

A METHODOLOGY FOR THE ASSESSMENT OF CLIMATE CHANGE EFFECTS ON HYDROPOWER

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ABSTRACT

Among the issues that are most relevant in the study of climate change, hydropower plays a double role. On one hand, it will be affected by the change in water availability feeding hydropower plants. On the other hand, as the present major source of renewable energy, an effort must be performed in order to maintain or, if possible, increase hydropower production. The aim of this activity is the study of the impact of expected climate change and of future scenarios of energy demand evolution on reservoir management, in order to assess the variations in hydropower production and identify the possible changes in reservoir management. This activity is part of ACQWA project, a EU FP7 large scale integration project whose aim is the use of advanced modelling techniques to quantify the influence of climate change on the major determinants of river discharge and analyse their impact on society and economy. In particular, the work packages devoted to the study of the drivers of change and the development and application of regional climate models and hydrological models will provide high quality data about the expected water availability and the evolution of electric power demand.

Our activity has been focused on the development of a model of the management of a complex hydropower system as a function of climate conditions and power demand. A conceptual scheme of the hydropower system in the case study, the Regione Valle d'Aosta, Italy, has been developed. Main hydroelectric reservoirs and hydropower plants has been identified, the topological structure of the system has been recognized and the hydraulic and electrical characteristics has been collected, together with the characterisation of present climate and present runoff in Valle d'Aosta. The management of the hydropower system has been computed by means of a simple optimisation tool and the expected variations in reservoir management and power production will be quantified through a comparison between optimisation results of present and future scenarios. At present only the present scenario has been completed.

1 INTRODUCTION

In recent years evidence of the man-made origin of climate change are becoming more numerous and, similarly, data of impacts on terrestrial ecosystems and the socio-economic system are gathering in several fields. Not all geographic areas, however, will suffer the same consequences, and it has been recognized that some regions are potentially more vulnerable than others, both for their physical characteristics and their effects. Mountains are recognized as one of the most sensitive environment, with significant potential impacts on the people who live here.

In these regions, most impacts are mediated by the influence of climate change on hydrological regimes. While temperature trends seems to be well understood, more uncertain is the impact on runoff that could have relevant feedbacks, in the near future, on the water management policies and engineering design. No clear signals of runoff changes at the global scale are documented by the IPCC (Bates et al., 2008), although several studies at the regional scale report about significant variations on a statistical basis in the 20th century.

This important issue has been already the subject of several studies. As for the Italian Alps, for instance, Barontini et al. (2009) reported the results of a study on the potential impact of climate change scenarios on the runoff regime in the Italian Alpine area. A decrease of about 7% of annual runoff volume for the 2050 scenario and of 13% for the 2090 scenario was estimated, on average, at the outlet of the Oglio river basin, the largest one. In the smaller Lys 25 basin, where the glaciated area is 8% of the total area, the annual runoff is foreseen to decrease by about 3% (for the 2050 scenario) and 14% at the end of this century. In this study, authors used output of three Global Circulation Models (PCM, HADCM, ECHAM). Analogously similar results were obtained for the impacts of climate change on hydropower production Ranzi et al. (2009).

In order to improve the assessment of climate change impacts using more recent modelling results and an integrated approach, ACQWA Project¹ was launched in the framework of the EU 7th FP. It aims to assess the expected impact of climate change on mountain regions, focusing on water sector and in areas where melting snow and ice is an important component of available water. In these regions, this component is a valuable local resource (for supply of fresh water, hydropower, irrigation) and also significantly influence the runoff downstream, the river and its water availability. To investigate fully and in an integrated these problems, the project aims to use advanced modelling techniques for:

- quantify the influence of climate change on key processes at different spatial and temporal scales and for all areas potentially affected;
- analyze their impact on society and the economy;
- identify the main feedback mechanisms.

The project began in October 2008 and is expected to end Sept. 30, 2013, is coordinated by the University of Geneva and the participation of 37 partners from seven European countries and three non-European nations. Within the project it was agreed to analyze the temporal evolution from 1960 to 2050, as this horizon has been identified as

¹ <http://www.acqwa.ch>.

one in which a more realistic assessment can be developed.

