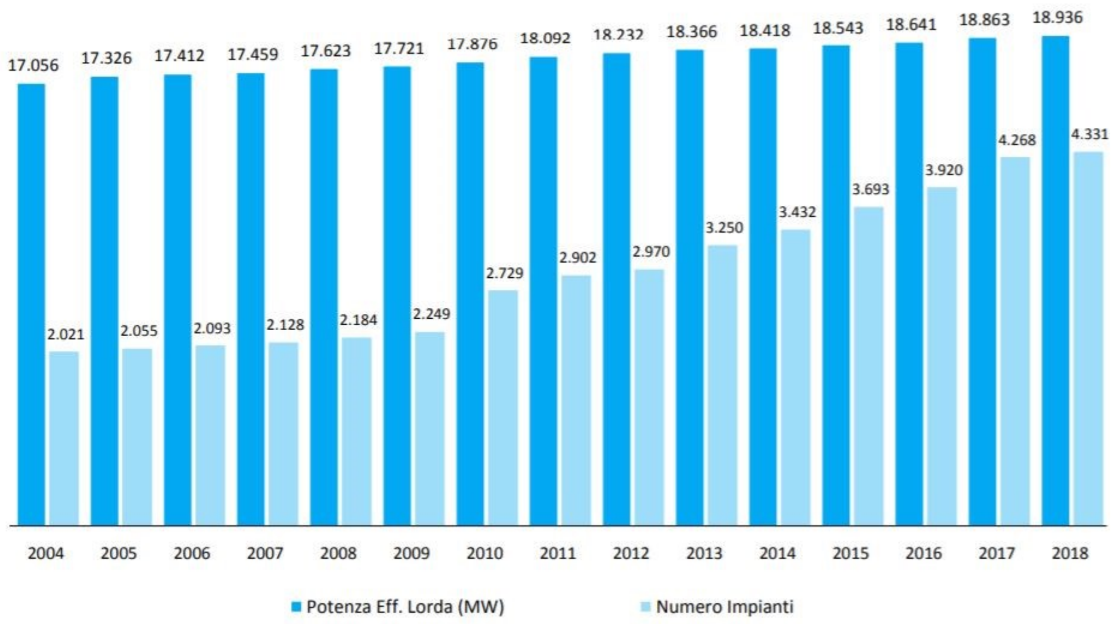

Figure 1 - Evolution of power and number of hydroelectric plants in Italy "GSE – gestore servizi energetici"

Figure 1 shows that the time span between 2004 and 2018 is mainly characterized by the installation of small plants, this can be seen by the large growth in the number of plants compared to power which has not changed much.

In the future it is expected that mainly mini and micro hydroelectric plants will be built, in line with what has happened in recent years.

Furthermore, the continuous decrease in the average size of hydroelectric plants continues, which went from 8.4 MW in 2004 to 4.4 MW in 2018. The decrease, which began in 2010, was significant in 2016 when numerous plants with power below 200 kW came into operation, significant in terms of number of plants but not in power.

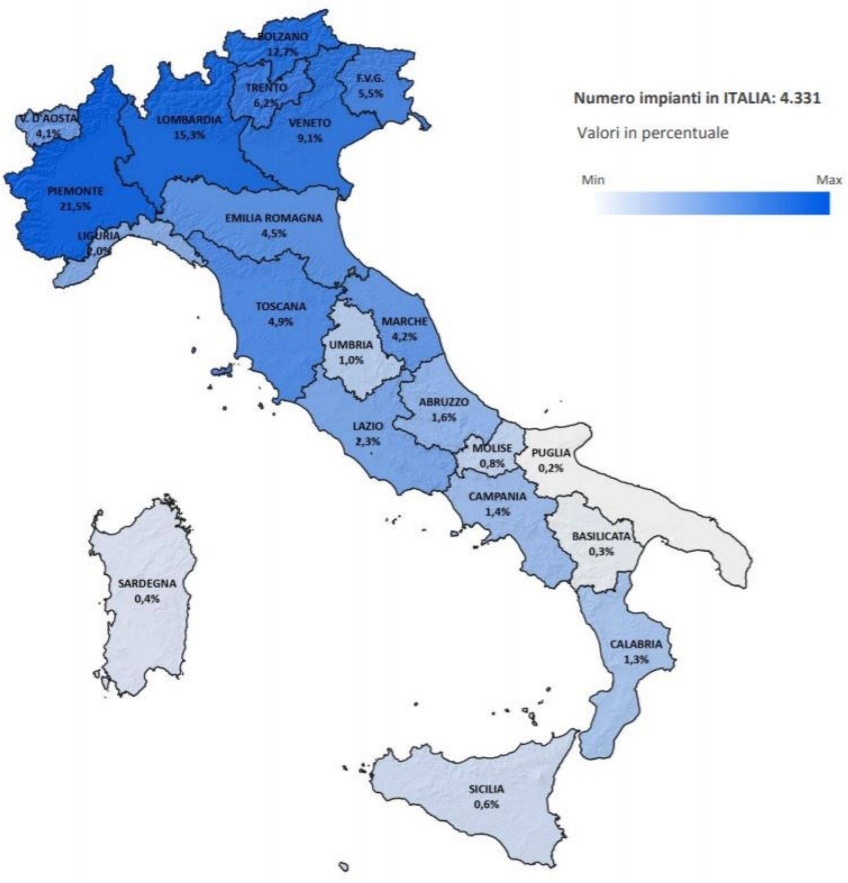

Figure 2 - Regional distribution of the number of hydroelectric plants at the end of 2018 "GSE – gestore servizi energetici"

As can be seen from Table 2, in Italy, hydroelectric plants increased by 63 units compared to the previous year, most of the plants installed are concentrated in the Northern area, in particular in Piedmont, Lombardy and in the provinces of Bolzano and Trento which represent over 55% of the total.

In central Italy, most of the plants are installed in Tuscany (4.9% of the total) and in the Marche (4.2%).

In the South, hydroelectric plants are less widespread.

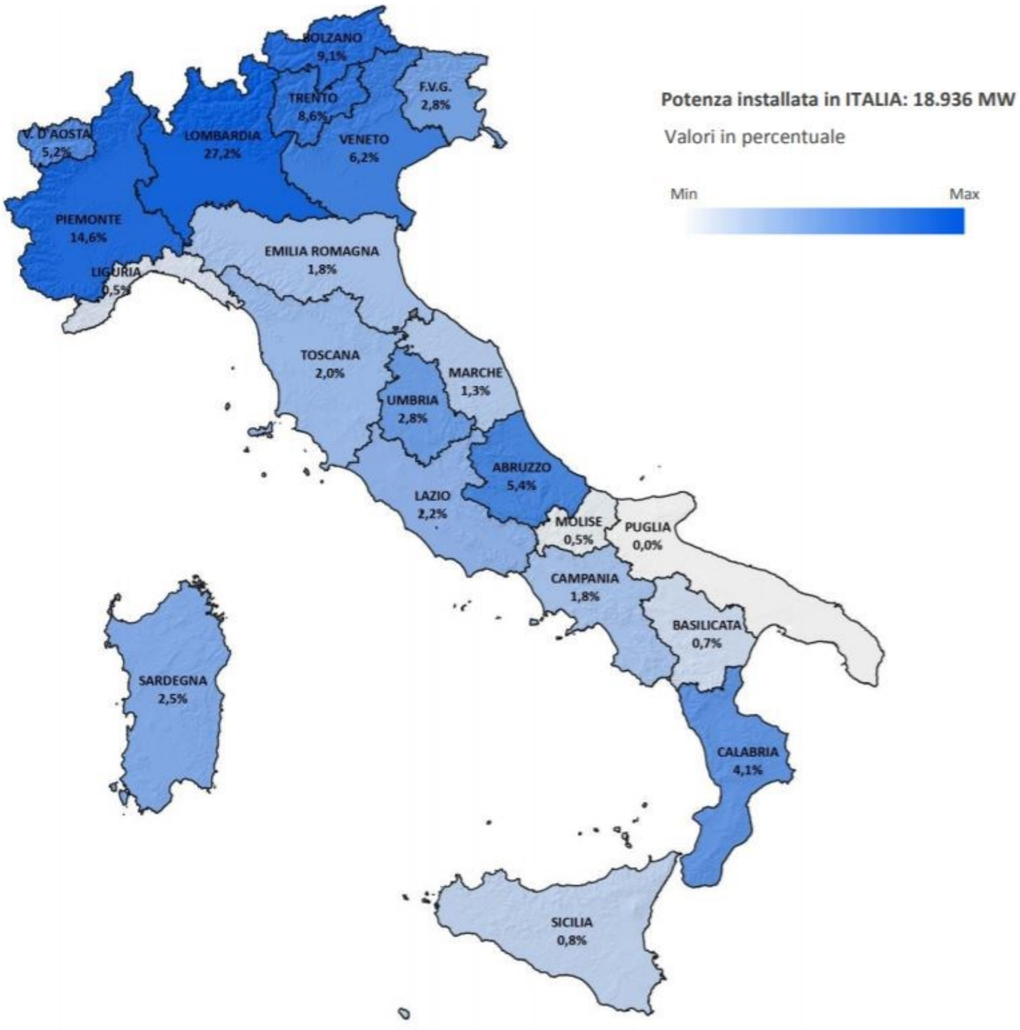

Figure 3 - Regional distribution of the installed power of hydroelectric plants at the end of 2018 "GSE – gestore servizi energetici"

The total power reached by the hydroelectric plants at the end of 2018 was 18,936 MW. As before, the North is the most concentrated area having in fact 76.0% of the total installed power. Once again regions such as Piedmont, Lombardy and the provinces of Bolzano and Trento stand out for their major powers. (Figure. 3)

Among the central regions, Umbria has the highest concentration of power, equal to 2.8%, followed by Lazio with 2.2%. In the South, Abruzzo (5.4%) and Calabria (4.1%) stand out.

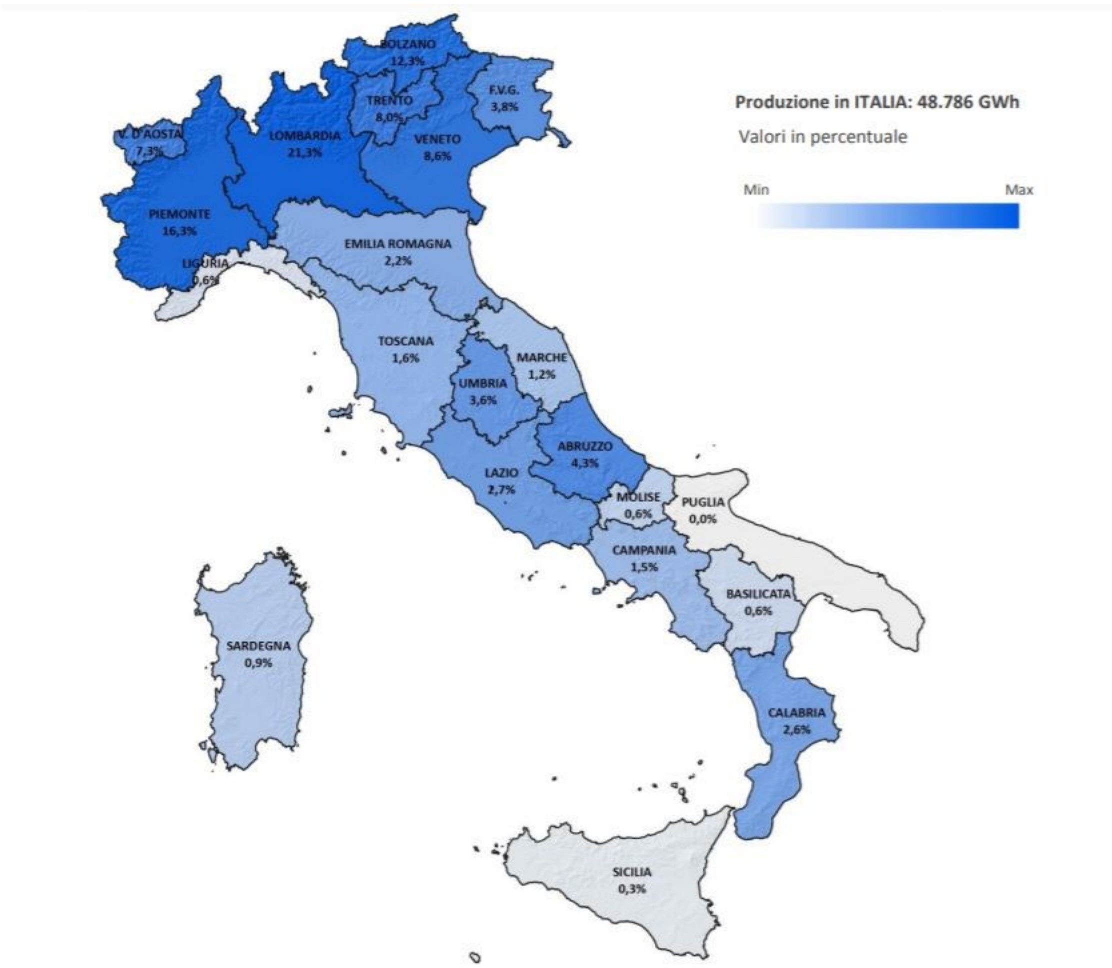

Figure 4 - Regional distribution of hydroelectric production in 2018 "GSE – gestore servizi energetici"

As can be seen from Figure 4, in 2018 hydroelectric production was 48,786 GWh. Once again there are high productions in correspondence with the northern regions, while in the southern regions and islands the values are decidedly lower. As already described above, the reasons are to be identified in the limited size of the plants.

Lombardy, the provinces of Trento and Bolzano, Piedmont and Veneto account for 66.5% of the total national production.

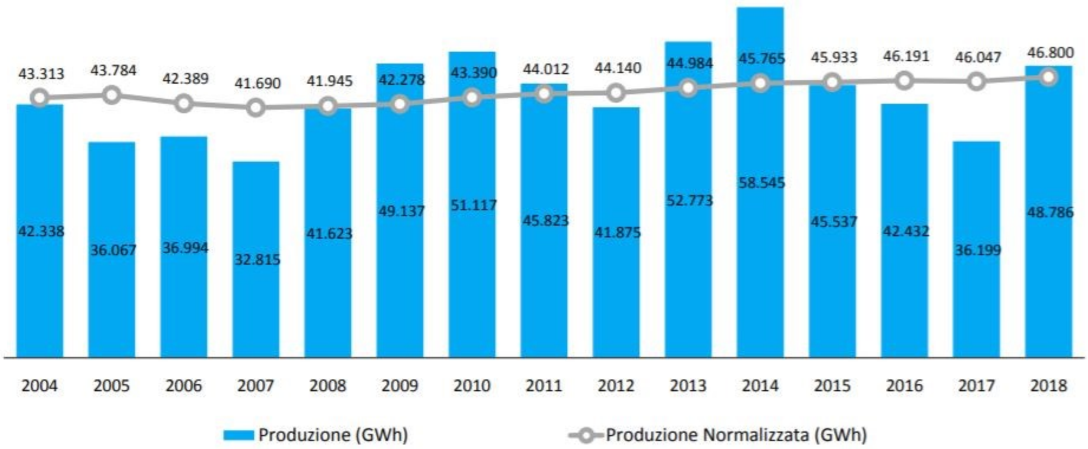

Figure 5 - Trend of actual and normalized hydroelectric production in Italy "GSE – gestore servizi energetici"

Directive 2009/28/EC provides that the contribution of the water source (Figure 5), in order to achieve the 20-20-20 objectives, is appropriately calculated through normalization with reference to the production of the last 15 years.

The calculation method allows to compare all the member countries of the European Union with uniformity of treatment.

In 2018, the normalized value of electricity production from water sources was 46.800 GWh, 1.6% more than in 2017.

The methodology imposed by *Directive 2009/28/EC* for calculating the effective contribution of the water source is shown below.

$$Q_N = C_N^{AP} * \frac{\left[\sum_{i=N-14}^{N} \frac{Q_i^{AP}}{C_i^{AP}}\right]}{15} + C_N^{PM} * \frac{\left[\sum_{i=N-14}^{N} \frac{Q_i^{PM}}{C_i^{PM}}\right]}{15}$$

Where:

- N = reference year
- Q_N = normalized renewable electricity generated by all hydroelectric plants of the Member State in year N
- Q_i = amount of electricity actually generated in GWh excluding production from pumping plants that use the water previously pumped upstream
- C_i= total installed power in MW
- AP = plants from natural contributions
- PM = Mixed Pumping Plants

A very useful indicator in order to identify the production efficiency of hydroelectric plants in a simple and direct way is represented by the equivalent hours of use. They are obtained as the ratio between gross production and gross efficient power.

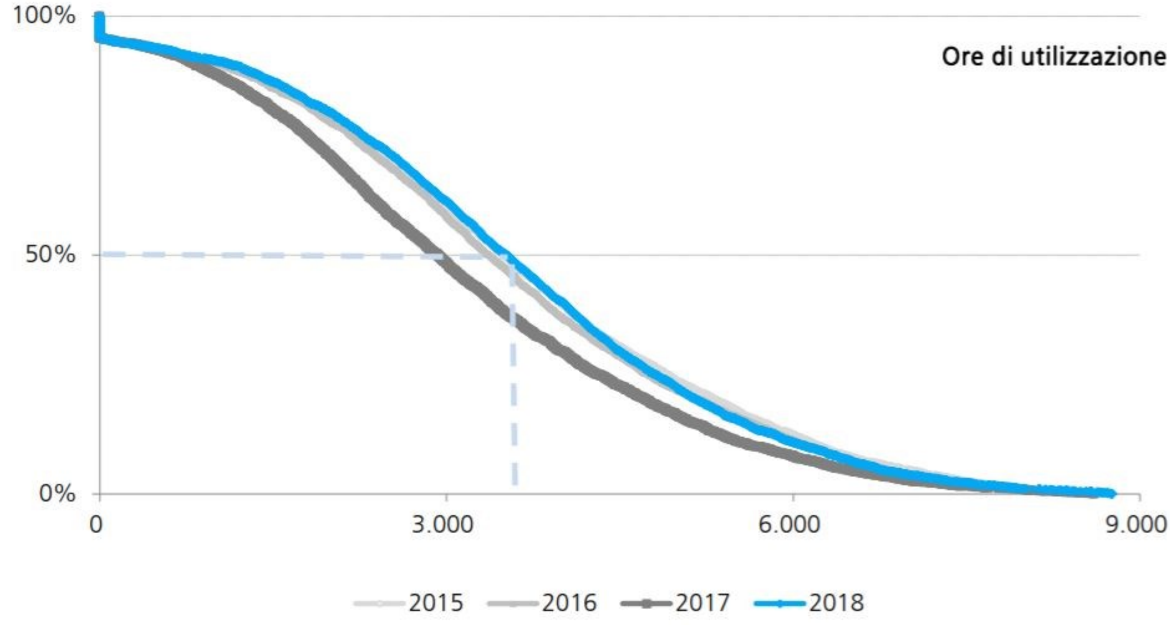

Figure 6 - Percentage distribution of the hours of use of hydroelectric plants in Italy "GSE – gestore servizi energetici"

As can be seen from the Figure 6 in 2018, 50% of hydroelectric plants produced for approximately 3.521 hours, a value higher than 3.485 hours in 2015 and 3.376 hours in 2016.

It is also possible to note how the curves relating to the years 2018, 2016 and 2015 are very similar while the curve relating to the year 2017 is much lower; this can be justified by the less favourable climatic conditions of 2017, a year characterized by low rainfall.

1.2 ENERGY FROM WATER SOURCE

By hydroelectric energy we mean the exploitation of the kinetic energy of a water flow, for the production of electricity using a turbine connected to a current generator. The use of the energy present in a water course is one of the oldest methods of efficiently exploiting the elements of nature. Since the nineteenth century, the use of water power has been one of the most used methods for the production of electricity and for industrial activity in general.

Now the production of hydroelectric energy has reached full technological maturity thanks to its extensive use in past years, which has allowed the construction of variable power plants. In Europe in the past large power plants have been built and therefore with the need for massive civil works that have had a strong impact on the territory and on the resident population. Just think of the construction of the large basins, monumental works that have forever changed the morphology of the territory.

Hydroelectricity has been used in European countries for about two centuries. Over this time, technology has undergone considerable changes, constantly improving up to the present day. A radical improvement in technology in this area is therefore not expected in the future.

The knowledge acquired has allowed us to obtain a good result in terms of effectiveness and efficiency for large-sized plants, allowing them to be built at low installation costs. In Italy, large hydroelectric plants have already used most of the usable sites and it does not seem possible to build others of such considerable size.

However, there are still possibilities for using the hydroelectric resource, its application on a small scale, creating mini-hydroelectric plants. These plants affect smaller companies and with a use of the energy produced different from the industrial one. Mini-hydraulics takes into account flows and jumps so far neglected and allows the powering of small businesses, perhaps difficult to reach from the electricity grid, or allows for the integration of national electricity generation by feeding the surplus of energy produced into the grid. Since water is a continuous and predictable primary source, this system can form the basis for future microgrids, especially for isolated sites. These small plants represent a form of distributed generation that allows to produce energy close to the users because, having little impact, they have a wide potential for diffusion on the territory, in terms of location there are many sites.

It is an application that has great investment potential thanks to the new sustainable development context linked to the reduction of consumption and the production of electricity from renewable sources. In fact, mini-hydraulics can count on various incentives and aid allocated both at national and community level which make the construction of the plants economically convenient.

