UNIVERSIDAD CARLOS III DE MADRID

DOCTORAL THESIS

HYDROPOWER SCHEDULING IN BASINS WITH HEAVY ECOLOGICAL AND HUMAN RESTRICTIONS

Author:

Gloria Hermida Garrote

Advisor:

Dr. Edgardo Daniel Castronuovo

Department of Electrical Engineering

Leganés, February 17, 2017

DOCTORAL THESIS

HYDROPOWER SCHEDULING IN BASINS WITH HEAVY ECOLOGICAL AND HUMAN RESTRICTIONS

Author: Gloria Hermida Garrote

Advisor: Dr. Edgardo Daniel Castronuovo

Tribunal:

Signature

President: Luis Fernandez Beites

Member: Juan Ignacio Pérez Díaz

Secretary: Mª Ángeles Moreno López de Saá

Qualification:

Leganés (Madrid), February 2017

"No tengas miedo de marcarte objetivos o metas elevadas. Por más altos que sean tus retos, por lejanas que parezcan tus metas, para alcanzarlos solo necesitas de las palabras. Las palabras crean realidades y tú, con ellas, la vida que quieres vivir"

Guillermo Ballenato en alguna de sus magníficas clases.

Agradecimientos

Gracias a esta Universidad por haberme dado la oportunidad y los medios, para que esto haya sido posible.

Gracias a mi tutor Edgardo Daniel Castronuovo por su comprensión, su infinita paciencia y su empatía. Él hizo posible llegar hasta el final de este recorrido.

Agradecer a Julio Usaola por su modo de enseñar con el ejemplo.

Agradecer al resto de profesores del departamento por su empatía y su comprensión, por todo lo que aprendí con ellos como profesional y como persona.

Agradecer a mis compañeros del departamento por los ratos de ocio y de deporte compartidos.

Agradecer a todos los que, en silencio, aportan motivación para seguir, para estar y para vivir intensamente cada momento.

Summary

The problem of water resources management aims to calculate the optimal energy bids of a set of hydro plants and to estimate costs for consumptive and nonconsumptive volumes of water, when meeting European and local regulations, consumption requirements and basin rights of use, respecting environmental flows, possible congestions in the electric transmission system and other important concerns. The goal of this thesis is to advance in the development of an effective tool for the management of hydro basins with different economic, social, policy, normative, restrictions and resources characteristics.

In first case, an optimisation problem for calculating the best offers of a set of hydro power plants is proposed, considering ecological flows and social consumptions. In the simulations, the costs related to the social consumptions and ecological requirements are compared in a relatively small real Spanish basin, for short-term (24-hour) planning.

In second case, an improved representation of the market and the optimization of the hydro plants are integrated in a nested algorithm, to calculate local prices and optimal energy bids in a congested electrical system. The algorithm is applied to a real basin in Italy.

In a third case, uncertainties in the resources, improved representations of the hydro plants and environmental constraints are integrated in a large basin, in southern Spain. Stochastic scenarios are used to evaluate the significance of uncertainties in a 72-hours horizon. The study provides a new tool for the coordinated management of large basins, complying with ecological restrictions

and governmental regulation on water resource allocation and considering the technical characteristics of hydropower plants and the hydropower production profits.

Resumen

El problema de gestión de recursos hídricos busca determinar las ofertas óptimas de energía para un conjunto de centrales hidroeléctricas y también una estimativa de los costos del agua para los volúmenes consutivos y no consuntivos, cumpliendo normativas europeas y locales, las necesidades de consumo y los derechos de uso de las cuencas, las posibles congestiones en el sistema de transmisión eléctrica y otras cuestiones relevantes. El objetivo de esta tesis es avanzar en el desarrollo de una herramienta eficaz para la gestión de cuencas con diferentes características económicas, sociales, políticas, normativas, restrictivas y de recursos.

En el primer caso estudiado, se propone un problema de optimización para el cálculo de las ofertas óptimas de un conjunto de centrales hidroeléctricas, en una cuenca española relativamente pequeña, considerando los flujos ecológicos y los consumos sociales. En las simulaciones de planificación a corto plazo (24 horas), se comparan los costes relacionados con los consumos sociales y los requisitos ecológicos.