This paper presents activities carried out in the framework of ACQWA Project and devoted to the assessment of consequences of expected climate change on reservoir management, in order to assess the variations in hydropower production and identify the possible changes in reservoir management.

To this aim a great integration with other ACQWA activity is needed. Regional climate models will provide information on patterns of precipitation and temperature and input information to hydrological models, whose aim is the evaluation of changes in the water availability and in its seasonality. Socioeconomic analysis will provide the future evolution of energy demand. On the basis of these inputs, a methodology has been developed in order to assess future hydropower production and reservoir management and it will be applied to a very significant case study as soon as data inputs will be available for the future scenario.

2 ASSESSMENT OF FUTURE HYDROPOWER PRODUCTION

Hydropower production is the most important renewable energy source in the Italian electricity system, with more than 2,000 plants, more than 17 GW power installed and a mean annual production of about 40 TWh. Among the issues that are most relevant in the study of climate change, hydropower plays a double role. On one hand, it will be affected by the change in water availability feeding hydropower plants. On the other hand, as the present major source of renewable energy, an effort must be performed in order to maintain or, if possible, increase hydropower production.

The impact analysis on hydropower systems requires that the results of the precipitation-runoff models are used to simulate various operational scenarios of reservoir management, which account for hydropower targets (safe hydraulic operations) and secondary targets (flood protection, water supply or irrigation purposes). The simulation of operational scenarios is ideally embedded in the precipitation-runoff model, thus enabling the couples long-term simulation of the natural and the technical system. The simulation of modified operational strategies requires additional information on the development of the energy demand, which can be defined by means of hypothetical scenarios or by specific targets set by the energy demand.

The future evolution of hydropower production depends on the evolution of both the natural system and the socioeconomic conditions. Moreover, it cannot be simply predicted by the use of deterministic, causal models that compute the output power from a given water flow: in fact, the management of hydropower system must also be considered and plays a major role. The management is characterised by its attitude towards one or more aims and objectives or, in other words, is finalistic in nature.

In the present work, only one objective has been considered in the determination of hydropower management: the total profit from the power selling. This simplification allows us to summarise socioeconomic conditions in a single variable: power price. Moreover it allows us to simulate future management of hydropower systems with a simple optimisation tool, called SOLARIS (Maran et al., 2006).

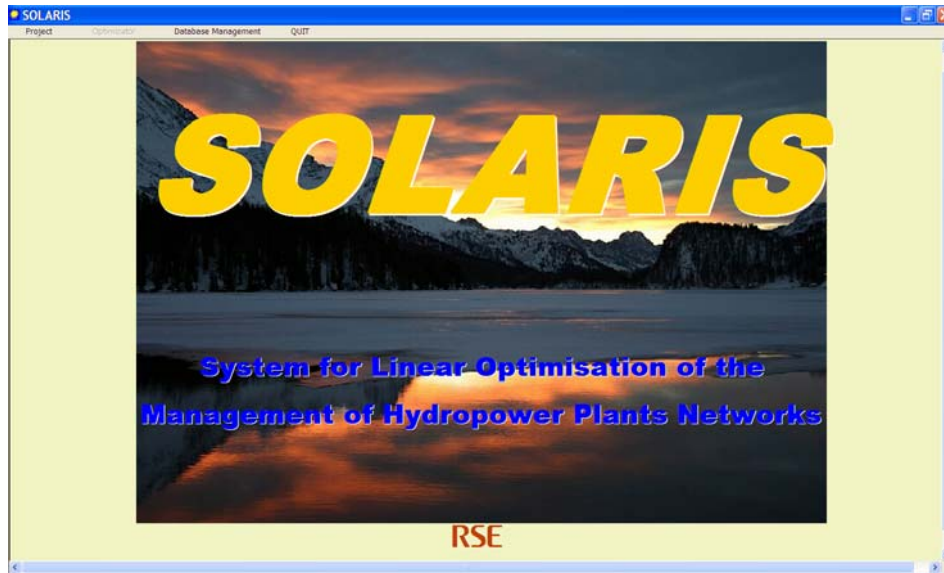


Figure 1: SOLARIS software (in Italian, Sistema di Ottimizzazione Lineare per Aste o Reti Idroelettriche e Serbatoi).