1.2.1 SMALL HYDROPOWER PALTS

With the terms minor hydroelectric and mini-hydropower plants we mean the exploitation of the potential of water in plants characterized by modest power. The official classification proposed by UNIDO (United Nations Industrial Development Organization) identifies four families of smaller hydroelectric plants:

- Small plants, with power below 10 MW;
- Mini plants, with power less than 1 MW;
- Micro plants, with power less than 100 kW;
- Pico systems, with power less than 5 kW.

This convention is also adopted by the European Commission, UNIPED (International Union of Producers and Distributors of Electricity) and ESHA (European Small Hydro Association).

In the Italian situation, however, the Authority for Electricity and Gas (AEEG) sets the limit between mini and small power plants at 3 MW.

Small-scale hydroelectricity is the subject of regulations and the AEEG has in fact reiterated that the energy produced by hydroelectric plants with power up to 3 MW is a form of energy of significant value from the point of view of environmental protection "*since such energy generally replaces that produced by other sources with a greater negative impact on the ecosystem and contributes to reducing the load on the national electricity grid, limiting transmission, transformation and distribution losses* ". For hydroelectric production with a power smaller than 3 MW there are therefore particularly favourable and encouraging prices for the production and sale of energy.

It is also possible to classify hydroelectric plants according to the available head:

- low jump, up to 50 m;
- medium jump, from 50 m to 250 m;
- high jump, from 250 m to 1000 m;
- very high jump, over 1000 m.

A third type of classification of hydroelectric plants refers to the methods of taking and accumulating water:

- run-of-the-river systems;
- storage hydropower plant;
- plants inserted in a canal;
- plants inserted in urban drainage systems.

RUN-OF-RIVER SYSTEM

This type of plant characterizes the vast majority of mini hydroelectric power plants which exploit the normal watercourse of rivers or streams. It is therefore obvious that flowing water systems have no possibility of accumulating water or regulating the flow rate that can be derived during the year. Their operation is in fact a function of the hydrogeological regime of the site, and when, for example, the flow rate falls below the minimum value for the operation of the turbine, the production of electricity stops.

The plants with low jump are built near the bed of a water course and often take the water through a short section of penstock up to the turbine entrance.

For medium and high head systems, on the other hand, weirs are generally used to divert the water towards the intake structure. To reduce the cost of the installation, i.e. by limiting the extension of the penstock, it is preferred to bring the water to the loading basin through a low-slope channel positioned next to the river and then the connection is concluded through a short section of pipeline under pressure that reaches the turbine.

STORAGE HYDROPOWER PLANT

This type of plant exploits particular situations in which the tank is already used for other purposes. Since the basin is one of the most important costs in terms of hydraulic works necessary for the construction of a hydroelectric plant, its multiple use would make the economic aspect of the investment even more interesting.

It will therefore be necessary to create a path for the water that hydraulically connects upstream and downstream of the existing dam and to choose the type of turbine that best suits the characteristics of the site.

Another great advantage of these systems is linked to the fact that it is possible to adjust the derived flow rate, compatibly with the storage capacity of the tank, while maintaining high availability.

PLANT INSERTED IN A CANAL

These systems are also called "multi-function systems" as the production of electricity occurs simultaneously with another function.

The exploitation of irrigation canals can take place through two different system solutions. In the event that the irrigation channel must also be designed entirely, the best solution is to provide an enlargement to accommodate the loading tank, the central unit, the return channel and the lateral by-pass. This last element is of fundamental importance as it is necessary to ensure the continuity of water supply for irrigation even in the event of system failure.

On the other hand, if the channel already exists, the best solution is to install the control unit near the intake mouth and the loading channel, creating an elongated spillway. A penstock, along the canal, conveys the pressurized water to the turbine, after its use it is re-introduced into the canal.

PLANTS INSERTED IN URBAN DRAINAGE SYSTEMS

Urban drainage systems consist of a set of systems that allow the removal of wastewater and rainwater from the inhabited centre. These systems work with free surface and, only in some sections, their operation can be under pressure. Such sewer networks can be:

- a unitary or mixed system: they collect and convey rainwater and wastewater with a single canalization system;
- a separate system: the wastewater is collected and conveyed using a canalization system different from the rainwater collection system.

Unlike water supply systems, urban drainage systems work with high flow rates and often limited jumps.

However, there are also non-negligible similarities between the plants inserted in urban drainage systems and those in water supply systems. In fact, even in urban drainage systems there is the great advantage of being able to exploit all the flow in transit, without having to remove the amount of water necessary to safeguard the aquatic habitat. Furthermore, the environmental impact associated with the construction of civil works that contain electromechanical equipment is almost zero. In fact, being careful it is possible to avoid the disfigurement of the landscape, incorporating the plant in the other buildings of the purification system or placing it close to the controlled drainage works, already unsightly, noisy and cumbersome.

1.2.2 ADVANTAGES AND DISADVANTAGES OF SMALL HYDROPOWER PLANT

In Italy there are many sites suitable for hosting small hydroelectric plants also in consideration of the wide range of contexts in which the plants can be installed. Small hydropower plants in fact require limited resources for the production of electricity. Thanks to the limited powers involved, they have a compact structure, easy to transport even in hard to reach places.

Experience allows one to state that small hydroelectric plants, if well-proportioned and installed in the right place, are economically competitive, once the actual global unit costs are considered, compared to both other renewable energy sources and, frequently, also compared to traditional sources. The benefits from an environmental point of view concern the low environmental impact and the possibility of reaching isolated users that cannot be reached through the national electricity grid or that can be reached through works of greater impact.

Small hydropower plants can make an important contribution in terms of the use of renewable sources for electricity production and energy diversification by helping to reduce dependence on fossil fuels and avoiding the emission of greenhouse gases and substances harmful to health.

The environmental impact is very low but not non-existent. The design must be carried out with great attention following the criterion of minimizing the impact on the territory and not considering only the production aspect. It will be necessary to take into account the occupation of the land and the transformation undergone by the territory, limiting the inconvenience resulting from the use of the water resource in question.

The uptake of water and its use must ensure the minimum vital outflow in order not to create alterations to the flora and fauna and to allow adequate use for human activities.

Further attention must be paid to the installation of systems in urban areas. The sound and vibrational impact of the system must be taken into account in order to contain disturbances within acceptable limits.

The main advantages and disadvantages of small hydropower plants are summarized below.

Advantages:

- they use sites discarded by the large hydroelectric plant;
- possibility of new applications in the energy recovery sector;
- minimum environmental impact and greater hydrogeological control;
- ease of installation and transport thanks to the compact size;
- possibility to take advantage of incentives;
- low costs, lower than other renewable sources;
- wide possibility of realization in the future.

Disadvantages:

- lower yield compared to large plants;
- must take into account the use of the water resource used for vital purposes, releasing an adequate minimum flow or in any case not altering the ecosystem in which it is inserted;
- noise and vibration problems in systems built in urban areas.

1.3 METHODOLOGY FOR THE CONSTRUCTION OF A MINI-HYDROELECTRIC PLANT

The production of energy from water sources is strongly influenced by the amount of water and the difference in height available. For this reason, the design of any mini-hydroelectric plant must be characterized by an accurate analysis of the available water flows, trying to have data that are as disconnected as possible from seasonal or occasional atmospheric events.

It is rare to find regular flow measurements in the stretch of watercourse on which the mini-hydroelectric power plant is to be developed. Therefore, it is necessary to evaluate the most effective method to estimate the average annual flow rate and the flow curve.

1.3.1 FLOW MEASURES

A single instantaneous flow measurement is of little use. It is in fact necessary to evaluate the water flow for at least one year.

Regarding to water courses, one of the following methods can be used:

- *Direct measurement by dilution of a solute in the stream*
  Suitable for small streams characterized by strong turbulence and reduced depth. The method is based on the injection of a water-soluble compound and in the sampling of the water at a certain distance downstream from the point of entry where complete mixing of the solvent is guaranteed. The solute

concentration is used to calculate the dilution and from this it is possible to find the flow rate value of the watercourse.

- *Velocity-area method*

  Method used for medium - large water courses which involves the measurement of the cross section of the river and the average speed of the water. For this type of measurement, it is necessary to choose an appropriate place, that is characterized by a regular flow and section of uniform width.

- *Measure using a weir*

  Useful for quite small streams. It consists of a weir placed transversely to the current to be measured. The measurement of the height difference between the water surface upstream and the edge of the weir is sufficient to know the flow that passes through.

Regarding the flow rates in closed channels, such as for example water supply pipes, they are measured with special instruments such as the Venturi tube or diaphragms.

- *Venturi tube*

  This tool uses the Venturi effect, for which the pressure of a fluid current increases with decreasing speed. It calculates the average speed as the relationship between this speed and the pressure. From the speed it is then easy to calculate the flow rate.

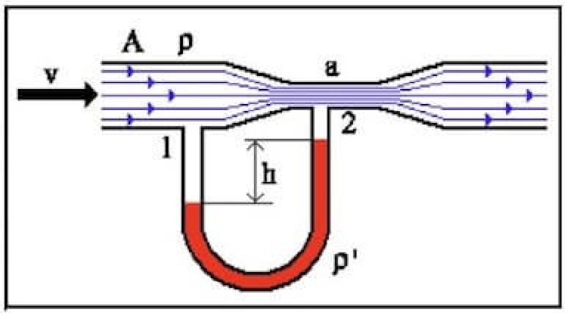

Figure 7 - Venturi tube

- *Diaphrams*

  The Diaphragm is based on the voluntary introduction in a conduct of a concentrated pressure drop. This flow measurement system is probably the most widespread, although it usually is less accurate than the Venturi tube. It adapts to very small flow rates (cm^3/h) up to very large ones (thousands of m^3/h).

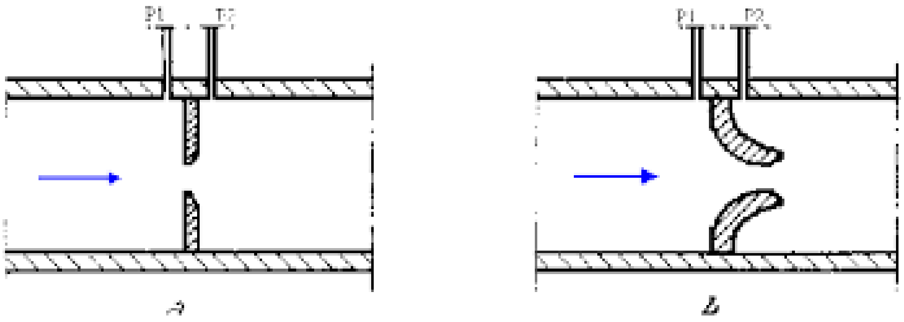

Figure 8 - Diaphragms

1.3.2 GROSS HEAD AND NET HEAD

Gross or geodetic head is defined as the difference in height between the free surface of the water intake section and the level in the section of the watercourse where the flow is returned.

The measurements of the gross head are carried out using the classic topographic techniques. Currently with digital electronic levels the work is simple, fast and very accurate.

Once the gross head has been established, it is necessary to take into account the pressure drops (distributed and concentrated). In addition, some types of turbines must be installed in such a way as to have the water outlet above the free surface of the downstream receiving body.

The gross head minus the sum of all the head losses is equal to the net head, which is the one effectively available to the turbine.

1.3.3 ESTIMATION OF PRODUCIBLE POWER AND ENERGY

In order to estimate the energy that can be produced by the plant, it is necessary to know the design discharge. A very useful tool for this calculation is the duration curve. This curve shows, for a particular point of the water course, the period of time during which the flow rate at that point is equal to or greater than a certain value. This curve can be obtained by ordering the discharge values in descending order, instead of chronologically.

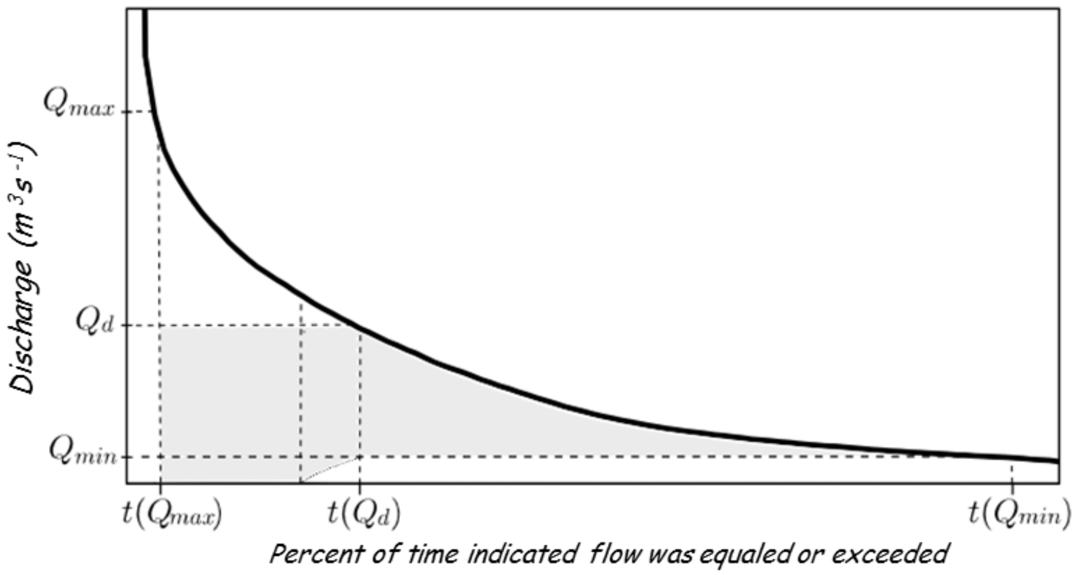

Figure 9 - Duration Curve

The design discharge is equal to the difference between the average discharge and the minimum flow.

Once the discharge has been defined and the net head estimated, it is necessary to identify the type of turbine most suitable for the analyzed hydroelectric project. The turbine will be selected by evaluating the discharge and the available head; in the following chapter the various operating fields of the different turbines are described.

The average annual energy, expressed in kWh, is a function of:

$$E = f(Q_d, H_n, \eta_g, \eta_t, h)$$

Where:

- Q_d= average discharge (m^3/s)
- H_n = net jump evaluated with the Q_d
- η_g= generator efficiency
- η_t = turbine efficiency
- h = number of hours during which a discharge greater than or equal to Q_d exists

The plant is designed on the basis of the maximum design discharge Q_{max}, which corresponds to a theoretical nominal power of the turbine calculated as:

$$P_{theoretical} = g\rho Q_{max} H_n$$

Instead, the system's average power is calculated using the following formula:

$$P_{average} = g\rho Q_d H_n \eta_t \eta_g$$

It is therefore possible to calculate the average annual energy that can be produced by the plant according to the formula:

$$E = P_{average} h$$

2 MINI-HYDROPOWER PLANTS

A mini hydro power plant consists of many elements that are similar (if not identical) to those used in a traditional hydropower plant. Clearly, being smaller, the dimensions and potential of each component are resized to the chosen site.

All the elements that compose a hydroelectric system can be divided into two main categories:

- *Civil works*
  They include everything that allows the water to be derived, appropriately conveyed to the turbine and then adequately returned to the receiving body. Also included are all works related to the protection of the electromechanical equipment from external agents.

- *Electromechanical equipment*
  It includes all the mechanical and electrical components necessary for the transformation of the potential energy possessed by water into electricity.

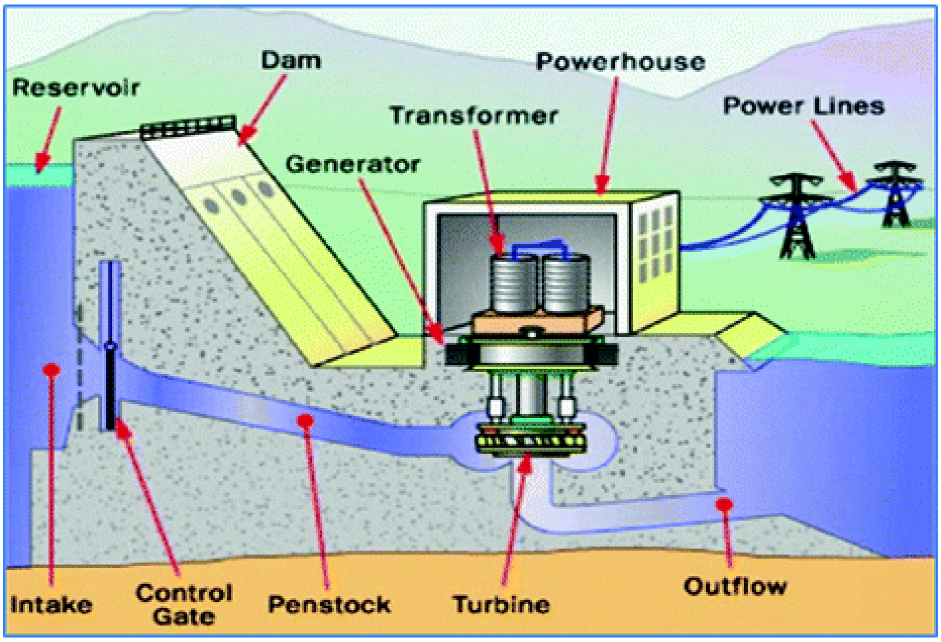

Figure 10 - System diagram and main components

The powerhouse contains the electromechanical equipment that converts the potential energy of the water into electricity. It is composed by:

- Control panel
- Gearbox
- Transformer
- Generator
- Turbine

2.1 CONTROL PANEL

They are devices that control the operation of the system. This control generally takes place by measuring the voltage level, the intensity and frequency of the generated current, the energy produced, the power factor and also the water level in the loading chamber.

For several years, thanks to technology, it has been possible to monitor the plant by remote control, that is, by means of a computer system that allows the hydroelectric plant to be managed even from kilometers and kilometers away. In fact, a simple computer enables one to receive all information relating to production but also to any faults, in order to guarantee rapid and efficient maintenance interventions. More precisely, each component is equipped with special devices that refer to a central control unit which, by analyzing the digital and analogue input pulses, outputs an appropriate signal.

Figure 11 - control and monitoring panels

These control systems make the turbines work in optimal conditions allowing for a higher conversion efficiency and therefore a greater energy produced.

2.2 GEARBOX

The gearbox is a mechanical component that allows the coupling between two parts characterized by different rotation speeds.

When the turbine and the generator rotate at the same speed, it is possible to carry out a direct coupling, that is installing them on the same axis. In this way mechanical losses are reduced and maintenance is minimized. If the impeller rotates at less than 400 rpm (very frequent case for Francis or Kaplan reaction turbines), it is necessary to use a multiplier to reach the 750 - 1,500 rpm of the standard generators.

2.3 GENERATOR

The generator is the electrical component that transforms the mechanical energy of rotation of the turbine into electrical energy. It can be directly connected to the turbine (as in the case of action turbines) or connected with a gearbox, which allows to increase the rotation speed at the output of the turbine and adapt it to that of the generator (as in the case of reaction turbines).

Depending on the network to be powered, the designer can choose between two types:

- *Synchronous generator*

  Devices with such generator type are equipped with an excitation system associated with a voltage regulator which, before connecting to the grid, allows to generate energy at the required frequency, voltage and phase angle. Synchronous generators can operate off the grid. This type is typically used for systems with power greater than 5,000 kW.

- *Asynchronous generator*

  Devices with such generator type are induction machines that do not give the possibility to regulate the output voltage level. They cannot generate current when they are disconnected from the grid. This type of electrical machines is generally used for systems with powers below 500 kW.

Finally, the generators can have a horizontal axis or a vertical axis; generally, there is a tendency to adopt the same configuration of the turbine in order to simplify and make the mechanical coupling more efficient.

2.4 TURBINE

The hydraulic turbine is a machine that allows to transform the potential energy of water into mechanical energy, which is thus converted into electrical energy if an electric generator is coupled to the turbine shaft.

The power P that can be extracted from a hydraulic turbine is obtained using the following formula:

$$P = \rho g H Q \eta$$

Where:

- P = power turbine [kW]
- ρ = water density [kg/m^3]
- g = gravity force [m/s^2]
- H = jump [m]
- Q = turbine discharge [m^3/s]
- η = turbine efficiency [%]

From the formula, it can be seen how a large jump can compensate for a small discharge and a large discharge can compensate for a small jump. Therefore, a stream with a small flow rate can have a difference in height of several hundred meters and therefore have the same energy potential as a channel with large flows but with low differences in height.

To have a good conversion efficiency, the turbine must be suitable for the discharge and the height difference of the site. In fact, these two parameters define the different types of hydraulic turbines.

All hydraulic machines of this type are characterized by an impeller and a distributor. The distributor has three essential tasks:

- directing the flow arriving at the impeller in an appropriate manner
- adjusting the discharge of water entering the turbine
- transforming the potential energy possessed by water into kinetic energy.

The percentage of potential energy converted into kinetic energy in the distributor determines the classification of the hydraulic turbines: when the transformation takes place completely in the distributor, then the turbine is called an action turbine; otherwise the turbine is called a reaction turbine.

2.4.1 ACTION TURBINES

In the action turbine, all the available potential energy is transformed into kinetic energy in the distributor, so there is no pressure variation between the input and output of the impeller. In fact, it limits itself to transforming the kinetic energy of water into mechanical work available on the machine shaft.

The types of action turbines on the market are:

- Pelton turbine;
- Turgo turbine;
- Cross-Flow turbine.