En el segundo caso de estudio, se integran en un algoritmo iterativo una representación mejorada del mercado y la optimización de las centrales hidroeléctricas, a fin de calcular precios locales y ofertas óptimas de energía en un sistema eléctrico congestionado. El algoritmo es aplicado a una cuenca real en el Norte de Italia.

En el tercer caso de estudio, las incertidumbres asociadas a los recursos y una representación mejorada de las centrales hidroeléctricas, junto con las limitaciones ambientales, se integran en un modelo que representa una cuenca

real de tamaño significativo en el sur de España. Se utilizan escenarios estocásticos para evaluar la influencia de las incertidumbres en un horizonte de 72 horas. El estudio proporciona así una nueva herramienta para la gestión coordinada de grandes cuencas, cumpliendo con las restricciones ecológicas y la regulación gubernamental sobre asignación de recursos hídricos, teniendo en cuenta las características técnicas de las centrales hidroeléctricas y los beneficios de producción de la energía hidroeléctrica.

Contents

List of figures

List of tables

Chapter 1.

Introduction

Abstract— **In this chapter, the objectives that motivate the study and development of this work are presented. Also, the organizational structure of the thesis is introduced.**

Contents

1.1 Motivation

Many researchers have focused the studies on the management optimization of hydro basins to achieve higher profits for companies. Since 1992, the Rio World Summit on Environment and Development/UNCED has stated that water resources are included into the core of sustainable development; they must be managed on a sustainable basis [1]. At present, profit is not sufficient for a realistic representation of the constraints affecting hydroelectric generation management and, currently, hydropower generation includes more implications than traditional considerations of economic performance. Many studies use different mathematical methods, approaches, constraints and characteristics of the systems, seeking better representations of the hydro systems [2-6]. Social, economic, political, environmental and geographical factors vary the optimal mode of operation and management of water resources. The population growth and the consequent increase in food demand, the need for intensive agriculture and the resulting increase in demand for water and for irrigation, they together have the effect of reducing the amount of available clean water, making it crucial to find and implement new strategies for improving water-use efficiency and to make the most forward-looking choices, to preserve existing water resources [4, 7]. Current legislation establishes the priority fulfilment of social consumption and ecological restrictions [8]. This circumstance forces in some cases the plants to operate in a less flexible manner and to obtain less profitability. Also, in [9] it is set that these objectives might reduce the overall plant technical efficiency. Traditional management, usage rights and European level laws can conflict with the interests of some users [10, 11]. It is often difficult to resolve a multi-objective problem, particularly when system managers cannot perceive the trade-offs among the different objectives, turning some conditions relevant to the system operation [12].

Therefore, the model for optimizing the efficient and sustainable management of a hydraulic system should include use restrictions, laws and regulations in a realistic representation of the study system. The optimization model implemented in this thesis is applied to two basins: Guadalquivir River in Andalusia, southern Spain, and Chiese River, northern Italy. These two basins have very different characteristics. Guadalquivir basin is in one of the most arid regions of Europe [13]. However, water management in this region also results in one of the continent's most productive agricultural areas [14, 15]. The high productivity, population density and scarcity of resources have required the construction of dams for better water resource management and flood control. Three types of reservoirs are used in the basin: traditional hydro-generation reservoirs, run-of-river plants and water supply reservoirs without hydro-generation. Among all countries with integrated basin organizations for managing water resources, the Guadalquivir Valley is one of the largest [16]. Recently, climate change has negatively affected the resources availability in this study area [17]. Research aims to provide tools for the management of this river basin, considering the particular restrictions of it and including all participants in a coordinated management [1-3], [18].

The influence of transmission constraints and zonal prices on optimal hydro dispatching has not been frequently considered in the literature. Italian power system has more than 20 GW of hydroelectric capacity, mostly in the Northern region. The particular geographic characteristics of the country and the location of generations and demand may cause transmission congestions in some hours of the day, restricting the electrical flows between Northern and other regions. In these congestion hours, the price in the Northern region is different from those of the other Italian regions. To deal with congestions, Italian electricity market splits into several areas that define critical sections, where congestions are considered more probable. Hydro plants in Chiese river basin have fundamental influence in Northern region, when transmission lines are congested, and can affect the zonal prices. Therefore, optimal market solution and hydro generation dispatch of the plants is difficult to determine.