The Solaris software is a tool developed by RSE and used to identify the optimal management of a network of hydroelectric reservoirs. Starting from the estimate of the inflows to the reservoirs and energy prices, the program computes the value of the releases from the reservoirs that are used in hydropower stations in order to achieve the objective of maximizing the monetary value of energy produced. Alternatively, instead of using the expected energy prices, a power profile can be set and the optimization identifies a reservoir management that deviates as little as possible from the pre-assigned profile.

The first step is the appropriate schematisation of the river basin and of the hydropower system and the development of a network composed by arc and nodes. In this respect an arc can represent the following elements of the real system:

- A hydropower plant
- A pumping station
- A water course
- A canal

while a node represents a hydraulic node in the real system, that is:

- A reservoir (used for seasonal modulation)
- A basin (used for weekly or daily modulation)
- A fluvial barrier (without storage capacity)
- A junction between two arcs, in general

For each node, a "natural flow" can be defined which represents the amount of water collected by the node. A negative value of this "natural flow" can be used to insert water withdrawal delivered, for instance, to a consortium.

The problem is characterised by several constraints. Equality constraints are

represented by the equations of mass balance on each node and at each time interval.

These equations express the dependence of the volume of water stored in each node in a given time period on the volume of water in the previous period, the amount of water coming from upstream arcs, natural inflow, water collected by withdrawals, and the amount of water flowing into downstream arcs. Inequality constraints represent technical constraints on the maximum storage capacity of hydraulic nodes and the maximum discharge that can flow in a hydraulic arc. The power plant output is computed from its energetic coefficient, representing the power produced by a unit volume of water (kW/m^3).

The program can be used for two different purposes. If a time series of energy prices is given, it optimises water used by hydropower plant and storage in reservoirs and basins in order to maximize the gross value of produced energy. If a target modulation of power demand is given, it computes the output variables (production and storage) in order to obtain the minimum difference between the real and the target modulation, in a least square sense. In both cases, the solution must satisfy the given constraints.

In reality, the management of a network of reservoirs for hydropower production may be complicated by various factors, both technical and environmental in nature. Secondly, the management of reservoir can be, and usually has, several objectives, other than the maximisation of total revenue, and they are usually competing to each others. Finally, for a time horizon that goes beyond a few days, it is unrealistic to assume to know in advance either inflows or energy prices with sufficient accuracy.

For these reasons, as it stands, the Solaris software is not suitable to be used for management purposes. It can, however, be a useful tool to compare different scenarios that arise, for example, by a change of climatic conditions, as it is the case in the present application.

3 CASE STUDY: THE VALLE D'AOSTA HYDROPOWER SYSTEM

In the case study, an important Italian hydropower system is considered; it is located in the Aosta Valley, which is characterized by the presence of very high massifs (Monte Bianco, 4810 m a.s.l., Monte Rosa, 4634 m a.s.l., Cervino, 4474 m a.s.l., Gran Paradiso 4061 m a.s.l.) and perennial glaciers.

The maximum elevation of the area is 4810 m a.s.l., while the minimum value of the elevation is 312 m a.s.l., at Quincinetto, the outlet of the watershed (Figure 2). The average elevation of the region is about 2106 m a.s.l..