PELTON TURBINE AND MINI-MICRO PELTON TURBINE

The Pelton turbine, that we can see from Figure 13, is the main action turbine that is used in practical applications. They are robust, reliable, easily disassembled and repairable machines and with few critical parts.

The water reaches the impeller through the penstock which is directly connected to the distributor. The distributor is a simple converging nozzle where the liquid stream is accelerated until it reaches the Torricellian speed. Inside there is the adjustment pin (Double needle) which, moved axially, regulates the flow of water and therefore the power of the machine.

The Double needle, as we can see from the Figure 12, has a dual function:

- adjusting the flow appropriately
- slowing down the internal threads thus giving rise to a much more uniform speed distribution compared to that which would occur with a simple converging tube.

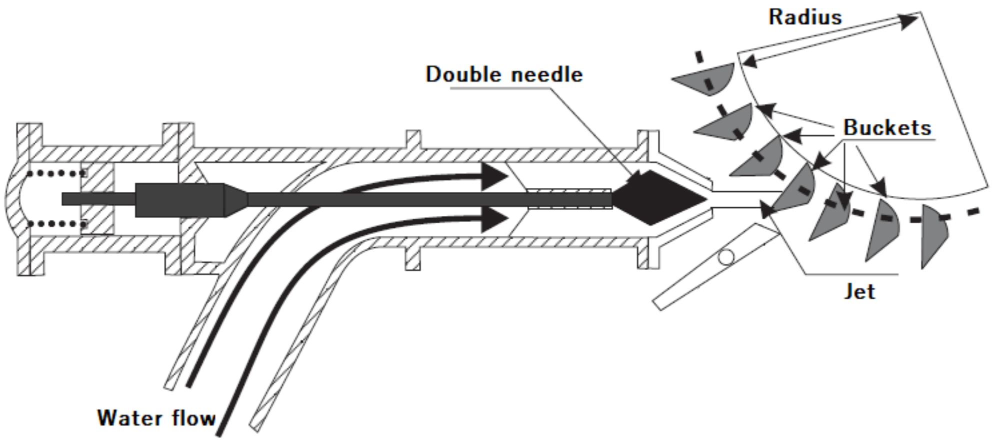

Figure 12 - Double needle scheme

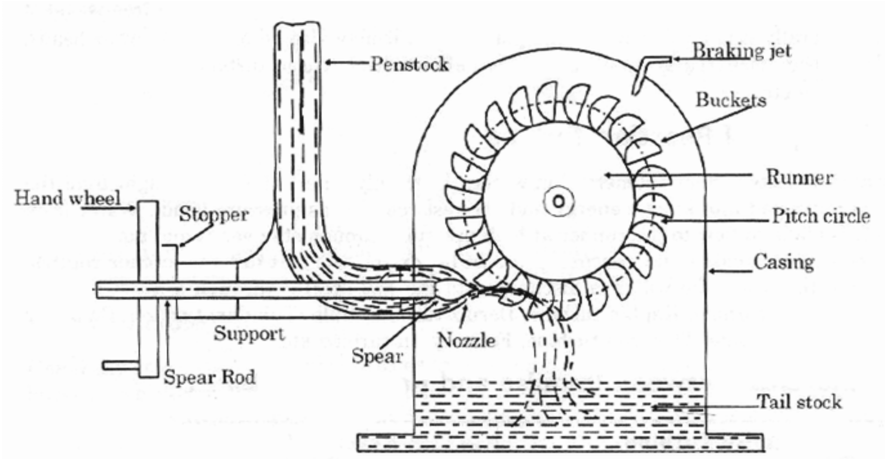

Figure 13 - Pelton turbine operation scheme

This type of machines is also equipped with a deflector which, in the event of an abrupt stop of the machine, has the purpose of diverting the main flow of water avoiding damage to the mechanical parts of the turbine.

The impeller is formed by a series of blades that have the shape of a double spoon with a central edge. The jet of water, which is directed by the distributor tangentially to the impeller, is cut into two equal parts in contact with the edge. The two flows run through each of the two spoons, giving all their energy to the shovel. The water outflow from the turbine is designed in such a way as to avoid impact with other blades (which would have a resistant effect) and making sure that the exit speed is as low as possible.

Furthermore, the Pelton turbine can have a number of jets ranging from two up to a maximum of six. The increase in the number of jets allows to improve the performance of the machine in relation to the specific characteristics of the system.

Figure 14 - 6- Pelton turbine jets

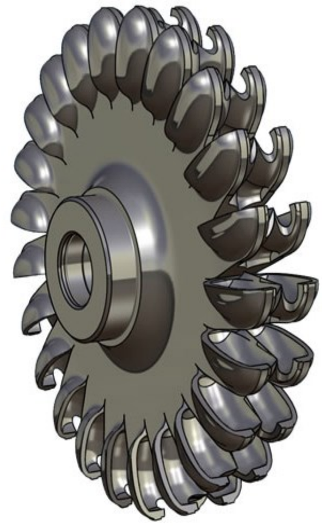

Figure 15 - Pelton turbine impeller

<u>*MINI AND MICRO PELTON*</u>

The Mini and Micro Pelton turbines are small-scale Pelton turbines. Both the first and the second typology are distinguished only by their dimensions, which will be reduced according to the fields of application.

The Mini Pelton turbine can be used for lower jumps and discharge than those required for typical Pelton turbines, while the main difference compared to Micro Pelton concerns the flow rates.

Table 3 - Fields of use Pelton, Mini and Micro Pelton turbines.

TYPE OF TURBINE	***NET HEAD (m)***	***DISHARGE (m^3/s)***
Pelton	50≤ H ≤1300	0,02≤Q≤7,00
Mini Pelton	50≤H≤400	0,004≤Q≤0,4
Micro Pelton	30≤H≤100	0,002≤Q≤0,04

In the Figure 16 the three different types of Pelton are compared. It can be noted that the areas of use are very different from each other: the new technologies for limit applications allow in fact to reach very low minimum levels so as to be able to exploit sites that were previously unusable.

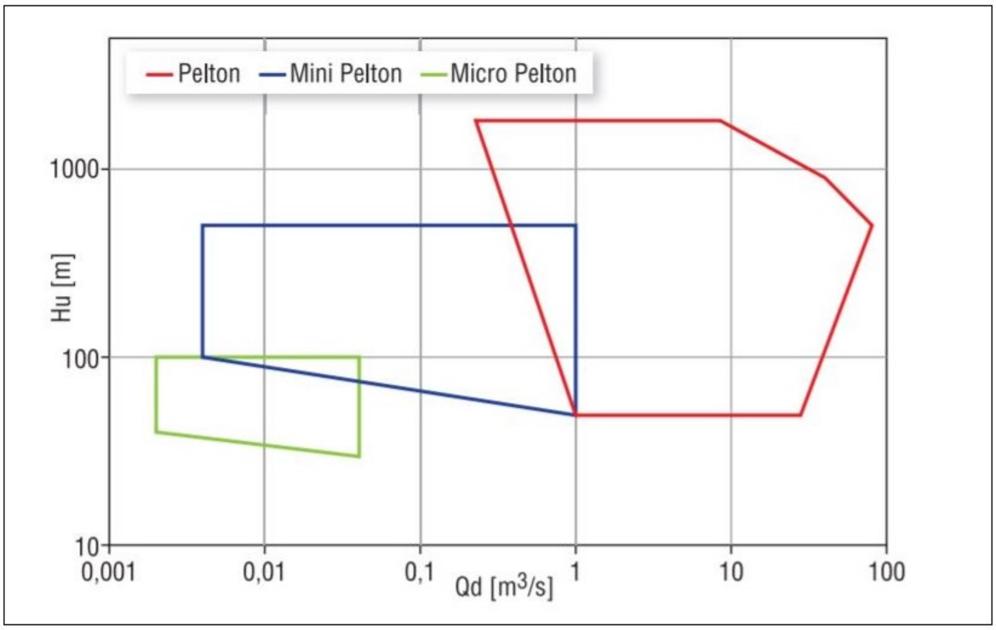

Figure 16 - Fields of use of the various Pelton turbines

In Figure 17 it is possible to see the efficiency of the different Pelton turbines.

The efficiency is closely linked to the adjustment capacity of the machine, which in a Pelton turbine is mainly influenced by the number of jets. By decreasing the size of the devices, the first big difference can be seen in the maximum number of jets that can be used, which goes from a maximum of 6 for a classic Pelton to typically 2 or 5 for the Mini, reaching only 1 unit for the Micro.

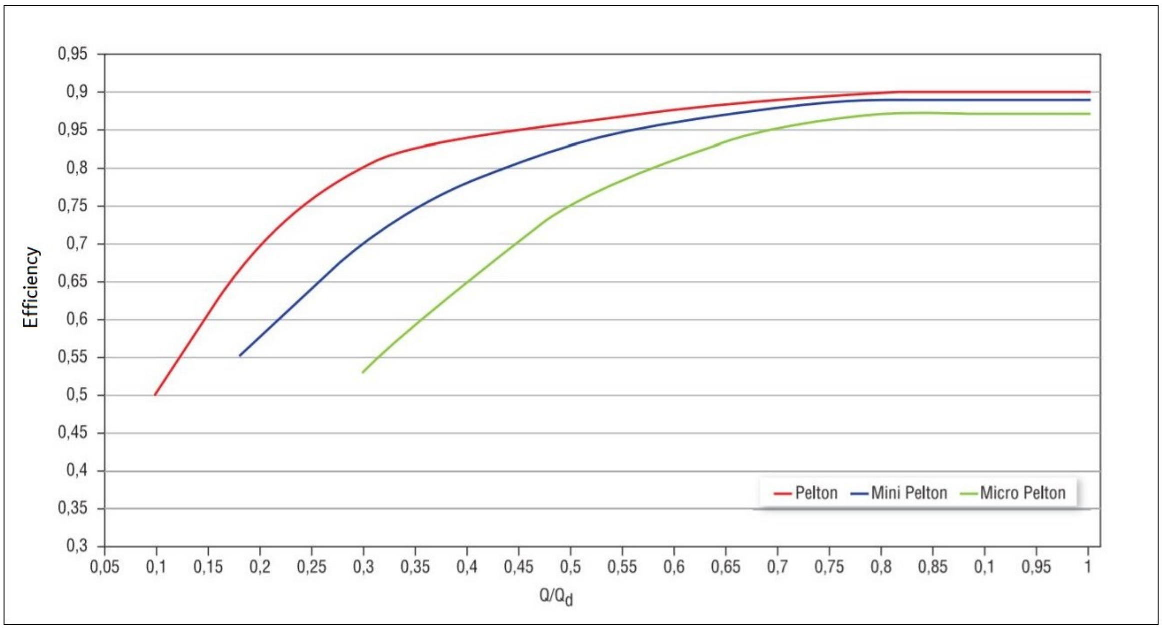

Figure 17 - Efficiencies of the different Pelton turbines

The application cases of the Mini and Micro Pelton can be, for example, the supply pipes of water supply systems, especially for those with sufficiently large differences in height.

TURGO TURBINE

Turgo turbines are action machines very similar to Pelton turbines. They use higher discharge than the Pelton turbine, and are able to exploit jumps between 50 m and 250 m. But they have a lower efficiency.

The impeller (Figure 18) is made up of blades that are half-spoon shaped, very different from the double spoon blades of a classic Pelton turbine.

The distributor is exactly the same as those of the classic Pelton, except for the maximum number of nozzles. Thanks to the fact that the jet strikes several blades simultaneously, it is not affected by the interference generated by the incoming and outgoing flows produced by nearby nozzles. This gives the possibility to have a greater number of jets and therefore to ensure that the Turgo can work with greater flow rates than the classic Pelton.

Figure 18 - Turgo turbine impeller

CROSS-FLOW AND MINI CROSS-FLOW TURBINES

Cross-flow turbines (Figure 19), also called Banki, are a particular two-stage turbines, which allows a double action of the water on the blades. The water comes out from the distributor and is directed towards the external part of the wheel, giving the rotation. The water then passes through the centre of the wheel, and provides additional thrust before exiting the turbine.

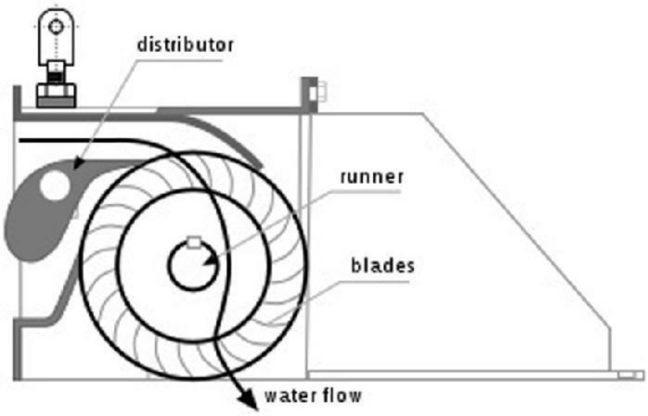

Figure 19 - Operation scheme of a cross-flow turbine

MINI CROSS-FLOW TURBINE

The Mini Cross-flow turbines are small scale models of the classic version. The variations will concern, as in the previous case, the dimensions, the fields of use and the efficiencies.

The fields of use of the Cross-flow and Mini Cross-flow are shown in Table 4 and in Figure 19.

Table 4 – Field of use Cross-flow and Mini Cross-flow turbine

TYPE OF TURBINE	***NET HEAD (m)***	***DISHARGE (m^3/s)***
Cross-Flow	5≤ H ≤200	0,2≤Q≤10,00
Mini Cross-Flow	50≤H≤400	0,01≤Q≤1,0

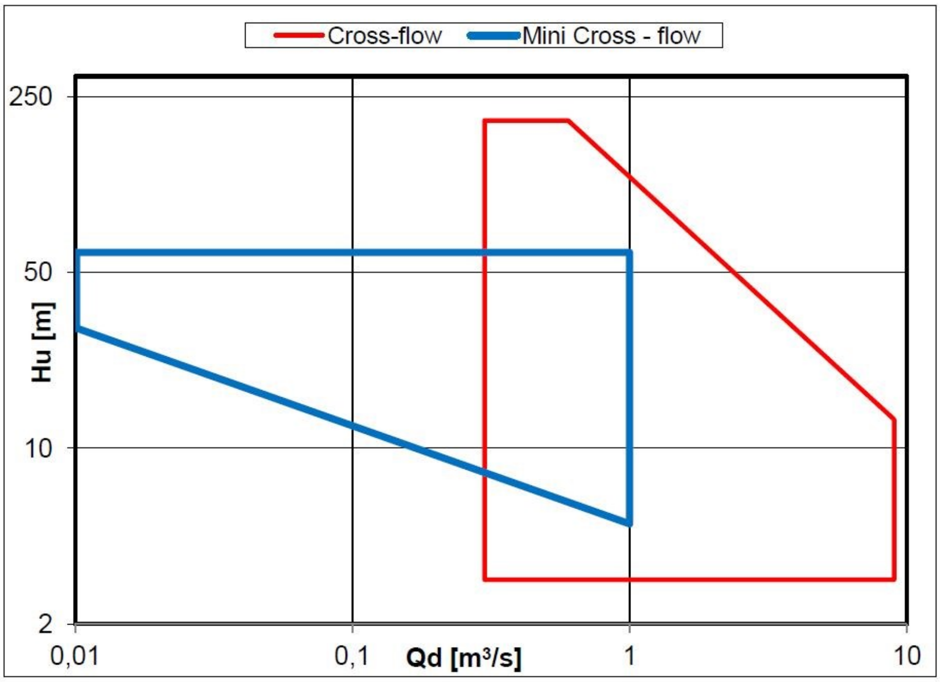

Figure 20 - Fields of use Cross-flow and Mini Cross-flow turbines

Thanks to its ease of construction and maintenance, the Banki turbine is particularly popular in developing countries.

2.4.2 REACTION TURBINES

In these types of turbines, the energy of the water leaving the distributor is partially kinetics and partially pressure (the transformation from potential to kinetics, which takes place in the distributor, is not complete: the water comes out at a lower speed compared to action turbines, but with a non-zero pressure). The reaction turbines work completely immersed in water and are equipped with a speaker in their terminal part.

The types of reaction turbines are:

- Francis turbines;
- Kaplan turbines.

FRANCIS TURBINE AND MINI FRANCIS TURBINE

Francis turbines are centripetal flow turbines, that is the water flow enters the impeller in the radial direction and exits in the axial direction.

The distributor, placed around the impeller, consists of two circular rings and between these the distributor blades are positioned. The water reaches the impeller through a spiral pipe. The disadvantages of their application are due to problems of friction and wear, called volute.

The water is conveyed from the distributor to the impeller which is composed of a hub and a crown, between which a certain number of shaped blades are positioned. The water then exits axially through a diverging tube called diffuser, which has the function of recovering the kinetic energy that the water still has when it exits the turbine.

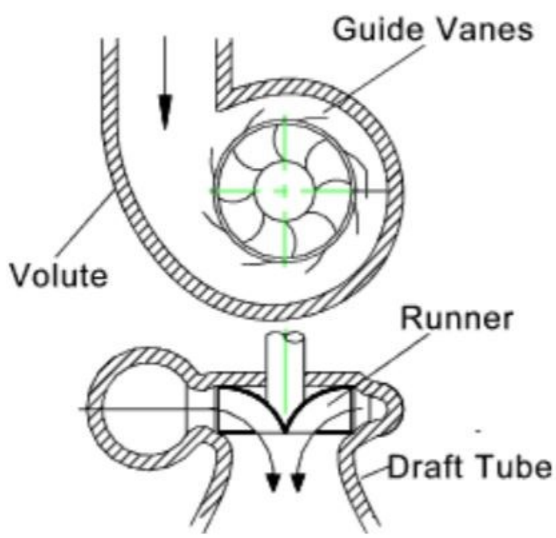

Figure 21 - Francis turbine scheme

<u>*MINI FRANCIS*</u>

Mini Francis turbines are characterized by a radial inlet flow and an axial exhaust as in classic turbines. Also, in this there is a diffuser at the outlet for the recovery of the kinetic energy of the flow of water leaving the impeller.

Compared to the classic Francis turbine, also in this case for the Mini Francis there is a move towards lower flow rates and jumps.

In the following Table 5 and Figure 22, we can see the field of use of the Francis and Mini Francis turbine

Table 5 - Field of use Francis and Mini Francis turbine

TYPE OF TURBINE	***NET HEAD (m)***	***DISHARGE (m^3/s)***
Francis	$10 \leq H \leq 350$	$0{,}4 \leq Q \leq 25{,}00$
Mini Francis	$15 \leq H \leq 100$	$0{,}2 \leq Q \leq 3{,}0$

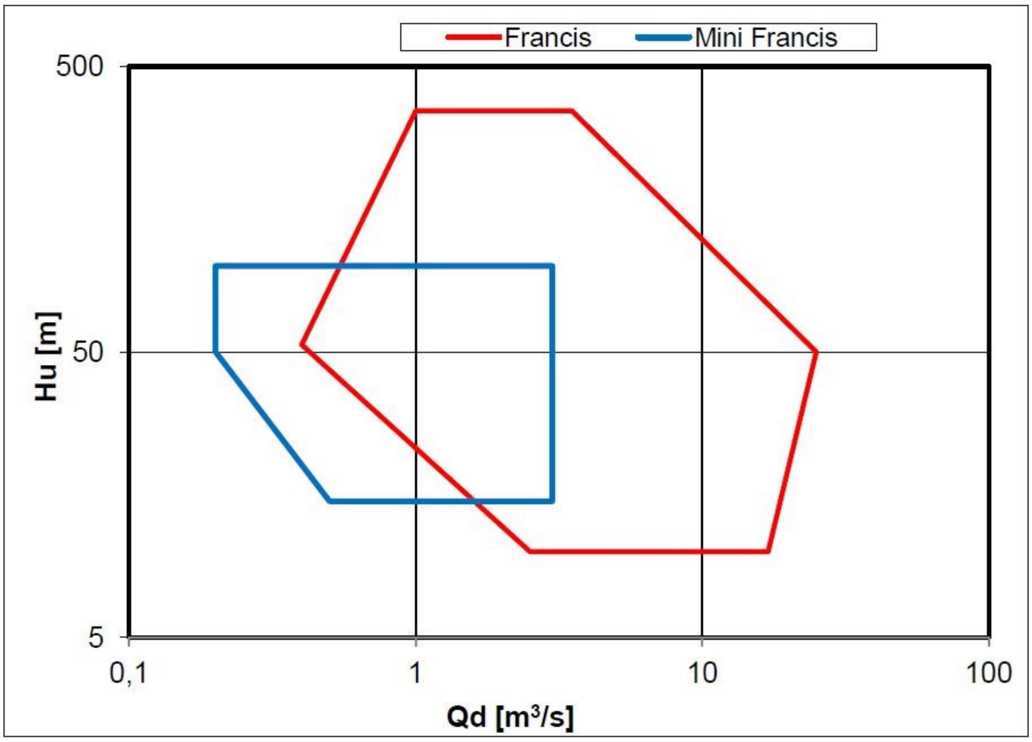

Figure 22 - Field of use Francis and Mini Francis turbine

<u>*KAPLAN TURBINE AND MINI KAPLAN TURBINE*</u>

Kaplan turbines are action turbines in which the flow of water passes through the impeller in an axial direction. They are characterized by a distributor with two possible configurations: fixed or adjustable blades. The impeller, on the other hand, is characterized by a limited number of blades which are always adjustable.

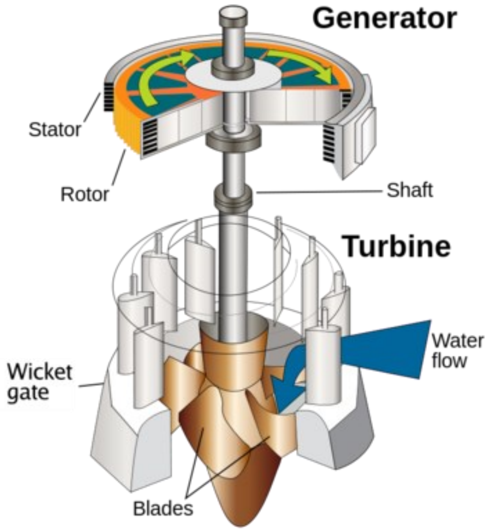

Figure 23 - Kaplan turbine scheme

Leaving the impeller, the water flows through a diverging suction pipe called diffuser. As for Francis turbines, also in the case of Kaplan turbines, recovering the kinetic energy at the outlet is possible through the depression generated by the diffuser itself.

MINI KAPLAN

As for the cases previously analyzed, also in this case the mini version is a reduced scale of the classic version.

What really distinguishes them from classic Kaplan turbines are the fields of use in terms of flow rates used, in fact they are able to manage lower flow rates than a classic Kaplan.

In the following Table 6 and Figure 24, we can see the field of use of the Francis and Mini Francis turbine

Table 6 - Field of use Kaplan and Mini Kaplan

TYPE OF TURBINE	***NET HEAD (m)***	***DISHARGE (m^3/s)***
Kaplan	2≤ H ≤40	2,0≤Q≤80,00
Mini Kaplan	1,5≤H≤15	1,0≤Q≤10,0

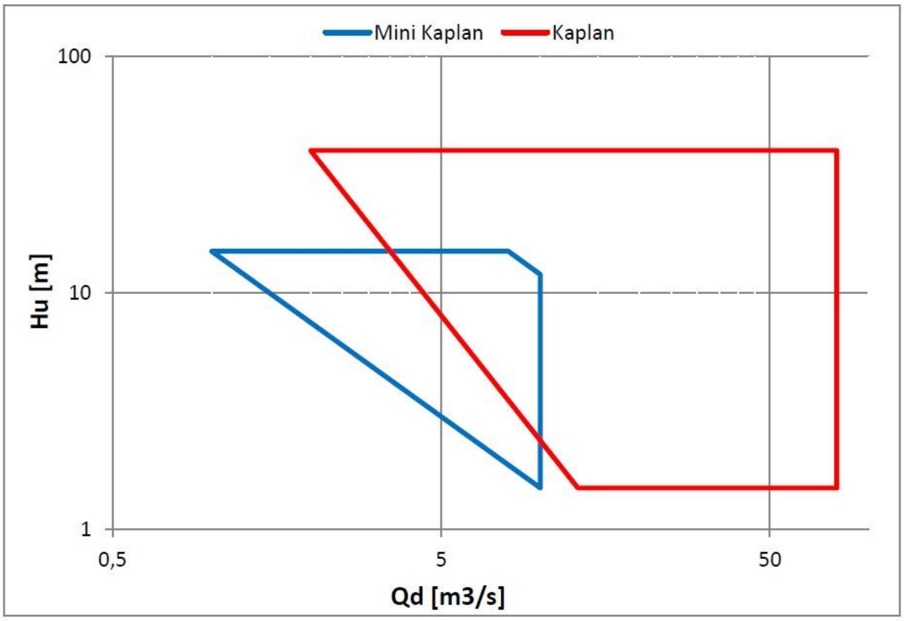

Figure 24 -Field of use Kaplan and Mini Kaplan turbines

Among the limit applications that this turbine can exploit we have, for example, urban drainage systems or industrial drains, where it is possible to have discrete flow rates and almost always limited net head.

Finally, Figure 25 shows the efficiency of the two different turbines.

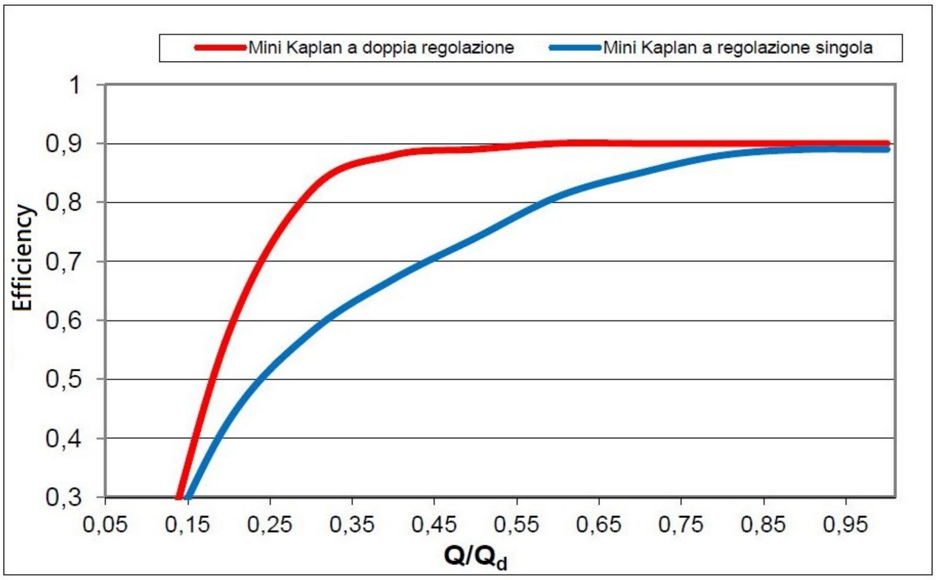

Figure 25 - Efficiencies of different Kaplan turbine

2.5 CRITERIA FOR CHOOSING THE TURBINES

The choice of the turbine strictly depends on the morphological characteristics of the watercourse, in particular the flow rate and the geodetic jump, that is the difference in altitude between the intake location and the turbine.

Table 7 specifies, for each type of turbine, the net head ranges in which each turbine can work. It is observed that there are evident overlaps, that is, for a given value of the head, different types of turbines can be adopted.

Table 7 - Field of net head

TYPE	NET HEAD
KAPLAN	2 < H < 20
FRANCIS	10 < H < 350
PELTON	50 < H < 1300
TURGO	50 < H < 250

This overlap is then resolved with the knowledge of the flow rates to be used for the different turbines.

Having a single flow rate value has no meaning, it is necessary to know the flow rate, it is important to have the flow duration curve obtained from hydrometric data or from hydrological studies.

It is important to know that each type of turbine can work with flow rates between the nominal flow rate and the minimum technical flow rate, under which the machine is not stable.

The flow rate and the net head identify a point in the plane where the operating ranges of each type of turbine are reported (Figure 26).

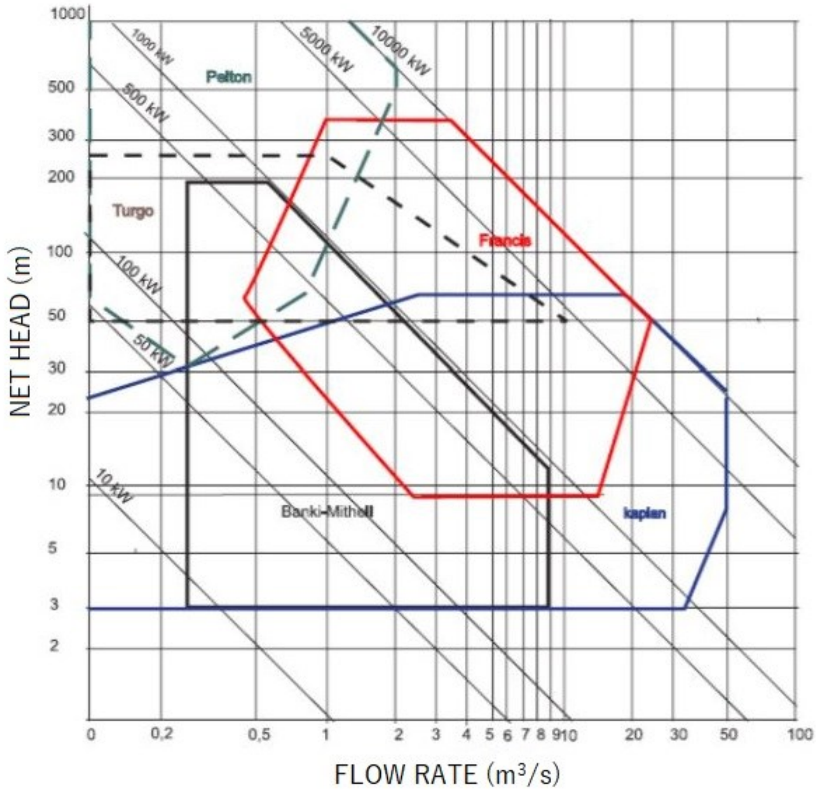

Figure 26 - Operating ranges of the main turbines

All turbines that fall within the defined point (found as a cross between net head and flow rate) can be used in the plant to be designed. The final choice will be the result of an iterative process, which takes into account the annual energy production, investment, maintenance costs and the reliability of the machinery.

2.6 TURBINES EFFICIENCIES

The efficiency is defined as the ratio between the mechanical power transmitted to the turbine axis and the hydraulic power absorbed in the head and nominal flow conditions.

The Figure 27 shows the curves of efficiency as a function of the nominal flow for different types of turbines.

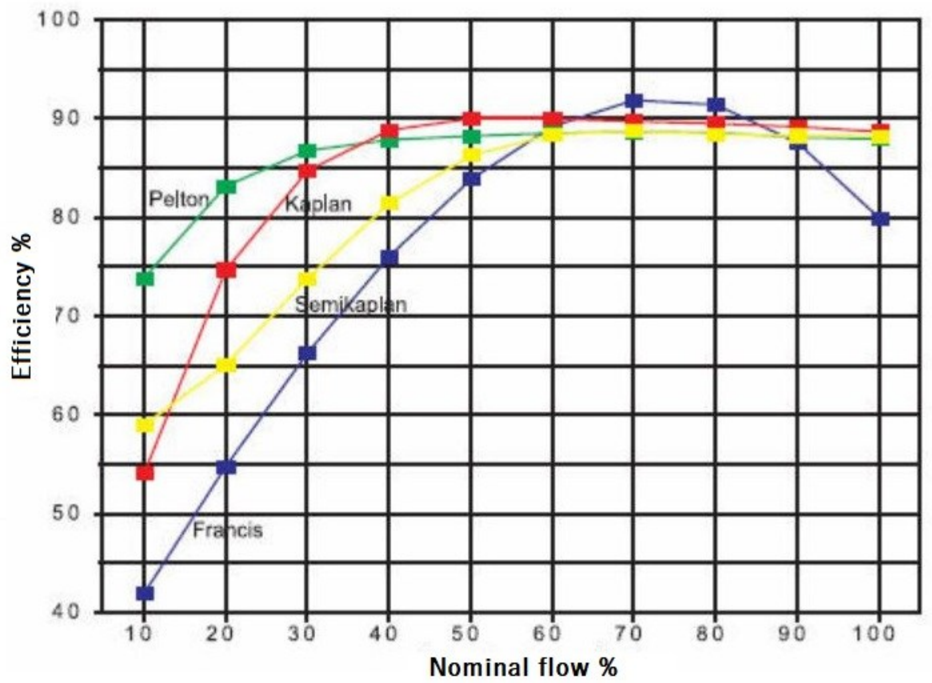

Figure 27 - Efficiency of different turbine types

The turbine is designed to operate at the point of maximum efficiency, which normally corresponds to 80% of the maximum flow.

When the flow moves away from this optimal point, whether increasing or decreasing, the efficiency drops until, once the technical minimum is reached, the turbine stops operating.

2.7 GENERATOR EFFICIENCY

There are different standards for the energy efficiency of electric generators around the world. For global standardization, the international standard IEC 60034-30-1: 2014 was created (Rotating electrical machines – Part 30-1). The efficiency considered by the IEC 60034-30-1 standard is based on the calculation of losses according to the IEC 60034-2-1: 2014 standard.

The efficiency classes are divided according to the following nomenclature (IE = International Efficiency):

- IE1 (Standard Efficiency)
- IE2 (High Efficiency)
- IE3 (Premium Efficiency)
- IE4 (Super Premium Efficiency)

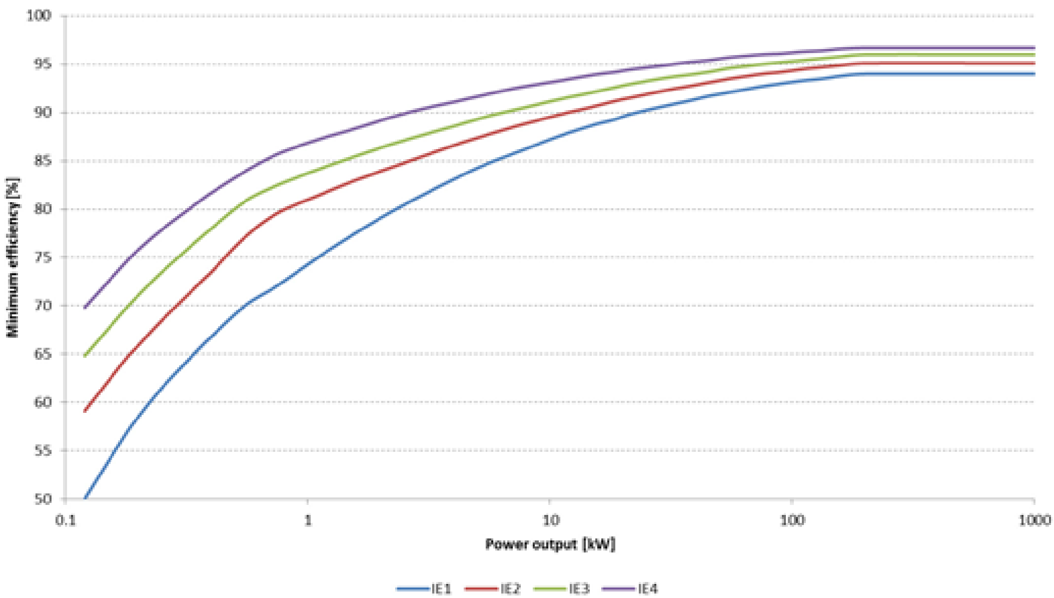

Figure 28 - Efficiences generator

3 CASE STUDY

3.1 TURBINES INSTALLED IN AQUEDUCTS

An additional resource compared to traditional hydroelectricity is represented by the possibility of installing mini hydroelectric power plants along the supply pipelines of the aqueduct networks.

A generic water supply system is composed of a series of works which allow the collection, conveyance, storage and finally the distribution of water in quantities and qualities such as to satisfy the needs of end users.

The water is withdrawn from mountain springs through intake works by means of pressure pipes (supply pipes). Downstream of these pipelines, before final distribution, there are accumulation works (tanks) which guarantee a constant supply of water that is independent of external agents as they act as storage tanks.

In sites characterized by high differences in altitude, between the intake works and the inhabited centres, the potential energy of the water is very high. This energy is connected to high pressures that could compromise the functionality of the pipelines: it is therefore necessary to dissipate part of this energy.

The dissipation occurs in part along the entire pipeline in the form of distributed pressure drops, while the main component is dissipated by means of special instruments called "dissipators" which represent concentrated pressure drops.

The dissipation of this energy is a waste. In fact, there is the possibility of being able to take advantage of this pressure variation by installing a turbine. This would transform the potential energy of water into mechanical rotational energy. The next stage is the transfer of this mechanical energy into electric energy through an electric generator.

It is possible to produce electricity through the exploitation of water supply networks as long as the primary use of water is not compromised in any way. This means that compliance with the law from a hygienic-sanitary point of view and compliance with the rules governing its treatment must be guaranteed.

In fact, the use of systems that have European patents for their suitability for the treatment of drinking water and which in no way exclude contact with pollutants such as lubricating oils, paints, etc. is mandatory by law.

Furthermore, to be sure of having a constant water supply independent of malfunctions of the mini hydroelectric power plant, a system of by-pass valves is provided.

In fact, in the event of out of service the turbine closes and the main by-pass valve automatically maintains the tank level. All valve opening and closing operations must be sufficiently slow to avoid abrupt changes in pressure and avoid dangerous water hammer.

The main reasons for which there are interests regarding the application of mini hydroelectric power plants in water supply networks are the following:

- considering that water is a good that has already been captured for water supply, its exploitation for hydroelectric purposes acquires even more value. In addition, no more water is taken from natural bodies, because in this case the water already present in the pipes is used, and there is no need to build new civil works with a strong environmental impact such as dams.
- the energy obtained from water, is fully included among the renewable energy sources, benefits from the "All-inclusive tariff" which guarantees the investment a good return over the entire useful life of the plant.

3.2 FRAMEWORK

The case examined evaluates the possibility of installing mini hydroelectric plants on the water supply networks of the province of Chieti (Abruzzo).

The aqueduct at hand is called "Acquedotto del Verde", fed by the “Sorgenti del Verde” in the municipality of Fara San Martino (CH).

The aqueduct consists of a main supply that goes from the municipality of Fara San Martino to the municipality of Casoli. In the municipality of Casoli a divider splits the main line into:

- “EAST ADDUCTOR”, which feeds the municipalities of the Vasto area (black line),
- “NORTH ADDUCTOR”, which feeds the municipalities of the Canosa and Vacri area (blue line),
- “MAIN ADDUCTOR”, which feeds the municipalities of the area of Lanciano and Ortona (red line).

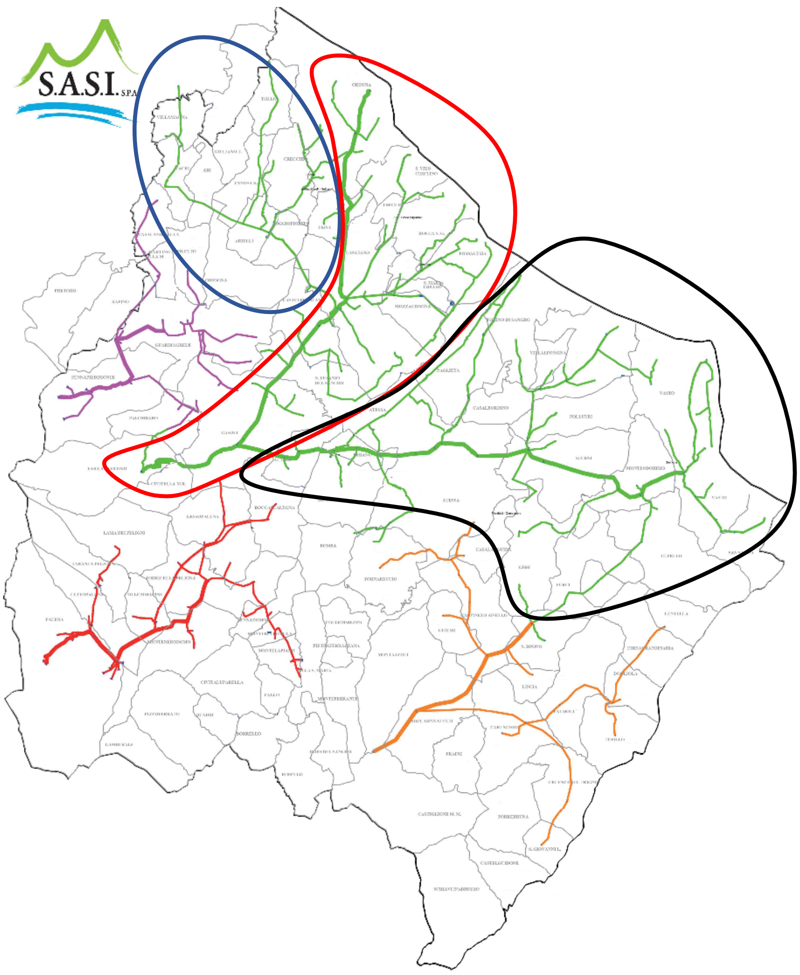

Figure 29 - "Acquedotto del Verde" network

The entire aqueduct network was examined to identify strategic points for the installation of hydroelectric turbines through which electricity production is possible. The research was carried out taking into account the different flow rates, pressures and dimensions of the pipelines.

Looking for the best position of the turbines, it was important to consider that the pressure after the turbine has a significant drop. Therefore, in order to avoid the decrease of the pressure along a pipeline, the turbine is chosen to be placed in the inlet pipeline, just before the tank where the pressure is zero.

After the aforementioned considerations, the field of analysis was reduced to the only pipelines entering the tanks.

After a thorough scan of the entire area, several areas of interest for the study were identified:

Table 8 - Sites identified

SITE ID	AVERAGE FLOW (m^3/s)	STARTING POINT ALTITUDE	ALTITUDE POINT OF ARRIVAL	PIPE DIAMETER (mm)	VELOCITY (m/s)	PIEZOMETRIC DIFFERENT IN HEIGHT (M)	LENGHT OF THE PIPELINE (Km)	PRESSURE (bar)
Pensile Liquirizia (SAN SALVO)	0,032	179	115	200	1,0191	64	\	3
Villa Nasci tank (VASTO)	0,03	234	125,24	300	0,4246	108,76	5,2	11
Old Villa Nasci tank (VASTO)	0,014	234	125	200	0,4459	109	5,2	11
New Fossacesia tank (FOSSACESIA)	0,025	394	175,8	220	0,6580	218,2	10,5	14
Mancini tank (SAN VITO)	0,005	394	194	200	0,1592	200	3,4	15
Nasuti tank (LANCIANO)	0,004	394	338	350	0,0416	56	0,425	5

Among the identified sites, the most interesting and most suited for the study at hand were chosen. These are characterized by high flow rates and piezometric jumps, and belongs to different adductors.