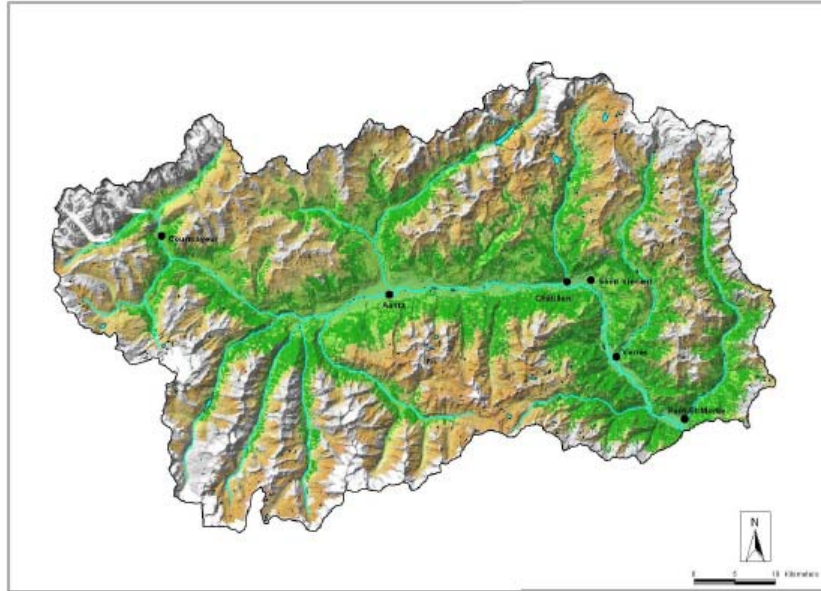


Figure 2: Altimetric map of Regione Valle d'Aosta

The amount of the glacierized area, in the region, is about 237 km², and the presence of the glaciers is concentrated in the northern part of the region. The presence of the glaciers determines the regime of the runoffs, which are characterized by minimum flow values in winter and maximum flow values in summer, when the glaciers melt.

Table I. Main hydropower reservoirs in Valle d'Aosta and their characteristics (storage capacity refers to the capacity useful for regulated storage not to the total capacity).

Reservoir	Catchment area (km ²)	Storage capacity (millions m ³)
Beauregard	93.6	70.0
Place Moulin	74.0	105.0
Goillet	6.3	11.0
Cignana	13.5	16.0
Gabiet	3.0	4.4

The hydrological system in Valle d'Aosta region is composed by Dora Baltea river and its main tributaries. Dora Baltea river is a left-hand tributary of Po river and it runs for about 100 km between Courmayeur and Quincinetto. It originates by Mont Blanc, at the confluence of the Dora of Ferret, fed by the Pré de Bar Glacier in Val Ferret, and the Dora of Veny, fed by the Miage Glacier in Val Veny. The surface of the basin is about 3222 km²; the mean rainfall is 1075 mm while the mean annual flow at the outlet of the river basin is 102.9 m³/s, yielding a mean runoff coefficient of 0.94.

The Dora Baltea river is connected with 16 tributary valleys. The Aosta Valley

region counts a great number of lakes, some of which are artificial and are used for seasonal regulation of hydropower production. The dams that will be simulated in the case study are listed in Table I, together with their main characteristics.

Water use, in the case study is mainly devoted to hydropower production. In 2009, the installed capacity of the region was estimated in about 859 MW, while the net hydroelectric production was about 3100 GWh².

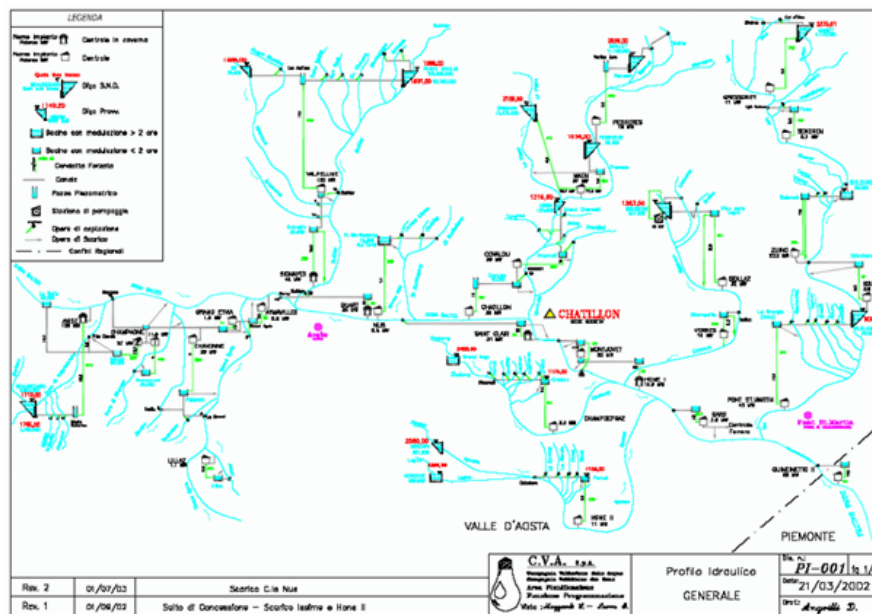


Figure 3: Hydraulic profile of the major hydropower system of Valle d'Aosta.