The first site was identified in the municipality of Vasto, at the "Serbatoio Nuovo Villa Nasci" (EAST ADDUCTOR), hereafter called "case 1", while the second site was identified in the municipality of Fossacesia, at the "New Fossacesia tank", hereafter "case 2" (MAIN ADDUCTOR).

4 RESULTS

4.1 SYSTEM CONFIGURATION

The choice of the most suitable design solution must be made taking into account two main aspects:

- *Maximization of extractable energy*

  Bearing in mind that the flow rates passing through the various water supply networks are not a parameter on which it is possible to act, the maximization of the energy that can be obtained turns into a maximization of the gross head / useful head.

- *Hydraulic-structural conservation*

  It is very important to try to minimize the plant engineering works to be carried out, both for an economic fact, since this helps minimizing costs, and for a purely environmental issue, which supports the protection of territories and natural landscapes.

  Where possible, it is therefore necessary to try to keep the supply pipes unaltered (after hydraulic-structural verification).

4.1.1 CASE 1

For the present case, the municipality of Vasto was examined, in particular the reservoir in the quarter of Villa Nasci.

Figure 30 - Villa nasci tank

Two outgoing pipelines depart from the Villa Nasci tank which feed the Port of Vasto area and the area called 167 respectively.

Case 1 will exploit the adduction networks conveyed to the Villa Nasci reservoir. A single steel pipeline reaches such tank from the "Sant'Antonio tank" with a diameter of 300mm.

Below we can see a graphic configuration of the network, starting from the Sorgente del Verde up to the Villa Nasci tank.

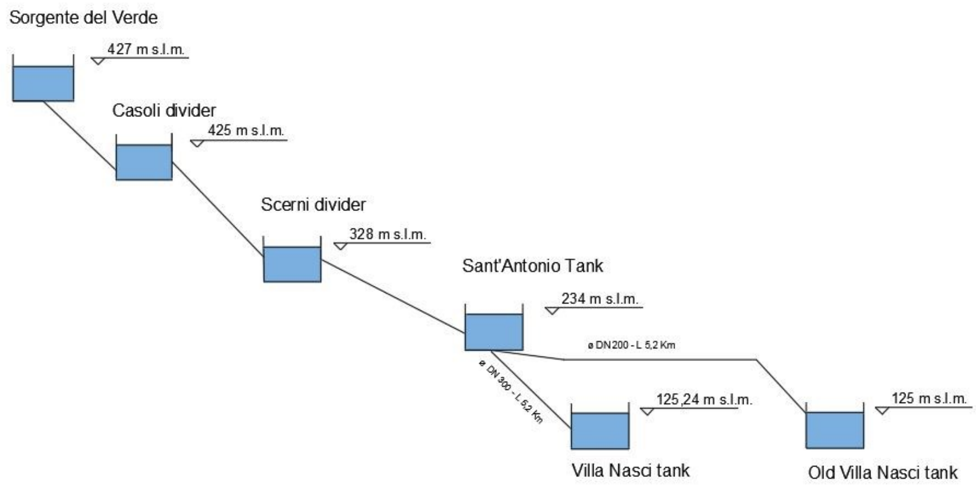

Figure 31 - network configuration

For the calculation of the gross head and the net head exploited downstream by the turbine, the collection artifact called "Sant'Antonio tank" was considered as the starting point, as such it will then define the starting altitude necessary for the calculation.

The gross head available to the turbine is therefore equal to:

$$H_{Sant'Antonio} - H_{Villa\ Nasci} = 234\ m - 125{,}24\ m = 108{,}76\ m$$

- *CONFIGURATION*

For the installation of the turbine, the overall space of the turbine plus generator was evaluated, and the need to install a by-pass was also evaluated to avoid problems of interruption of the water supply due to repairs or malfunctions of the turbine.

As for the turbine loading pipes, the design path is that of hydraulic-structural conservation of the existing supply pipeline, after verifying the actual capacity of the pipeline to withstand the pressures resulting from the planned use.

This means that, where possible, the loading pipe will have the same characteristics currently configured for the adduction network.

The pipes entering the tank are made of steel with a diameter of 300mm.

From the following image, the structural configuration can be analysed more closely.

Figure 32 - Pipe at the inlet to the tank

The blue pipe is the inlet pipe to the tank, this can be used as a by-pass to the turbine, on this pipe a valve called "pressure reducing valve" must be mounted and will work synchronously with the turbine. In other words when the turbine unit will be in operation the valve will be closed, when the turbine stops working due to maintenance or malfunctions, the valve will dissipate the pressure entering the tank.

From the following image we can see the plant configuration.
The installation of the turbine was considered above the tank, with the flow rates leaving the turbine above the free surface of the tank.

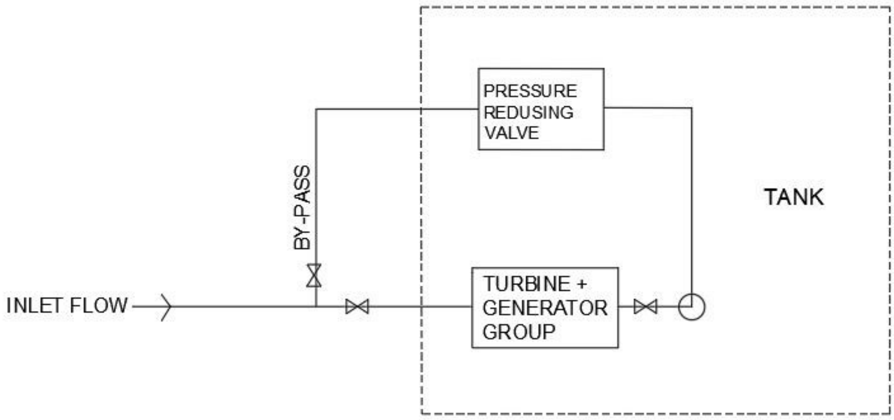

Figure 33 - Turbine configuration

- *AVAILABLE FLOW RATE*

The flow rate values, measured at the inlet pipeline to the “Villa Nasci” tank, are shown in Tab.9

On this site, the average daily flow rates for the year 2020 have been provided by the company SASI spa, which deals with the management of the water service for the district of Chieti.

It can be noted that in some cases the daily data were not reported; this is due to a malfunction of the flow measurement instruments which have not always guaranteed a continuous detection of the transiting flows.

For the purposes of a preliminary study, the amount of flow rates detected, therefore daily averages of the year 2020, can be taken as suitable. But for a subsequent advanced study it is very important to have daily flow measurements relating to different years, in order to fully evaluate the seasonal influence on water flows and in order to also eliminate any influences of extraordinary annual atmospheric events.

Table 9 shows the average daily flow rates for the year 2020.

Table 9 - Average daily flow rate Villa Nasci tank (year 2020)

JANUARY (l/s)	FEBRUARY (l/s)	MARCH (l/s)	APRIL (l/s)	MAY (l/s)	JUNE (l/s)	JULY (l/s)	AUGUST (l/s)	SEPTEMBER (l/s)	OCTOBER (l/s)
\	32	25	26	26,4	29,5	28,8	34,4	32	30,04
30	32	25	26	26,4	29,5	28,8	34,4	32	30,04
\	32	26	26,4	26,4	29	29	33,6	32	30,04
\	32	25,6	26,4	26,4	29	29	33	32	30,04
\	30	25,6	26,4	26,4	29	29	33,5	32	30
\	30	26	26	26	29	29	33,5	32	30
32	30	25,5	26	26	29	29	33,2	32	29,6
32	30	25,5	26	26	29,5	29	33,2	32	29,6
32	30	25,5	26	26	29,5	28,8	33,2	31,2	30,2
32	35	25,5	26	26	29,5	31,2	32	31,2	30,2
\	35	25,5	26	26	29,4	31,2	32	32	30,2
\	35	25,5	26	28,8	28,8	33,6	32	32	30,4
32	35	25,5	26	29,6	28,8	33,6	32	32	30,4
32	26	25,5	26,4	29,4	28,8	33,6	33,6	32	30,4
\	25,5	25,5	26	29,4	28	32	33,6	32	30
32	\	25	26	29,4	28	32	33,6	32	30
\	\	25	26,4	29,4	28	32,8	33,6	32	30
\	\	26	26,4	29,4	30	32,8	33,6	32	30
\	\	26	26,4	29,4	30	32,8	34,4	32	30
\	\	28,5	26,4	29,4	30	33,2	33,6	32	30
\	24,5	28,5	26,4	29,4	30	31,8	33,6	32	30
\	24,5	28,5	26,4	29,4	29,6	31,8	33,6	32	30
\	24,5	28,5	26,4	29,4	29,6	31,8	33,6	32	30
\	24,5	28,5	26,4	29,4	26,4	31,8	33,6	32	30
\	24,5	27,8	26,4	29,6	26,4	31,8	32,8	32	30
\	24,5	28	26,4	29,6	31,2	31,8	32,8	32	30
32	24,5	26,8	26,4	29,2	31,2	31,8	32,8	32	29,6
32	25	26,8	26,4	29,2	31,2	34,4	32,8	32	29,6
\	25	26,8	26	29,4	31,2	34,4	32,8	32	29
\	\	26,4	26,4	29,4	29	34,4	32,8	32	29
32	\	26	\	29,4	\	\	32,8	\	29

For clarity sake, the monthly flow rate and the daily flow rate trends in the "Villa Nasci" tank are illustrated in figure.

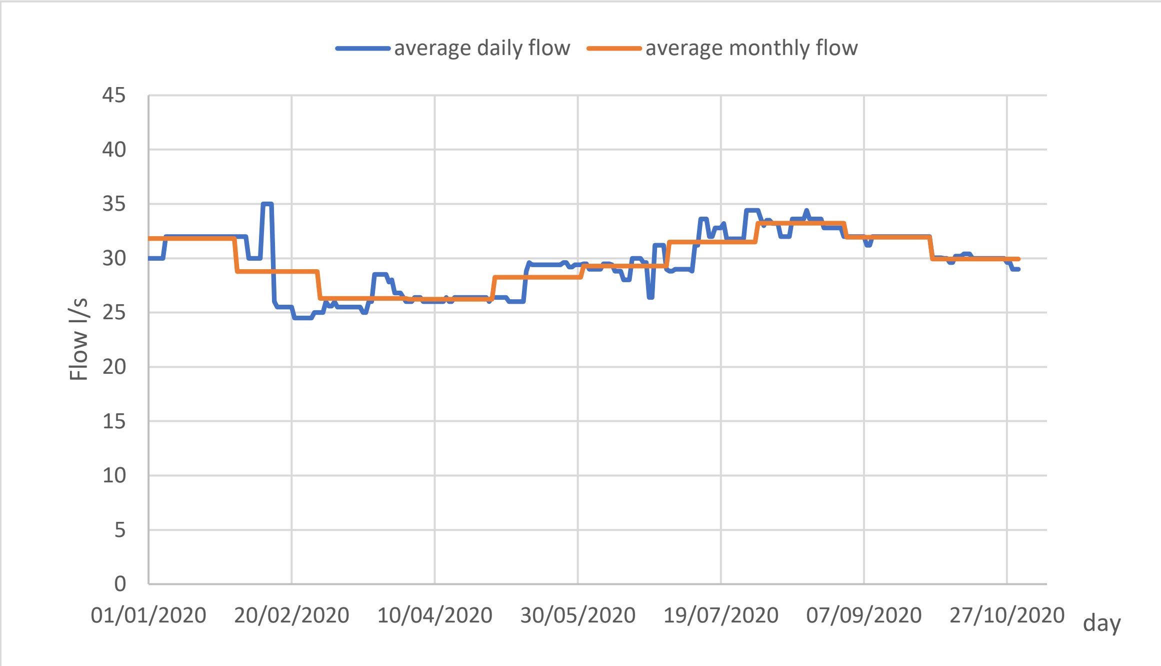

Figure 34 -Average monthly flow and average daily flow Villa Nasci tank

- *CHOICE AND DESIGN OF THE TURBINE*

Having jumps of the order of hundreds of meters and flow rates of the order of 25-30 m^3/s, the evaluation of the hydraulic machine, based on the observations made in the previous chapters regarding the choice of the turbine, leads to the choice of a Pelton turbine.

The sizing of the machine was carried out taking into account the maximum flow rate available for the "case 1", so as to be able to exploit as much as possible the water power.

Concerning the head losses in this study, the concentrated pressure drops have been neglected, because they are very small and therefore insignificant compared to the distributed pressure drops.

So, it is necessary to calculate the distributed head losses using the Chezy formula with the Gauckler - Strickler roughness coefficient:

$$\varDelta H = \frac{L \times v^2}{k^2 \times R_h^{4/3}} = \frac{5200 \times 0{,}495^2}{80^2 \times 0{,}075^{4/3}} = 6{,}3\ m$$

Where:

- L = length of the considered pipeline
- v = speed of the water flow, calculated as the ratio between the maximum flow rate and the cross section of the duct
- k = Gauckler-Strickler roughness coefficient characteristic of the pipeline material
- R_h= hydraulic radius, calculated as the ratio between the wet area and the wet perimeter (for a pipe with a circular section it is equal to d / 4, where d is the section diameter)

Once the head losses are known, it is therefore possible to evaluate the net head and consequently also the characteristic powers of the electromechanical unit calculated as follows:

$$P_{THEORETICAL} = \rho \cdot g \cdot [(H_{Sant'Antonio} - H_{Villa\ Nasci}) - \Delta H] \cdot Q_{max}$$

$$P_{OUT\ TURBINE} = P_{THEORETICAL} \cdot \eta_{TURBINE}$$

$$P_{OUT\ GENERATOR} = P_{OUT\ TURBINE} \cdot \eta_{GENERATOR}$$

Where:

- ρ = water density
- $H_{Sant'Antonio}$ = height initial reservoir
- $H_{Villa\ Nasci}$ = height final reservoir
- ΔH = distributed head losses evaluated at the average flow rate
- Q_{max} = maximum flow rate

Based on the previous calculations and on the Figure 27, 28 efficiencies values are equal to:

$$\eta_{TURBINE} = 0{,}88$$

$$\eta_{GENERATOR} = 0{,}90$$

The generation group was impotized formed by a Pelton type turbine directly coupled to the generator shaft, characterized by the following parameters:

Table 10 - Result of calculation

Maximum flow rate	30 l/s
Gross jump	108,76m
Net jump	102,45m
Theoretical power	35,18 KW
Power out turbine	30,96 KW
Power out generator	27,86 KW

- *ANNUAL PRODUCTIVITY*

The "all-inclusive rate" is recognized as an incentive factor for mini hydroelectric plants, which recognizes a fixed tariff for the remuneration of the electricity fed into the network.

Regarding this plant, it has not been decided whether the electricity production given by the turbine will be used for its own use, therefore for lighting or other services that serve the same tank, or it will be fed into the network, and therefore in this the "all-inclusive rate" will be recognized.

For the calculation of the average power and annual energy that can be produced, the net head was calculated as the difference between the gross head and the distributed head losses, the latter calculated however on the average flow rate. Using the head losses calculated in the previous paragraph (quantified for the sizing of the machine and therefore evaluated at the maximum flow rate) would have given an estimate less consistent with the real case as it would have been assumed to always have the maximum flow rate during the entire period of year.

Below is the calculation of the average developable power:

$$P = \rho \cdot g \cdot [(H_{Sant'Antonio} - H_{Villa\ Nasci}) - \Delta H] \cdot Q_{average} \cdot \eta_{TURB} \cdot \eta_{GEN}$$

Where:

- P = average developable power = 23,97 kW
- ρ = water density = 1000 kg/m^3
- $H_{Sant'Antonio}$ = height of initial reservoir= 234 m
- $H_{Villa\ Nasci}$ = height of final reservoir = 125.24 m
- ΔH = distributed head losses evaluated at the average flow rate = 4.5 m
- $Q_{average}$ = 29,6 l/s

The estimate of the energy that can be produced by the turbine is based on the values obtained from the flow measure at the entrance to the “Villa Nasci” tank.

Based on this information, considering an overall average conversion efficiency of the plant equal to 80% (calculated as the product of the turbine efficiency and that of the generator) and considering the turbine operating hours (i.e. 8000 hours of operation, considering the maintenance hours and the hours of non-operation of the turbine due to breakage or malfunctions), the energy produced monthly was calculated, as we can see in the Table 11 and Figure 35.

Table 11 - Monthly production

	ENERGY PRODUCTION [kWh]
JANUARY	17352,85
FEBRUARY	15705,39
MARCH	14352,52
APRIL	14308,87
MAY	15410,82
JUNE	15967,24
JULY	17183,74
AUGUST	18132,94
SEPTEMBER	17429,22
OCTOBER	16349,10
TOTAL	162192,70

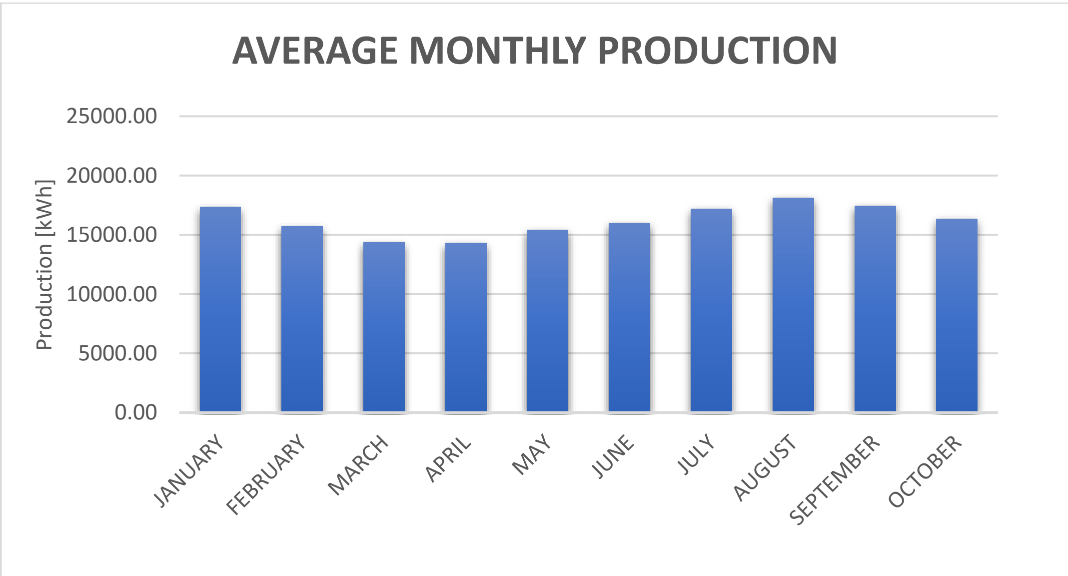

Figure 35 - Average monthly production

In the result reported below, the annual production was estimated, considering for the months of November and December a trend similar to that of October and January. Because for these two months we have no useful data for the study.

$$E_{annual} = 195.894{,}65 \text{ kWh/anno}$$

4.1.2 CASE 2

For "case 2", the municipality of Fossacesia was examined, in particular the "New Fossacesia tank".

Figure 36 – New Fossacesia tank

The "New Fossacesia tank" feeds the utilities of the town of Fossacesia and the Fossacesia Marina tank through two outgoing pipes. The generation group will exploit the adduction networks conveyed to the "New Fossacesia tank". A 220mm diameter steel pipeline reaches this tank from the divider called "zona industrial Lanciano". Figure 36 illustrates a graphical configuration of the network, starting from the Sorgente del Verde up to the "New Fossacesia tank".

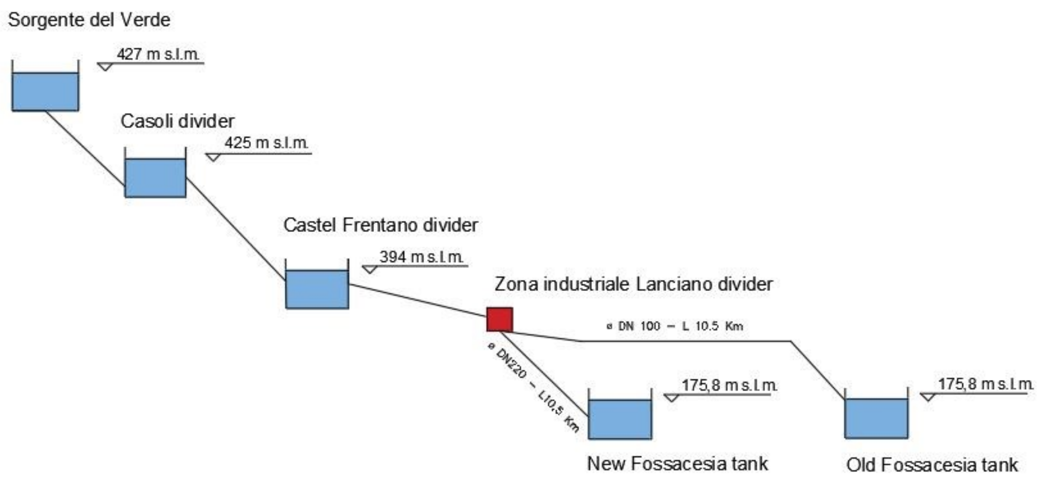

Figure 37 - Network configuration

For the calculation of the gross head and the net head exploited downstream of the turbine, the collection divider called "Castel Frentano" was considered as the starting point, even if the pipeline originates from the "Zona Industriale Lanciano" divider. This choice is related to the characteristics of the divider "Zona Industriale Lanciano", that has the advantage of not zeroing the pressure detectable at the inlet of the divider itself.