The hydropower plant system is very complex. The major electricity producer of the region (CVA) has more than 130 water abstractions for hydroelectric use and a sketch of the system is outlined in Figure 3.

3.1 Conceptual model

The first step was to simplify the real system in order to get a manageable system. In collaboration with the electricity producer, the most important basins and power plants were identified and a conceptual model was developed in order to be able to insert it into the software program Solaris. The conceptual model is reported in Figure 4 and must be compared to the real system of Figure 3.

² Data from Terna, the Italian TSO (Transmission System Operator): <http://statistiche.terna.it/statistiche/documenti/bilanci/aosta09.pdf>.

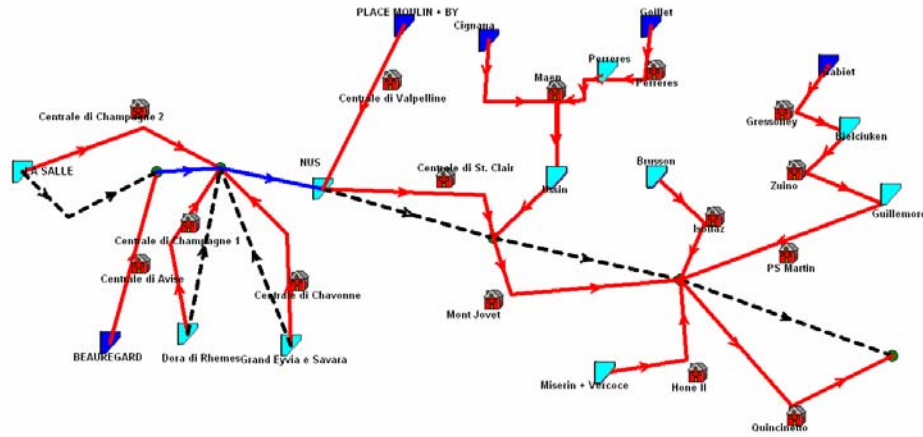


Figure 4: Conceptual model of the hydropower system in Regione Valle d'Aosta (plants are indicated as red houses, dams are indicated in blue - significant storage capacity – and light blue - small storage capacity – red lines represent artificial canals and penstocks, blue and black lines represent the river channel).

For every hydropower plant, user must enter: the minimum and maximum flow used by the turbines, the corrivation time (if relevant in respect to the considered time step), and the energetic coefficient. For each reservoir, the following data must be provided: minimum and maximum height for regulation, external inflow and outflow, and the stage – volume relationship. For each basin, the storage capacity must be provided, together with external inflow and outflow. Finally, for the river channel and the artificial canals, the maximum flow and the corrivation time must be inserted. This information, together with the initial and final conditions for the reservoir capacities, completes the conceptual model of the system.

4 PRELIMINARY SIMULATION OF THE PRESENT SCENARIO

In order to test the ability of the methodology in describing the actual management of the hydropower system, a study of the present scenario was conducted in a limited portion of the region, the high valley. The system takes into account the upper stretch of Dora Baltea river that is located upstream the Nus water chamber. Along this stretch the hydropower plants of Avise, Champagne1, Champagne2, Chavonne, and Valpelline are taken into consideration. The Nus water chamber feeds the St. Clair hydropower plant.

The simulation is structured with 730 time steps (two steps for each day), with a time horizon of one year. The reference year for all time series is 2006. The duration of the time steps is not homogeneous because, within each day, we have determined the extent of the peak/off peak hours, associating to each of them a different energy cost. In particular, the extent of the pick hours is from 9:00 a.m. to 7:00 p.m, so the peak hour time step lasts ten hours while the off-peak hour time step lasts 14 hours.

The data that are necessary to create the input files for the simulation were provided by the local energy producer CVA and are represented by:

- Water level/Volume curves for Beauregard and Place Moulin reservoirs;
- Hourly price of energy;
- Hourly energy productions from Avisa, Champagne1, Champagne2, Chavonne, Valpelline and St. Clair hydropower plants.

As for the reservoirs (Place Moulin and Beauregard), natural inflows were computed by a mass balance among reservoir water volume and the water flow used by the hydropower plant.