The gross head available to turbine is therefore equal to:

$$H_{C.Frentano\ divider} - H_{New\ Fossacesia\ tank} = 394\ m - 175{,}8\ m = 218{,}2\ m$$

- *CONFIGURATION*

Regarding the configuration for the Fossacesia plant, a size assessment was first made for the installation of the turbine, and also in this case, as in the previous site, the system can be installed inside the existing building.

Figure 38 – Pipe at the inlet to the tank

The installation of the turbine unit was planned on the second floor of the building. The turbine must have the water outlet upstream of the free surface of the tank. The existing piping at the inlet to the tank will be used as a by-pass, useful for turbine maintenance and malfunctions. Also, in this case the design process follows the hydraulic-structural conservation of the existing pipes.

- *AVAILABLE FLOW RATE*

On this specific site, the measurements, provided by the company that manages the water service, are monthly averages measured at the entrance of the "New Fossacesia tank".

Table 12 - average monthly flow rate new Fosssacesia tank

	Flow rate [l/s]
January	18
February	18
March	18
April	18
May	18
June	25
July	30
August	30
September	18
October	18
November	18
December	18

To perform this study, daily flow rates are required. To obtain them, a simulation was made by constructing a pattern with the daily flows of the previously analyzed site. In this way it was possible to obtain the daily flow rates of the “New Fossacesia tank”.

A dimensionless coefficient was calculated for each daily flow rate of the Villa Nasci reservoir, through the ratio between the daily flow and the monthly average.

By multiplying the daily coefficient by the monthly averages of the Fossacesia site, the daily flow rates of the site to be analyzed were found.

An excerpt from the construction of the pattern is shown in Table 13.

Table 13 - Pattern

PATTERN						
day	**JANUARY (l/s)**	**Coeff.**	**FEBRUARY (l/s)**	**Coeff.**	**MARCH (l/s)**	**Coeff.**
1	29	0,910656402	32	1,14615829	25	0,949987742
2	30	0,942058347	32	1,14615829	25	0,949987742
3	32	1,004862237	32	1,14615829	26	0,987987252
4	31,6	0,992301459	32	1,14615829	25,6	0,972787448
5	31,6	0,992301459	30	1,074523397	25,6	0,972787448
6	30	0,942058347	30	1,074523397	26	0,987987252
7	32	1,004862237	30	1,074523397	25,5	0,968987497
8	32	1,004862237	30	1,074523397	25,5	0,968987497
9	32	1,004862237	30	1,074523397	25,5	0,968987497
10	32	1,004862237	35	1,25361063	25,5	0,968987497
11	31,5	0,989161264	35	1,25361063	25,5	0,968987497
12	31,5	0,989161264	35	1,25361063	25,5	0,968987497
13	32	1,004862237	35	1,25361063	25,5	0,968987497
14	32	1,004862237	26	0,931253611	25,5	0,968987497
15	31,5	0,989161264	25,5	0,913344887	25,5	0,968987497
16	32	1,004862237	25	0,895436164	25	0,949987742
17	31	0,973460292	25	0,895436164	25	0,949987742
18	32	1,004862237	25	0,895436164	26	0,987987252
19	32	1,004862237	25	0,895436164	26	0,987987252
20	32,5	1,020563209	25,5	0,913344887	28,5	1,082986026
21	34,5	1,083367099	24,5	0,877527441	28,5	1,082986026
22	32,5	1,020563209	24,5	0,877527441	28,5	1,082986026
23	34,5	1,083367099	24,5	0,877527441	28,5	1,082986026
24	34,5	1,083367099	24,5	0,877527441	28,5	1,082986026
25	31,8	0,998581848	24,5	0,877527441	27,8	1,056386369
26	32	1,004862237	24,5	0,877527441	28	1,063986271
27	32	1,004862237	24,5	0,877527441	26,8	1,01838686
28	32	1,004862237	25	0,895436164	26,8	1,01838686
29	30,8	0,967179903	25	0,895436164	26,8	1,01838686
30	30,4	0,954619125	24,5	0,877527441	26,4	1,003187056
31	32	1,004862237	24,5	0,877527441	26	0,987987252
	31,84516129		27,91935484		26,31612903	

The following are the estimated daily flow rates of the “New Fossacesia tank”.

Table 14 - Daily flow rate

JANUARY (l/s)	FEBRUARY (l/s)	MARCH (l/s)	APRIL (l/s)	MAY (l/s)	JUNE (l/s)	JULY (l/s)	AUGUST (l/s)	SEPTEMBER (l/s)	OCTOBER (l/s)
16,4	20,6	17,1	17,8	16,8	25,2	27,3	31,1	18,0	18,0
17,0	20,6	17,1	17,8	16,8	25,2	32,8	31,1	18,0	18,0
18,1	20,6	17,8	18,1	16,8	24,8	33,1	30,3	18,0	18,0
17,9	20,6	17,5	18,1	16,8	24,8	33,1	29,8	18,0	18,0
17,9	19,3	17,5	18,1	16,8	24,8	33,1	30,2	18,0	18,0
17,0	19,3	17,8	17,8	16,6	24,8	33,1	30,2	18,0	18,0
18,1	19,3	17,4	17,8	16,6	24,8	33,1	30,0	18,0	17,8
18,1	19,3	17,4	17,8	16,6	25,2	33,1	30,0	18,0	17,8
18,1	19,3	17,4	17,8	16,6	25,2	32,8	30,0	17,6	17,8
18,1	22,6	17,4	17,8	16,6	25,2	35,6	28,9	17,6	18,1
17,8	22,6	17,4	17,8	16,6	25,1	35,6	28,9	18,0	18,1
17,8	22,6	17,4	17,8	18,4	24,6	38,3	28,9	18,0	18,1
18,1	22,6	17,4	17,8	18,9	24,6	38,3	28,9	18,0	18,3
18,1	16,8	17,4	18,1	18,7	24,6	38,3	30,3	18,0	18,3
17,8	16,4	17,4	17,8	18,7	23,9	36,5	30,3	18,0	18,3
18,1	16,1	17,1	17,8	18,7	23,9	36,5	30,3	18,0	18,0
17,5	16,1	17,1	18,1	18,7	23,9	37,4	30,3	18,0	18,0
18,1	16,1	17,8	18,1	18,7	25,6	37,4	30,3	18,0	18,0
18,1	16,1	17,8	18,1	18,7	25,6	37,4	31,1	18,0	18,0
18,4	16,4	19,5	18,1	18,7	25,6	37,8	30,3	18,0	18,0
19,5	15,8	19,5	18,1	18,7	25,6	36,3	30,3	18,0	18,0
18,4	15,8	19,5	18,1	18,7	25,3	36,3	30,3	18,0	18,0
19,5	15,8	19,5	18,1	18,7	25,3	36,3	30,3	18,0	18,0
19,5	15,8	19,5	18,1	18,7	22,6	36,3	30,3	18,0	18,0
18,0	15,8	19,0	18,1	18,9	22,6	36,3	29,6	18,0	18,0
18,1	15,8	19,2	18,1	18,9	26,7	36,3	29,6	18,0	18,0
18,1	15,8	18,3	18,1	18,6	26,7	36,3	29,6	18,0	18,0
18,1	16,1	18,3	18,1	18,6	26,7	39,2	29,6	18,0	17,8
17,4	16,1	18,3	17,8	18,7	26,7	39,2	29,6	18,0	17,8
17,2	15,8	18,1	18,1	18,7	24,8	39,2	29,6	18,0	17,4
18,1	15,8	17,8	18,1	18,7	24,8	39,2	29,6	18,0	17,4

For greater clarity of the flow rate trend in the tank called "New Fossacesia tank", the graph, illustrated below, of the average daily flows and average monthly flow was created.

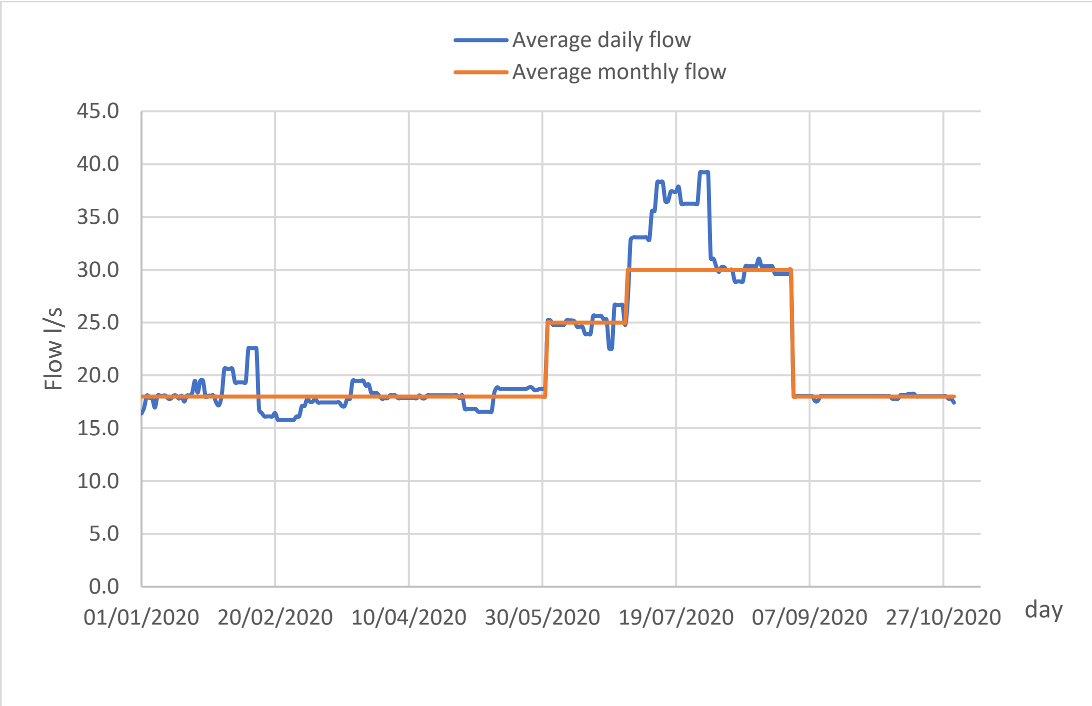

Figure 39 - Average monthly flow and average daily flow New Fossacesia tank

- *CHOICE AND DESIGN OF THE TURBINE*

Even in this case, as in the site previously analyzed there are jumps in the order of hundreds of meters and flow rate of the order of 20-30 l/s, so the choice of the turbine falls again on the Pelton turbine.

The sizing of the machine was carried out taking into account the maximum flow rate available for the turbine, in order to exploit the maximum energy from the water.

First of all, it is necessary to calculate the distributed head losses using the Chezy formula with Gauckler - Strickler roughness coefficient:

$$\varDelta H = \frac{L \times v^2}{k^2 \times R_h^{4/3}} = \frac{10500 \times 1{,}032^2}{80^2 \times 0{,}055^{4/3}} = 15{,}39\ m$$

Once the head losses are known, it is therefore possible to evaluate the net head and consequently also the characteristic powers of the electromechanical unit calculated as follows:

$$P_{THEORETICAL} = \rho \cdot g \cdot [(H_{C.Frent.div.} - H_{New\ Foss.tank}) - \Delta H] \cdot Q_{max}$$

$$P_{OUT\ TURBINE} = P_{THEORETICAL} \cdot \eta_{TURBINE}$$

$$P_{OUT\ GENERATOR} = P_{OUT\ TURBINE} \cdot \eta_{GENERATOR}$$

For the previous calculations, yield values equal to:

$$\eta_{TURBINE} = 0{,}88$$

$$\eta_{GENERATOR} = 0{,}90$$

The generation group is therefore formed by a Pelton-type turbine directly coupled to the generator shaft, characterized by the following parameters:

Table 15 - Result of calculation

Average flow rate	21,99 l/s
Gross jump	218,2m
Net jump	202,8m
Theoretical power	77,59 KW
Power out turbine	68,28 KW
Power out generator	61,45 KW

- *ANNUAL PRODUCTIVITY*

For the calculation of the average power and annual energy that can be produced, the net head was calculated as the difference between the gross head and the distributed head losses, these calculated however on the average flow rate. Using the head losses calculated in the previous paragraph (quantified for the sizing of the machine and therefore evaluated at the maximum flow rate) would have given an estimate less consistent with the real case as it would have been assumed to always have the maximum flow rate during the entire period of year.

Below is the calculation of the average developable power:

$$P = \rho \cdot g \cdot [(H_{C.Frent.div.} - H_{New\ Foss.tank}) - \Delta H] \cdot Q_{average} \cdot \eta_{TURB} \cdot \eta_{GEN}$$

Where:

- P = average developable power = **32,92 kW**
- ρ = water density = 1000 kg/m^3
- $H_{C.Frent.div}$ = height initial reservoir= 394 m
- $H_{New\ Foss.tank}$ = height final reservoir = 175,8 m
- ΔH = distributed head losses evaluated at the average flow rate=25,5 m
- $Q_{average}$ = 21,68 l/s

The estimate of the energy that can be produced by the turbine is based on the values obtained from the flow measure at the entrance to the “New Fossacesia tank”.

Based on this information, considering an overall average conversion efficiency of the plant equal to 80% (calculated as the product of the turbine efficiency and that of the generator) and considering the turbine operating hours (i.e 8000 hours d of operation, considering maintenance hours of and the hours of non-operation of the turbine due to breakage or malfunctions), the energy produced monthly in Case 2 was calculated, as we can see in the Table 16 and Figure 40.

Table 16 - Monthly production

	ENERGY PRODUCED [kWh]
JANUARY	18.144,44
FEBRUARY	18.144,44
MARCH	18.144,44
APRIL	18.144,44
MAY	18.144,44
JUNE	25.200,61
JULY	30.240,73
AUGUST	30.240,73
SEPTEMBER	18.144,44
OCTOBER	18.144,44
TOTAL	212.693,17

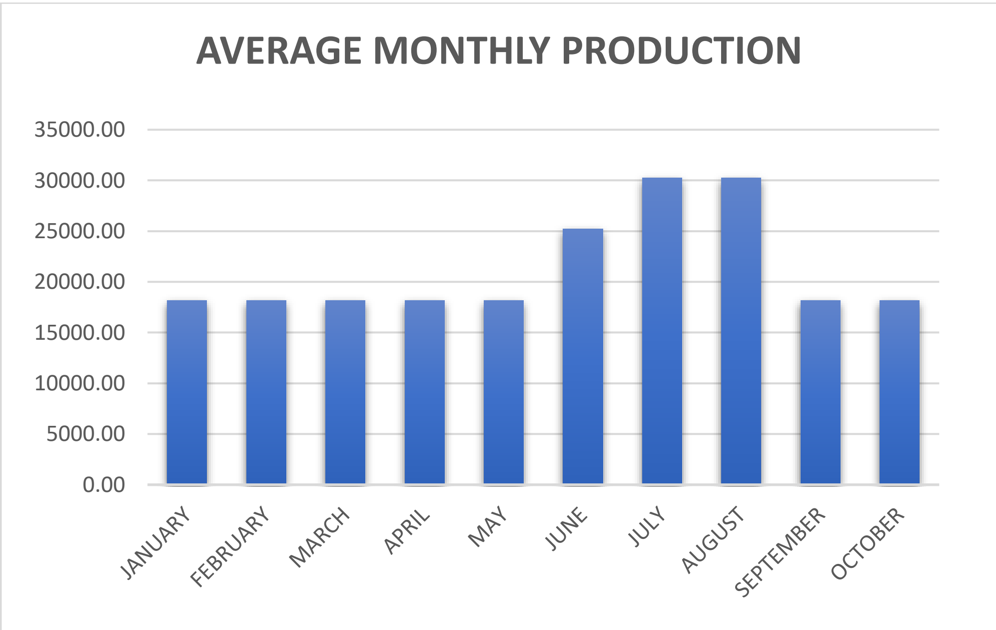

Figure 40 - Average monthly production

In the result reported below, the annual production was estimated, considering for the months of November and December a trend similar to that of October and January. Because for these two months we have no useful data for the study.

$$E_{annual} = 248.982{,}05 \text{ kWh/anno}$$

4.2 ECONOMIC-FINANCIAL ANALYSIS

The analysis illustrated in the following paragraph is aimed at assessing the economic convenience of the investment relating to the two sites described above. The evaluation will be made by calculating the value of the Net Present Value (NPV) and the Payback Time (PBT).

The NPV gives an idea of the total value of the investment over the entire useful life, instead the PBT gives an idea of the time required to recover the initial investment cost.

A good investment must therefore be characterized by a high NPV and a low PBT.

The calculation of the NPV is done through the following relations:

$$Revenues = \ annual\ energy\ produced\ * rate$$

$$EBITDA = Revenues - cost$$

$$CAPEX = f(mortgage, F, CI)$$

$$CF_{tot} = EBITDA - CAPEX = \sum_{i=1}^{Vu} \frac{Cash\ Flow_{tot}}{(1+t)^i}$$

Where:

- **Revenues** = amount of money obtained from the sale of energy
- **Rate** = value recognized for each kWh produced according to the characteristic power of the system calculated previously
- **EBITDA =** it is an index representing the difference between the revenues and the cost
- **Cost** = annual costs including maintenance, insurance and various administrative costs assumed equal to € 3,500
- **CAPEX** = it represents the annual rate of the loan that the investor should pay to the bank. It is a value that varies according to:
  - **F** = interest rate taken equal to 5%;
  - **mortgage** = 10 years
  - **CI** = Initial investment cost
- $\mathbf{CF_{tot}}$= Total cash flow
- **t** = discount rate, assumed to be 9%
- **Vu** = assumed useful life of 20 years

Therefore, by evaluating the Cash Flow values of each year and subsequently discounting these values, it is possible to calculate the NPV for each individual plant.

Instead, the PBT is calculated using the following relationship:

$$PBT = \frac{CI}{Revenues}$$

In order to proceed with the economic analysis, it is necessary to estimate the parameters that help to analyse the convenience of the investment. These parameters can be divided into:

- Cost
- Revenues
- Time

The <u>costs</u> represent the capital necessary for the realization of the work and for its correct maintenance to ensure proper and correct operations. They can be divided into different types, such as:

- *Construction costs*: represent the costs for the construction of the plant and all the works connected to it, as well as those relating to the design of hydraulic, electrical and building works. In the present study, the need to replace the adduction pipeline is not taken into account, considering it suitable for the new configuration plant engineering.
  This category includes the costs for:
    - The civil work;
    - The turbine and the generator;
    - The control panel;
    - The assembly of the various components and their commissioning;
    - The design of all hydraulic, electrical, mechanical and building works;
    - The connection to the national electricity grid.

  Estimated cost of **€ 300.000,00** (precautionary price).

- *Annual operating and maintenance costs*: they include all costs of management of the system during its operation and all costs of periodic ordinary and extraordinary maintenance. Costs related to concession fees also fall on this class. Estimated cost of **€ 70.000,00** for the entire useful life.
- *General costs*: include costs related to insurance and plant administration, manufacturing tax, services and lighting, operating taxes are also included. Estimated cost of **€ 1.000,00** per years.

The revenues are represented by revenues from the sale of the electricity produced. In this case, a revenue from the sale of energy of **€ 155 MW/h** was assumed (established by the 2019 RES directive).

The time parameter is linked to the physical, technical and commercial life of the goods characterizing the investment. In this case estimated at about 20 years.

Based on the provided information, it is possible to carry out an investment analysis, in order to understand whether or not it is convenient to proceed with the installation of these systems.

The following paragraphs show the economic evaluations of the sites previously analyzed.

4.2.1 CASE 1

In the tables 17 it is possible to see the estimated costs and revenues of the site.

Table 17 - data used for the economic study

IMPUT DATA	VALUES	U.M
AVERAGE FLOW RATE	29,6	l/s
EFFECTIVE OUTPUT	23,97	kW
INVESTMENT COST	300.000,00	€
YEARS OF INVESTMENT	10	Years
ANNUAL ELECTRICITY PRODUCTION	195,89	MWh
TARIFF OF ENERGY	155,00	€/MWh
ANNUAL REVENUES	30362,95	€
MAINTEINANCE COST	3500	€
GENERAL COST	1000	€
INTEREST RATE	5	%
ANNUAL AVERAGE RATE	3.181,97	€
DISCOUNTING RATE	5	%

Table 18 - economic result for 5 years

YEARS	2021	2022	2023	2024	2025
CAPEX	€ -3.181,97	€ -3.181,97	€ -3.181,97	€ -3.181,97	€ -3.181,97
RENEVUES	€ 0,00	€ 30362,95	€ 30362,95	€ 30362,95	€ 30362,95
MAINTEINANCE COST	€ 0,00	€ -1.000,00	€ -1.000,00	€ -1.000,00	€ -10.000,00
GENERAL COST	€ -1000,00	€ -1.000,00	€ -1.000,00	€ -1.000,00	€ -1.000,00
EBITDA	€ -1.000,00	€ 28.362,95	€ 28.362,95	€ 28.362,95	€ 19.362,95
NET CASH FLOW	€ -4.181,97	€ 25.180,98	€ 25.180,98	€ 25.180,98	€ 16.180,98
CUMULATIVE CASH FLOW	€ -327.000,00	€ -301.819,02	€ -276.638,04	€ -251.457,06	€ -235.276,08
DISCOUNTED CASH FLOW	€ -3982,83	€ 22839,89	€ 21752,28	€ 20716,45	€ 12678,22
CUMULATIVE DISCOUNTED CASH FLOW	€ -3982,83	€ 18857,06	€ 40609,34	€ 61325,79	€ 74004,02

From the following calculations it was possible to build a graph on which we can see more clearly the trend of costs and revenues and therefore how many years are needed for the investment to return.