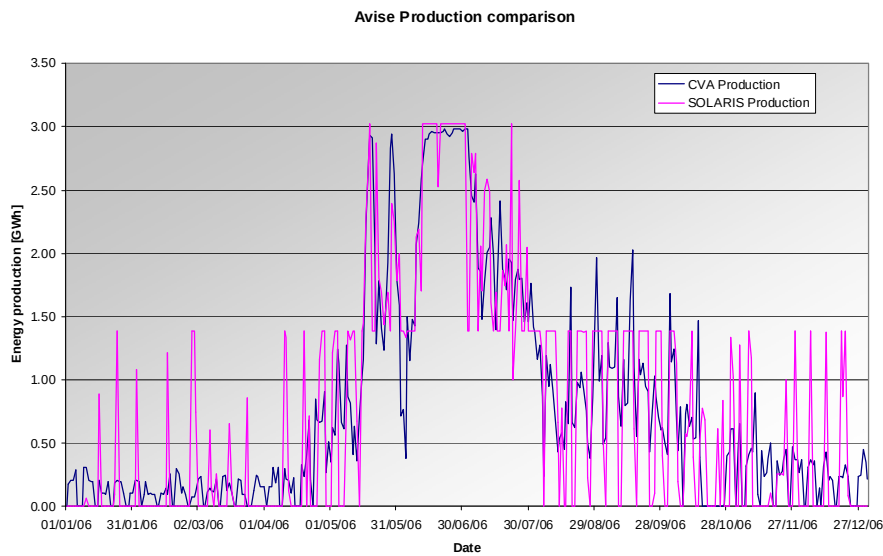


Figure 5: Daily hydropower production from Avisa HPP: Comparison between real and simulated production.

As the same kind of information is not available for the other basins (La Salle, Dora di Rhemes, Grand Eyvia and Savara), we assumed as a first approximation that these inflows could be reasonably quantified as the flow directly used by the hydropower plant located just downstream the basin itself. This means that for most upstream hydropower plants (namely Avisa, Champagne1, Champagne2, Chavonne and Valpelline), overflows from the basins were neglected. Finally, for St. Clair power plant, which is the only power plant affected by the operation of the other HPPs, we evaluated the direct inflows, by means of a balance equation. At the Nus water chamber, natural inflows were estimated as difference between the flow used by St. Clair hydropower plant and the flow used by all the hydropower plants located upstream the node (namely Champagne1, Champagne2, Chavonne, Avisa, and Valpelline).

5 RESULTS

A comparison was made between the daily real production (coming from the local hydropower producer, CVA) and the daily simulated production (coming from SOLARIS). We found out that in most cases, the software is able to follow the real

operation of the system very accurately. The comparisons between the real and simulated operation of the system for a couple of hydropower plant are shown in Figure 5 and 6.

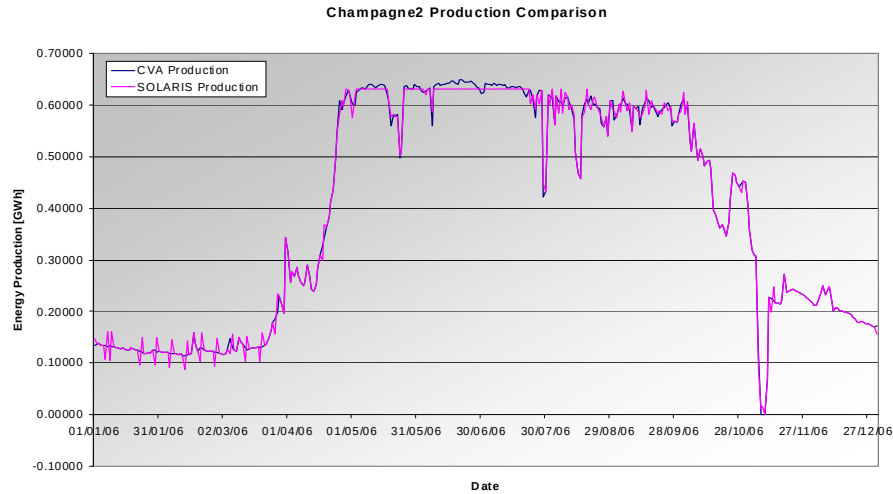


Figure 6: Daily hydropower production from Champagne 2 HPP: Comparison between real and simulated production.

The only exception is represented by Valpelline hydropower plant where the simulated trend shows a weekly modulation, as well as a seasonal one (see Figure 7).

In the simulation, the hydropower plant seems to use the maximum amount of water in the peak hours and to produce nothing in the off peak hours, as expected. In fact, the reservoir capacity is enough to support this kind of policy that wants to maximise the revenues. In the operative management, other requirements could occur that affect the final trend. For instance, it seems that in October the power plant produced at its maximum capacity, also in the off-peak hours. It is possible that some limitations were imposed by maintenance operations on the dam or by requirements following other uses of the reservoir (for instance, some artificial lakes are maintained at their maximum level during summer for touristic reasons). Other discrepancies, in particular those in the first part of the year, are due to the limitation of the present simulation to the high portion of the valley. Actual operations of the reservoir take into account also the hydropower plants located downstream in order to minimise exedances of their maximum capacity. This aspect will be solved in the continuation of these activity, when data on all power plants, reservoirs and basins will be available.

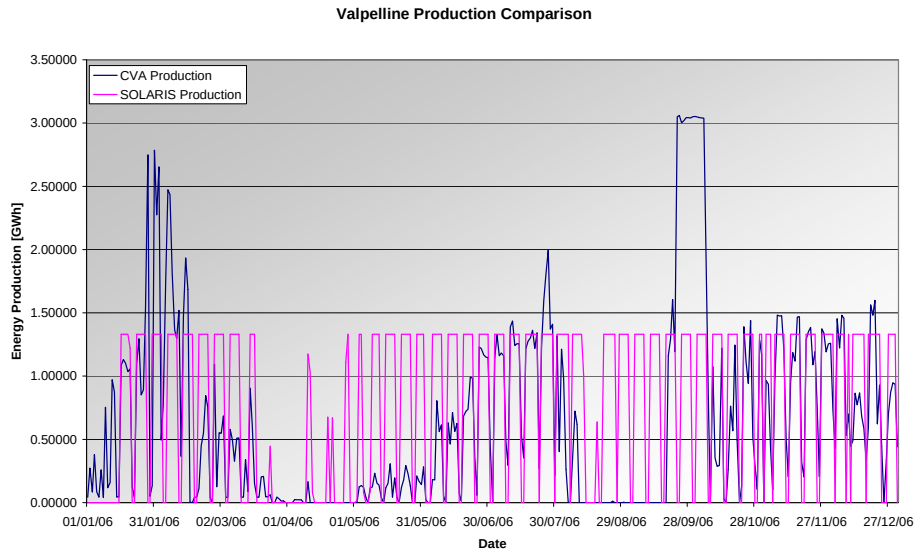


Figure 7: Daily hydropower production from Valpelline HPP: Comparison between real and simulated production.

Apart from the details of operations of single hydropower plants, a total balance of mass and energy was computed and compared to real values, in order to test the performance of the methodology from a regional point of view, which is of greater importance in the present activity.