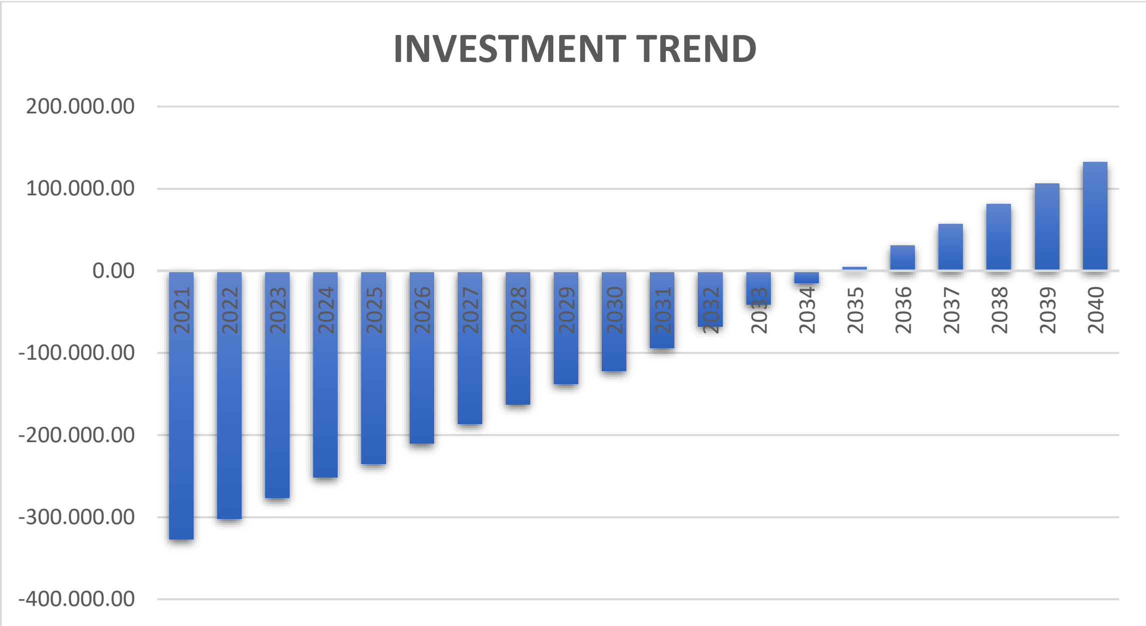

Figure 41 - Cumulative cash flow Vasto

Subsequently, the PBT and NPV were calculated using the procedures described above.

NPV (5%)	PBT [years]
272.354,94 €	9,9

4.2.2 CASE 2

As in the economic-financial analysis of Fossacesia, tables with costs and revenues were also built on the Vasto site, shown below:

Table 19 - data used for the economic study

IMPUT DATA	VALUE	U.M.
AVERAGE FLOW RATE	21,68	m^3/s
EFFECTIVE OUTPUT	32,92	kW
INVESTMENT COST	300.000,00	€
YEARS OF INVESTMENT	10	Years
ANNUAL ELECTRICITY PRODUCTION	248,98	MWh
TARIFF OF ENERGY	155,00	€/MWh
ANNUAL REVENUES	38.591,9	€
MAINTEINANCE COST	3.500,00	€
GENERAL COST	1.000,00	€
INTEREST RATE	5	%
ANNUAL AVERAGE RATE	3.181,97	€
DISCOUNTING RATE	5	%

Table 20 - Economic resul for 5 years

YEARS	2021	2022	2023	2024	2025
CAPEX	€ -3.182,0	€ -3.182,0	€ -3.182,0	€ -3.182,0	€ -3.182,0
RENEVUES	€ 0,00	€ 38.591,9	€ 38.591,9	€ 38.591,9	€ 38.591,9
MAINTEINANCE COST	€ 0,00	€ -1.000,0	€ -1.000,0	€ -1.000,0	€ -10.000,0
GENERAL COST	€ -1.000,0	€ -1.000,0	€ -1.000,0	€ -1.000,0	€ -1.000,0
EBITDA	€ -1.000,0	€ 36.591,9	€ 36.591,9	€ 36.591,9	€ 27.591,9
NET CASH FLOW	€ -4.182,0	€ 33.409,9	€ 33.409,9	€ 33.409,9	€ 24.409,9
CUMULATIVE CASH FLOW	€ -327.000,0	€ -293.590,1	€ -260.180,1	€ -226.770,2	€ -202.360,3
DISCOUNTED CAH FLOW	€ -3.982,8	€ 30.303,8	€ 28.860,8	€ 27.486,4	€ 19.125,8
CUMULATIVE DISCOUNTED CASH FLOW	€ -3.982,8	€ 26.321,0	€ 55.181,7	€ 82.668,1	€ 101.794,0

In the Figure 42 it is possible to see the trend of costs and revenues calculated on the useful life of the turbine, that is 20 years.

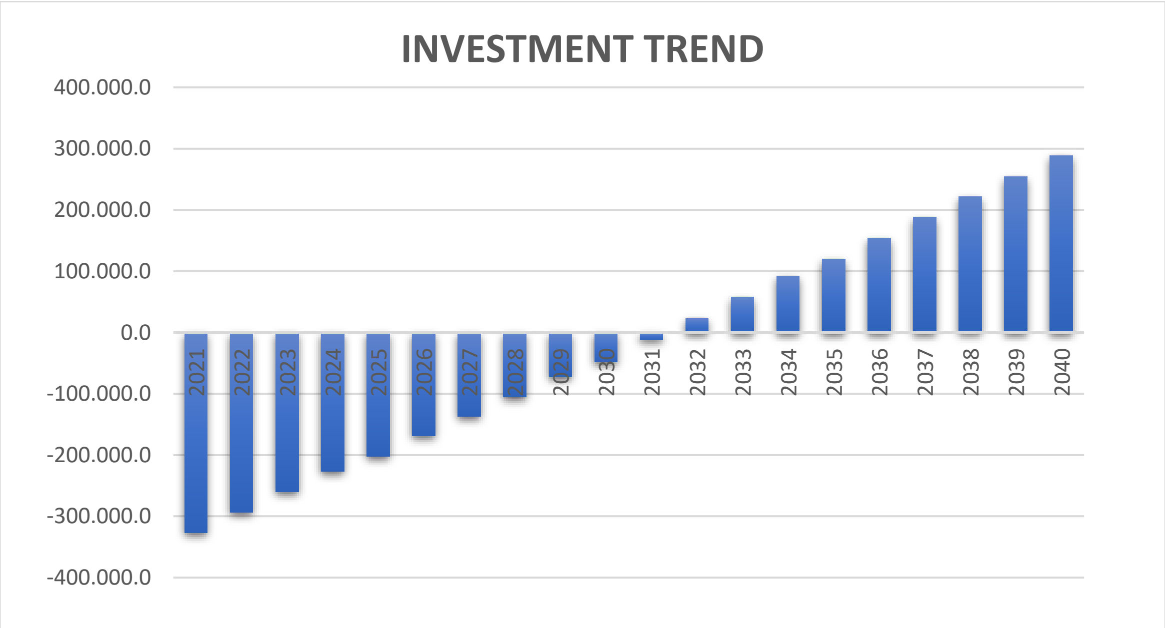

Figure 42 - Cumulative cash flow Fossacesia

Also, in this case, the PBT and NPV were calculated with the procedures described above:

NPV (5%)	PBT [years]
367.068,75 €	7,8

4.3 CORRELATION STUDY

In the "del Verde" aqueduct network, a study of observations of the flow rate over time was conducted. The main purpose of this analysis was to build a model, after appropriate calibrations, that would allow us to: 1) understand the time required by flow to go from the source to one of the tanks; 2) therefore help us to reconstruct the flow rates between the source and the tanks; 3) give hints on possible water leakages along the pipelines. Such analysis will also allow us to understand the optimal point in which to install the turbine and it would help to predict turbine malfunctions caused by low flow rates and therefore critical events for the plant.

It is important to know that the "Sorgente del Verde" has been monitored through a digital Venturi connected remotely since 2001, which allows for a large amount of data with very high reliability, however, regarding the pipelines entering the tanks, they have poor monitoring, only some of them are monitored by mechanical Venturi with low reliability, caused by poor maintenance and malfunctions.

At the beginning of this study, an accurate search was made of the flow rate data of the source and that entering the Villa Nasci tank. This reservoir was chosen as it is located in the final part of the aqueduct network, and this aspect was very interesting to understand how the trend of the source affected the supply network. Between the "Sorgente del Verde" and the Villa Nasci tank there are approximately 52 km of pipelines.

In Figure 43 we can see the trends of the source in the years between 2001 and 2020.

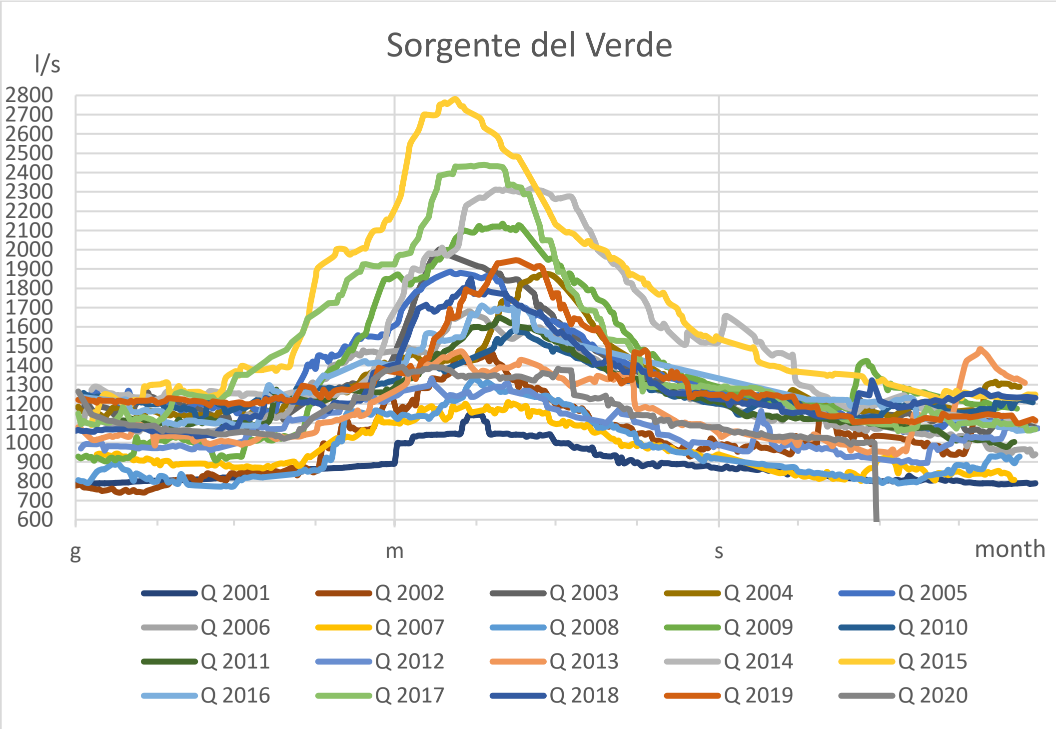

Figure 43 - Flow rate of the Sorgente del Verde from 2001 to 2020

From the graph it is possible to see that the year characterized by the highest values in the last 10 decades is the 2015, with a peak approaching 2800 l/s. On the other hand, in the year 2001 the lowest values were recorded.

Regarding the trend, it is possible to highlight that the months with the greatest flow of water are those between May and July, on this aspect it is possible to hypothesize that the Sorgente del Verde is recharged above all by the melting of the snow, which usually occurs in the months when the source has greater flow rates.

Subsequently, a data collection was made of the flows entering the Villa Nasci tank. For this study, the years 2016, 2017, 2019 and 2020 were analysed. Regarding 2018, it was not possible to find any data, while for 2019, 6 months of measurements were recovered.

Figure 44 illustrates the trend of the flows entering the Villa Nasci tank.

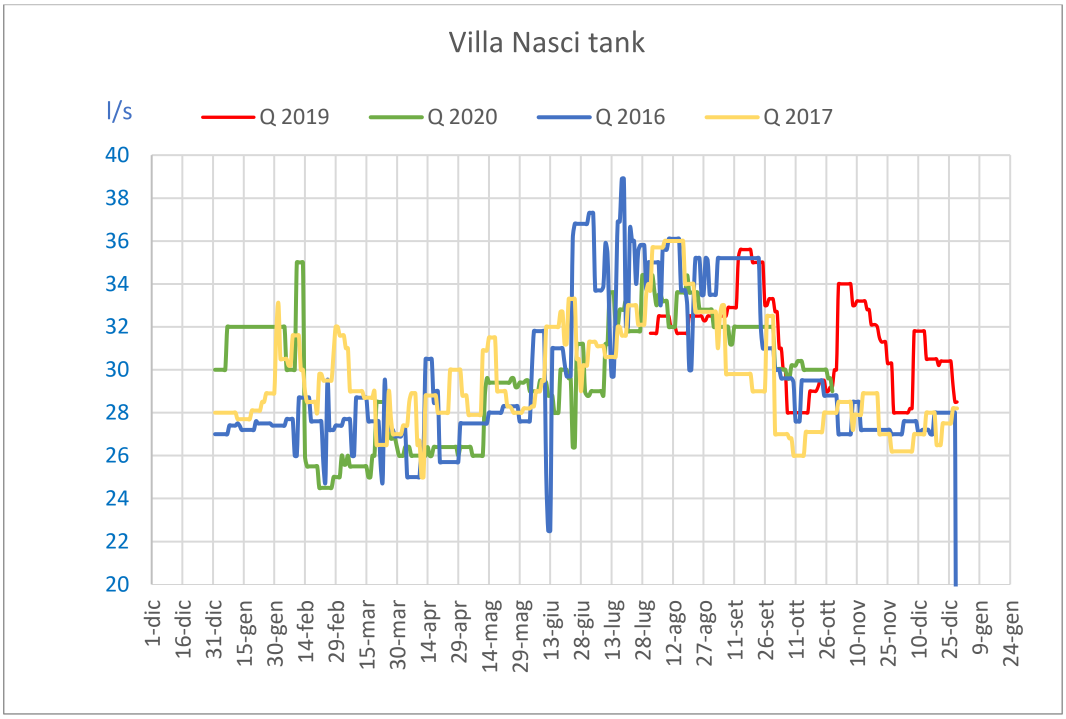

Figure 44 - Flow rate inlet Villa Nsasci tank (2016, 2017, 2019, 2020)

In this case we can see that the greatest flow of water occurs between the months of June and September. And that the trends between the different years are very similar to each other.

Considering that the SASI company, which deals with the management and supply of the water service, performs a proportional distribution of consumption on the flow rates of the source, i.e. divides proportionally the flow rate of the source for all the municipalities that are part of the aqueduct network. We can proceed with a correlation study between the flow rates of the source and those entering the Villa Nasci tank.

In Figure 45,46 we can see the trends of the source and the Villa Nasci tank compared.

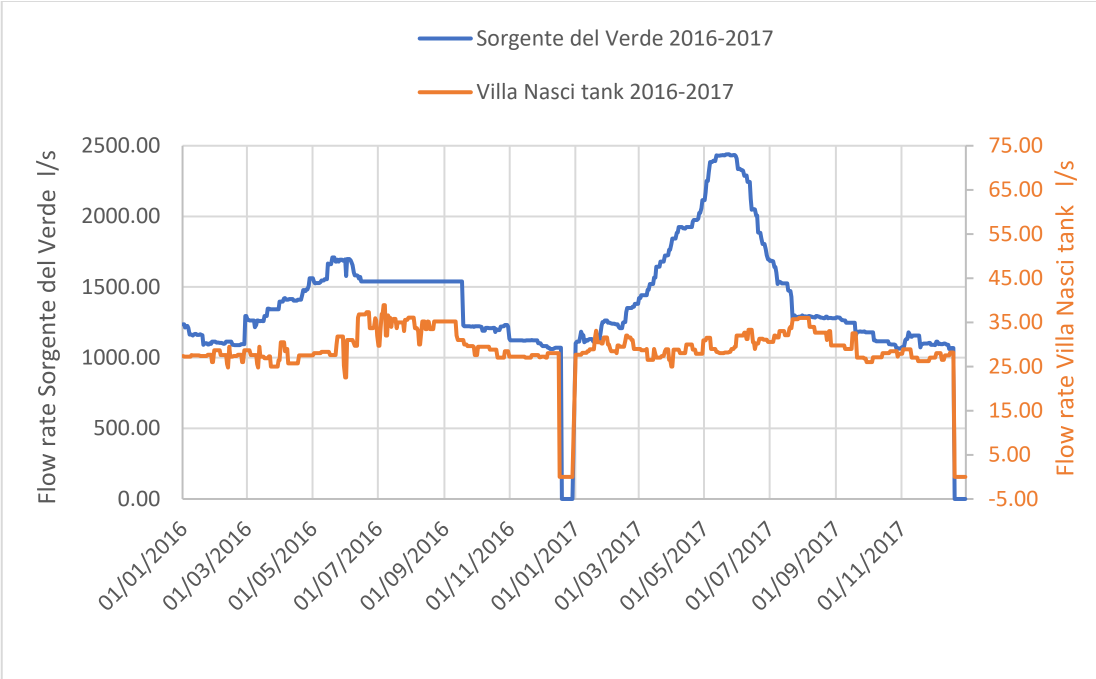

Figure 45 - Comparison of the flow rates of the Sorgente del Verde and the flow rates at the inlet to the Villa Nasci tank (2016-2017)

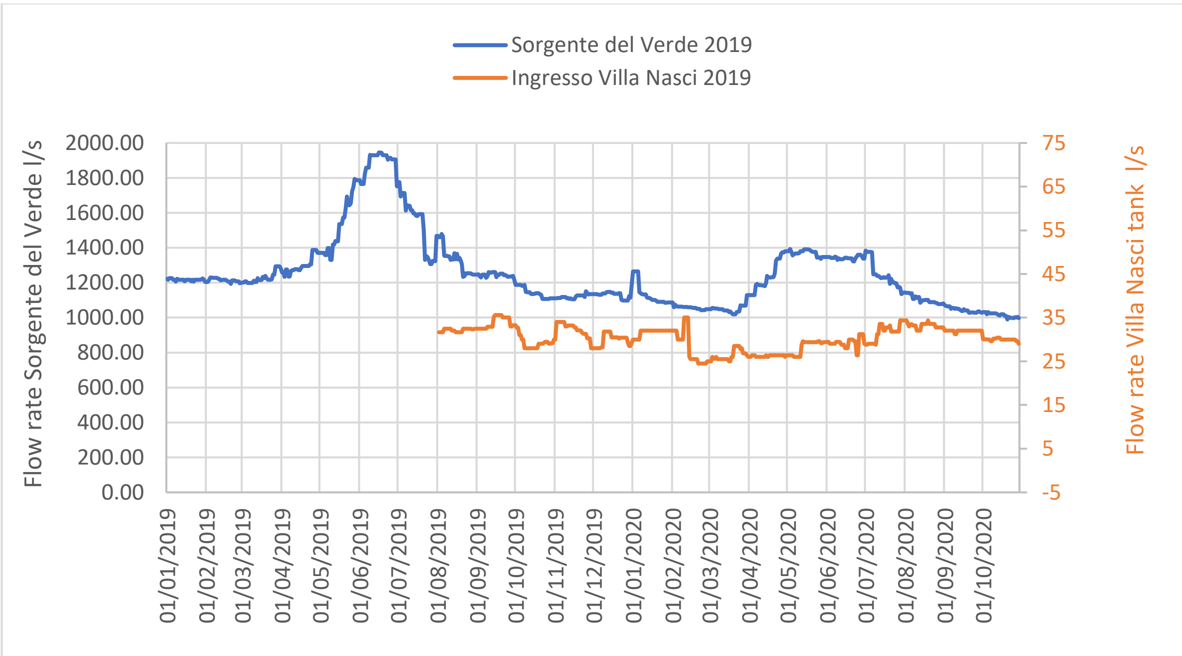

Figure 46 - Comparison of the flow rates of the Sorgente del Verde and the flow rates at the inlet to the Villa Nasci tank (2019-2020)

Two years for each graph were compared to understand how the source flows influenced the reservoir inflows. From a visual analysis of the graph it is possible to note that the flow rates available at the source directly affect the flow rates entering the tank.

In order to validate this hypothesis, a statistical analysis was carried out on the flow rates. a correlation index was calculated between the data of the years taken into consideration for the "Sorgente del Verde" and the reservoir of Villa Nasci.

Correlation analysis is a statistical evaluation method used to study the relationship between two continuous variables, measured numerically. This particular type of analysis is useful when you want to establish if there are possible connections between variables.

Generally, if a correlation is found between two variables, it means that when there is a systematic variation in one variable, there is also a systematic variation in the other; that is, the variables change together over a certain period of time.

The degree of correlation between two variables is expressed through the correlation index. The value it assumes is between -1 (inverse correlation) and 1 (direct and absolute correlation), an index equal to 0 implies the absence of correlation.

To calculate the degree of the relationship between linearly correlated variables x and y, a very common correlation index is that of Pearson. Which is calculated with the following formula:

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2}}$$

Where:

- $\bar{x}$ is the mean value of the variable x
- $\bar{y}$ is the mean values of the variable y
- at the numerator there is the covariance between x and y
- at the denominator there is the product between the standard deviations of x and y

Eight data series were used, of which 4 from the Source and 4 from the arrival at Villa Nasci, the sample used has a number of data equal to 2.928. Below is an extract from the different series.

Table 21 - Extract of the input data

	Sorgente del Verde 2015	Sorgente del Verde 2016	Intel Villa Nasci 2016	Sorgente del Verde 2017	Inlet Villa Nasci 2017	Sorgente del Verde 2018	Sorgente del Verde 2019	Inlet Villa Nasci 2019	Sorgente del Verde 2020	Inlet Villa Nasci 2020
01-gen	1091	1235,02	27,40	1103,40	27,70	1061,02	1221,69	\	1264,875	30
02-gen	1156	1235,02	27,20	1113,73	27,70	1066,02	1216,69	\	1264,875	30
03-gen	1156	1214,50	27,20	1113,73	27,70	1061,02	1226,69	\	1264,875	30
04-gen	1156	1221,83	27,20	1113,73	27,70	1059,02	1226,69	\	1264,875	30
05-gen	1156	1223,65	27,20	1144,73	27,70	1061,02	1226,69	\	1264,875	30
06-gen	1251	1211,83	27,20	1183,06	27,70	1061,02	1217,69	\	1144,875	30
07-gen	1251	1164,31	27,20	1158,25	28,10	1056,02	1217,69	\	1140,875	32
08-gen	1251	1164,31	27,20	1158,25	28,10	1056,02	1206,69	\	1134,875	32
09-gen	1251	1164,31	27,60	1108,50	28,10	1065,69	1222,69	\	1132,875	32
10-gen	1251	1157,81	27,50	1116,50	28,10	1065,69	1216,69	\	1132,875	32
11-gen	1251	1163,81	27,50	1125,50	28,10	1064,35	1216,69	\	1132,875	32
12-gen	1251	1168,17	27,50	1121,17	28,50	1069,35	1216,69	\	1113,875	32
13-gen	1202	1169,17	27,50	1130,17	28,50	1069,35	1216,69	\	1111,875	32
14-gen	1198	1160,83	27,50	1131,50	28,90	1069,35	1217,69	\	1111,875	32
15-gen	1202	1160,83	27,50	1131,50	28,90	1068,35	1207,69	\	1106,875	32
16-gen	1197	1160,83	27,50	1131,50	28,90	1069,35	1216,69	\	1101,875	32
17-gen	1219	1166,83	27,40	1118,83	28,90	1069,35	1217,69	\	1101,875	32
18-gen	1219	1162,31	27,40	1109,17	28,90	1069,35	1217,69	\	1101,875	32
19-gen	1219	1158,50	27,40	1106,25	31,80	1069,35	1217,69	\	1097,875	32
20-gen	1226	1090,69	27,40	1118,25	33,10	1072,83	1207,69	\	1089,875	32
21-gen	1290	1103,35	27,40	1123,25	30,50	1072,83	1217,69	\	1089,875	32
22-gen	1288	1103,35	27,40	1123,25	30,50	1072,83	1206,69	\	1089,875	32
23-gen	1297	1103,35	27,40	1123,25	30,50	1066,83	1216,69	\	1089,875	32
24-gen	1299	1093,00	27,70	1177,73	30,50	1065,50	1217,02	\	1089,875	32
25-gen	1299	1093,35	27,70	1227,73	30,20	1066,50	1217,02	\	1089,875	32
26-gen	1299	1102,31	27,70	1252,73	30,20	1075,50	1217,02	\	1084,875	32
27-gen	1302	1098,17	27,70	1252,73	31,60	1076,50	1217,02	\	1084,875	32

Below are the results obtained from the statistical correlation analysis of the years highlighted above, i.e. the results of the coefficient r described above.

Table 22 - Correlation Index

	r
2016	0,5860
2017	0,1230
2019	0,3860
2020	-0,1853

From the results of the correlation analysis from year to year, we can see a low link between the flows of the Sorgente del Verde and those of the entrance to the Villa Nasci tank.

It is possible to note the negative value of the year 2020 which indicates an inverse correlation, that is, as the flow rate of the source decreases, there is an increase in the inlet flow to the Villa Nasci tank. This can be explained by the fact that the analysis tries to correlate the two data series at the same time instant, without considering any delay between the two series.

For this reason, a cross-correlation was made with the help of the MATLAB environment. The code that has been written accounts for the translation over time of one series with respect to the other, evaluating the different correlations point by point, and calculating the delay time between one series and another.

The correlation was again made for the years 2016, 2017, 2019 and 2020. But in this case the years 2016-2017 and 2019-2020 were coupled to have a longer time series of data.

Below we can see the graphs of the two time series.

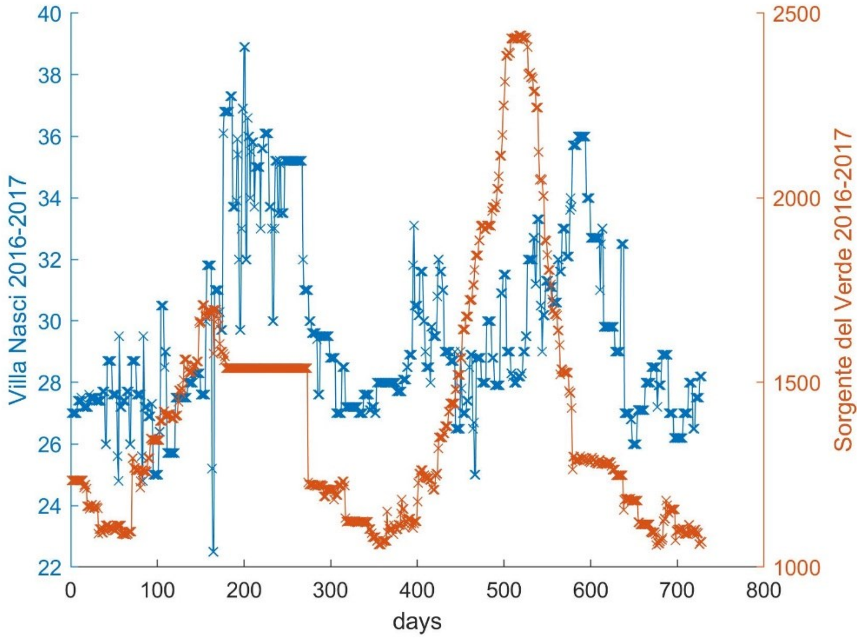

Figure 47 - 2016-2017 time series

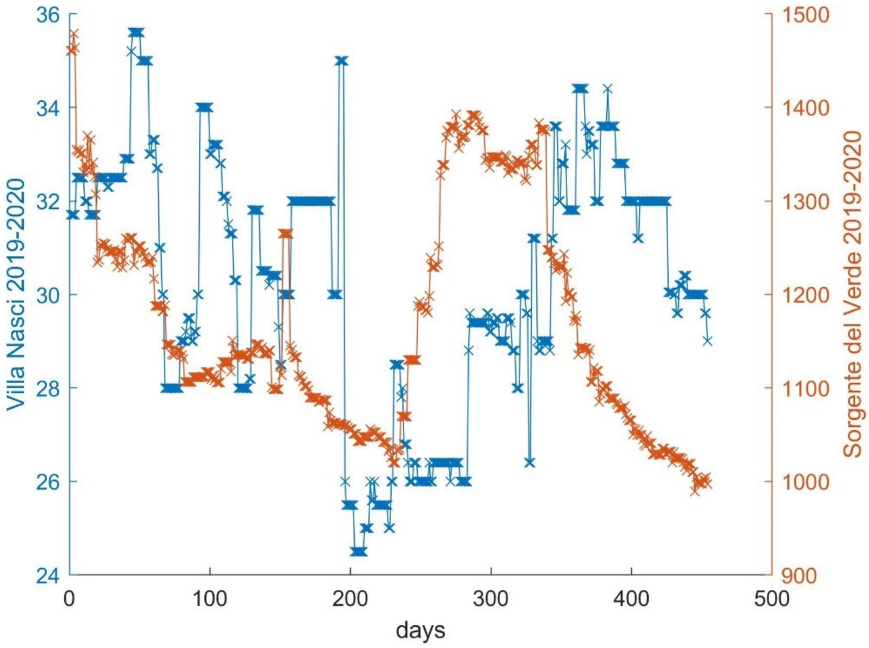

Figure 48 - 2019-2020 time series

For each time series, the maximum correlation index and the corresponding delay time were calculated, as follows:

- 2016-2017 series: Best correlation = 2399.7018
  Best lag = 60.0833 hours

- 2019-2020 series: Best correlation = 2273.925
  Best lag = 39.4167 hours

In the following Figure 49,50 we can see the lag-correlation analyzes.

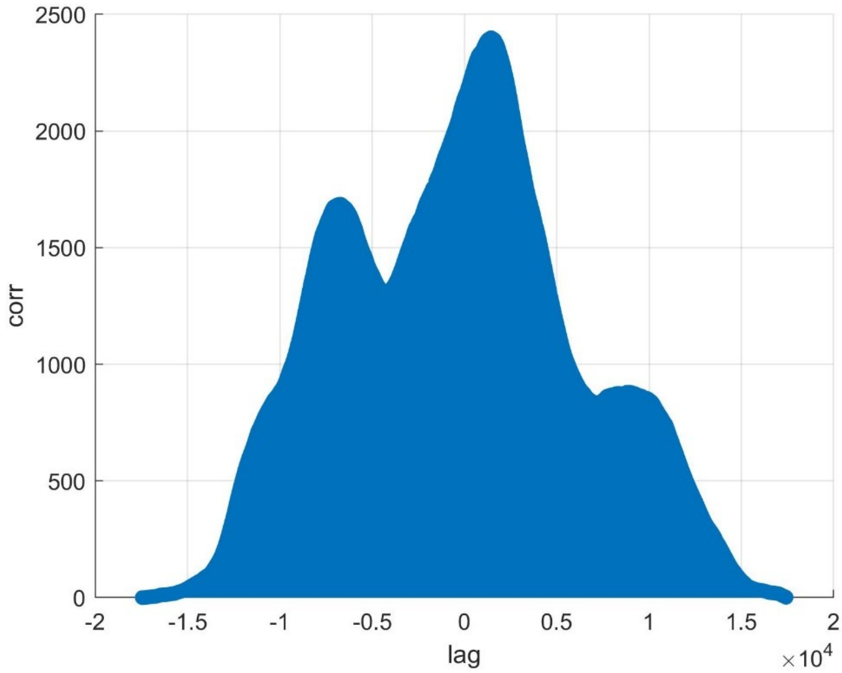

Figure 49 - 2016-2017 lag-correlation

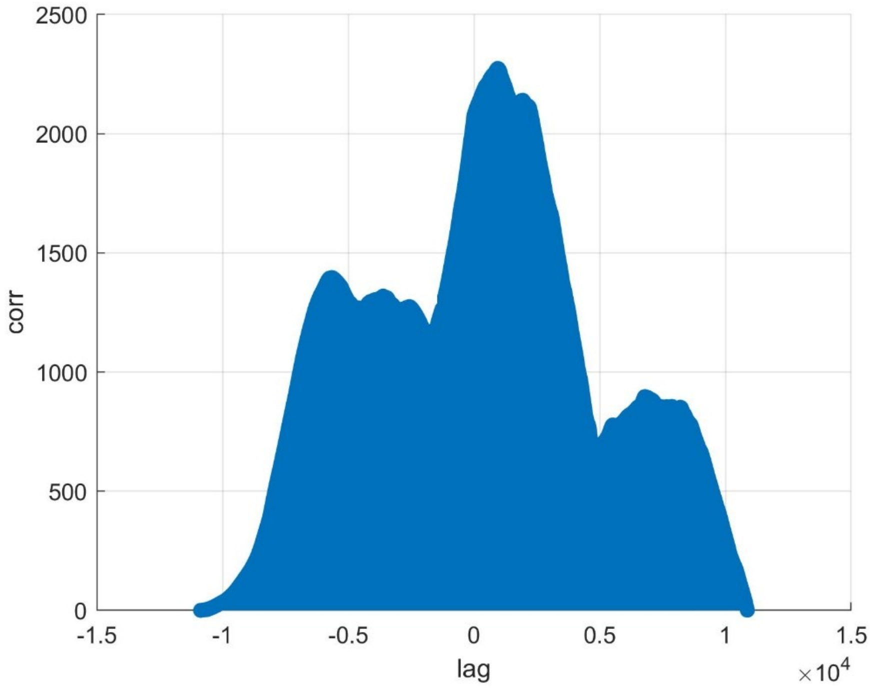

Figure 50 - 2019-2020 lag-correlation

Finally, the normalized time series were created, in which we can see the flow rates of the source translated according to the optimal delay time.

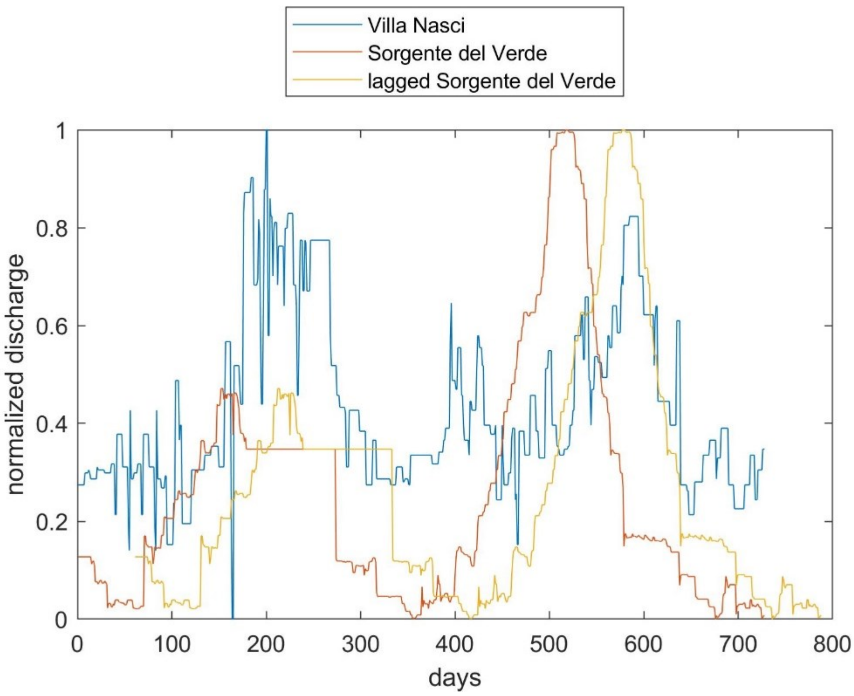

Figure 51 - 2016-2017 normalized time series

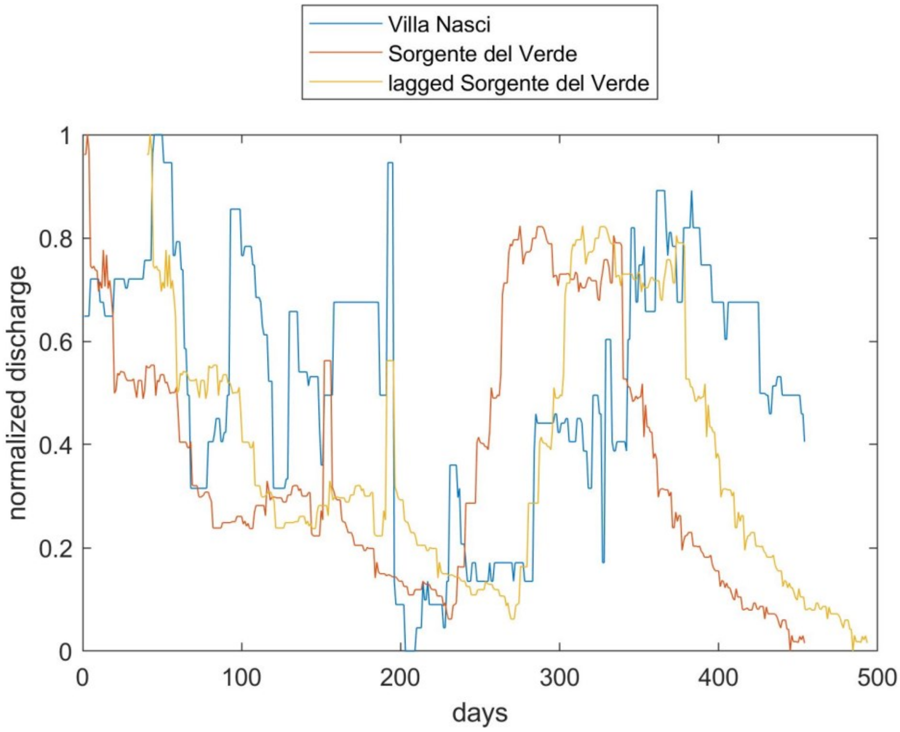

Figure 52 - 2019-2020 normalized time series

5 DISCUSSION

In this thesis, the main objective was to hypothesize a possible installation of hydroelectric turbines within the water supply system of the Chieti Province, with the aim of producing electricity from a renewable energy source.

After having analysed the "del Verde" aqueduct network for the positioning of the turbines, two suitable locations were identified because they are characterized by high flow rates and high piezometric jumps. Two case studies were therefore considered:

- CASE 1: identified in Villa Nasci tank in the municipality of Vasto.
- CASE 2: identified in New Fossacesia tank in the municipality of Fossacesia.

A design and economic analysis was carried out on both sites.

From a design point of view, the flow rates were analyzed, obtained by mechanical Venturi meters positioned on the inlet pipelines to the tanks. Through the flow rates (Q), the hydraulic head (S) and the efficiencies (eta), it was possible to calculate the powers that can be supplied by the turbine annually.

The main quantities for the studied cases are reported:

- CASE 1:

head drop = 104,26 m
average flow rate = 29,59 l/s

$$\text{annual energy production} = 195.894{,}65\ \mathrm{kWh/anno}$$

- CASO 2:

head drop = 192,7 m
average flow rate = 21,68 l/s

$$\text{annual energy production} = 248.982{,}05\ \mathrm{kWh/anno}$$

By comparing the results, it emerges that the greater head drop corresponds to a greater energy.

From an economic point of view, two variables were analyzed, the NPV and the PBT. The NPV gives an idea of the total value of the investment over the entire useful life, instead the PBT gives an idea of the time required to recover the initial investment cost.

The goal is to have an estimate of the cost-benefits for the realization of the hydroturbine, for both cases:

- CASE 1: **NPV** 272.354,94 €
  PBT 9,9

- CASE 2: **NPV** 367.068,75 €
  PBT 7,8

On the basis of these data, it can be summarized that the investment of the case 1 is not convenient in terms of revenues and recovery of the investment; compared to case 2 which would have a lower payback and higher revenues.

A further analysis was carried out on the del Verde aqueduct with the aim of evaluating how the flow of the source influences the flow rates arriving at the tank and to understand the optimum installation point of the turbine and any flow monitoring.

As source we mean the source of the del Verde aqueduct while the Villa Nasci tank was selected as the tank, because it is located at the end of the del Verde aqueduct.

In this study, some series of flow rates were analyzed and compared, in particular the flow rates of the years 2016, 2017, 2019 and 2020.

The results obtained from this analysis were the best correlation and the respective delay times for the two different series analyzed, that provide the optimal overlapping between time series. Hence, the time during which the water flows from the Sorgente del Verde to the Villa Nasci tank was of about 60 hours in 2016-2017 and 39 hours in 2019-2020.

Considering that the average flow rate of the source in the years 2016-2017 is 1.413,8 while for the years 2019-2020 it is 1.170,00, it seems that greater delays were recorded at higher flow rates.
This could be validated by the fact that the SASI company, when it has low source flow rates, alternates the use of the pipelines as needed, making the system more rigid.

6 CONCLUSIONS

Today when we talk about hydroelectric, we are typically talking about mini hydroelectric, and this is mainly due to the fact that the basins that allow the construction of large power plants are fully exploited. Furthermore, the technology has now reached a level that allows the efficient and economical exploitation of sites characterized by low jumps and reduced flow rates. It should also be said that currently, for the mini hydroelectric sector, the incentives are very interesting and make the investment economically very profitable.

In addition to exploiting a proven technology, this sector has some advantages compared to large plants, such as, for example, limited investments, high automation that reduces management costs and maintenance costs.

Therefore, referring to the project analyzed in this thesis it is clear that an investment of this type would bring advantages, especially of an economic nature, to the company SASI spa, which could use the energy generated by these turbines both independently, using it for lighting, or for the operation of the pumps located near the turbine, or to sell this energy and make a profit in monetary terms.

In addition to the availability of hydraulic jumps or investment returns, the factor that most limits the actual construction of mini hydroelectric power plants is the legislation. The bureaucratic process that is necessary to obtain all the authorizations is very long, discouraging investments in this sector. In fact, water is a public good and as such must be subjected to careful control in order to ensure availability for all. The legislation makes watercourses very protected and if on one hand it avoids the immense intervention of man, on the other hand it penalizes the creation of mini hydroelectric plants that would contribute to a more sustainable development and to a reduction in pollution caused by this sector.

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