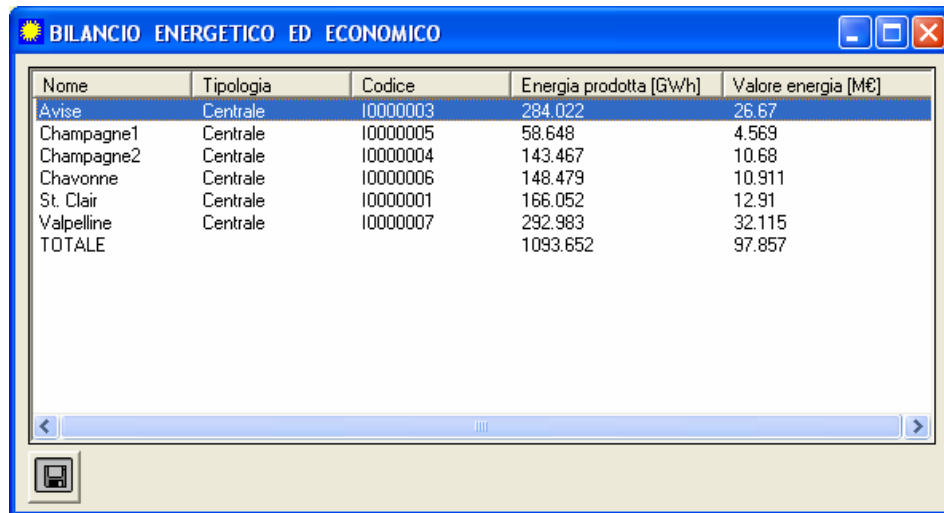
● BILANCIO IDRICO							
Nome	Tipologia	Codice	Aff. - Rilasci [Mm³]	Vol.turbinato [Mm³]	Vol.Sfiori [Mm³]	Delta vol. [Mm³]	Vol.pompato [Mm³]
Avise	Centrale	I0000003		133.973			
Beauregard	Serbatoio	S0000004	133.975		0	0	
Champagne1	Centrale	I0000005		74.238			
Champagne2	Centrale	I0000004		333.644			
Chavonne	Centrale	I0000006		129.112			
Grand Eyvia	Bacino	B0000004	129.113		0		
LA SALLE	Bacino	B0000002	334.425		0.78		
NodoNC N0000001	NodoNC	N0000001	0		1174.811		
NodoNC N0000003	NodoNC	N0000003	0		0		
NodoNC N0000004	NodoNC	N0000004	0		0		
PLACE MOULIN	Serbatoio	S0000002	139.516		0	0	
Rhemes	Bacino	B0000003	74.238		0		
St. Clair	Centrale	I0000001		1064.435			
Valpelline	Centrale	I0000007		139.516			
vasca carico quart	Bacino	B0000001	363.544		110.382		

Figure 8: Mass balance: the first numeric column contains inflows, the second water amount used by hydropower plants, the third overflows, and the fourth errors in mass balance.

The mass balance (Figure 8) shows how water it is used along the river and the amount of overflows. Note that the overflow for the Node N0000001 simply represents the outlet of the river basin and so it is not a real overflow. Instead overflows for La Salle and Quart are actual overflows, representing water that is not used for hydropower

production and is lost.

The overall energy balance is reported in Figure 9 together with the estimation of its monetary value computed from energy prices..



The screenshot shows a software window titled "BILANCIO ENERGETICO ED ECONOMICO". Inside the window is a table with the following data:

Nome	Tipologia	Codice	Energia prodotta [GWh]	Valore energia [M€]
Avisè	Centrale	10000003	284.022	26.67
Champagne1	Centrale	10000005	58.648	4.569
Champagne2	Centrale	10000004	143.467	10.68
Chavonne	Centrale	10000006	148.479	10.911
St. Clair	Centrale	10000001	166.052	12.91
Valpelline	Centrale	10000007	292.983	32.115
TOTALE			1093.652	97.857

Figure 9: Energy and economic results: the first numeric column contains produced energy and the second its monetary values.

The result of the simulation can be compared with the official datum declared by the local producer (CVA) for year 2006. The result is satisfying, as CVA gives an overall production of 1025 GWh, while the simulation brings as result about 1093 GWh (slightly less than 7% of deviation). An overestimation is expected because the model makes use of information that is not available (the daily inflow) in practice.

6 CONCLUSIONS

The assessment of expected climate change on hydropower production requires the knowledge not only of the effects on the water cycle, that directly feeds hydropower plants, but also on the energy demand and on the management of reservoirs. For this purpose a methodology is developed and has been tested on real data.

Comparison between preliminary results and historic data, provided by the local hydropower producer, shows that the methodology yields results similar to the actual management of the plant network, in spite of some discrepancies due to requirements that cannot be taken into account in a mathematical model. More in general, it is worth stating that the results that are coming from SOLARIS can reflect only a theoretical management of the system and are not able to take into account any forcing cause that can create a particular situation.

Anyway the comparison of the integrated results (i.e. total energy production) shows that the methodology is suitable to be used for the objectives of the present activity. When results on future hydrologic regime will be available from the ACQWA project, the methodology will be applied to the case study for the assessment of the effects of expected climate change on hydropower

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