In the present thesis, optimal alternatives for improving the management of the two previous basins are proposed and analysed.

1.2 Phases scope and objectives

The purpose of this work is to develop a tool to help watershed management with hydroelectric generation under heavy social, environmental, legal and climate restrictions of use. Appropriate management of available water resources is critical in water scarce areas. The effects of global climate change may exacerbate this problem. Achieving optimal water allocation for multi uses utilization is important for water management and is rather complicated, as some mathematical relations between variables are nonlinear. This is a problem of optimization with several commitments: to obtain economic profits, to meet European and local regulations and to fulfil consumption requirements, basin rights of use and environmental flows. The proposed model represents, in a realistic way, two river basins with strong restrictions of use and management. In the same study, an estimative of consumptive and non-consumptive costs is performed. Other basins with less or equal number of restrictions can be represented by using the proposed model.

For the integration of these diverse purposes, a model including the main constraints affecting the study basins is implemented. One of the main difficulties to achieve common goals is to reach an adequate degree of coordination and collaboration for all the parties involved. To achieve this collaboration, in this work coordinated management is assumed, ensuring compliance with the basin requirements and achieving the maximum individual benefits, within the possibilities offered by existing resources.

Other objective of this research is to run the implemented models with commercial solvers, widely available and proven, allowing the diffusion and comparison of the proposed methodology.

These purposes and the realistic representation of the basins in the mathematical model have been carried out in several stages. Each one of these stages allows reaching a goal, as the basis for developing a robust, versatile, and effective model. The stages of this process are represented schematically in following tables.

TABLE 1.1: FIRST STAGE

FIRST STAGE	
SUPPORT	Matlab
SOLVER	fmincon
THE ANALYZED BASIN	Head of the river Guadalquivir
Number of hydro power plants(HPP's) considered	4 HPPs
INTERVAL STUDY	T= 24 hours
KEY STRENGTHS	
RESTRICTIONS	MODELLING THROUGH
Spatial and temporal coordination of hydro power plants	Actual values for water travel times between different plants are considered
Social consumption	Equations for human consumption with typical values for the watershed study are included.
Legal restrictions that establish the mandatory environmental flows	Ecological flow equations with the values established by regulations are included.
Geographical disposition	Influx is considered only in the hydro power plants in the basin's head
Different types of hydro power plants	Two modes of operation are considered: traditional hydro power plant and run of river.
Realistic representation of the reservoirs' system	Nonlinear relationships in height vs stored volumes are used.
CPU time: 1200 minutes	

The optimal planning of plants in a basin presents significant challenges, due to the technical interrelationships between the plants in the basin. Hydro plants in a basin cannot be considered as independent producers in the market, because the availability of energy in one of the plants depends on the ability to store water, the proper water inflows and the water delivered by upper hydro plants into the basin. Water delivered by upper hydro plants is available for production in lower hydro plants after travel times. In Guadalquivir basin, these travel times are considerably long. Therefore, the objective on this initial stage is to create a model allowing the coordinated management of HPPs in a basin with adequate representation of the hydro system. In this initial case, human consumptions and ecological flows are considered, in a nonlinear optimization problem. The model is implemented in Matlab, requiring considerable cpu time for attaining the solution. The results of this work were partially presented in “On the Optimization of the Short-Term Operation of a Spanish Hydro Basin”, MixGenera 2011, http://electrica.uc3m.es/geste/Anteriores/MixGenera2011es.html, and published in the paper "On the Short-Term Optimisation of a Hydro Basin with Social Constraints", Computational Water, Energy, and Environmental Engineering, Volume 2, Issue 1, Jan. 2013, http://dx.doi.org/10.4236/cweee.2013.21002. After this initial stage, the following challenges are detected: high cpu time, small number of plants (considered unrepresentative respect to the whole basin) and simple relationship between the market and the hydro producers.

TABLE 1.2: SECOND STAGE

SECOND STAGE	
SUPPORT	Matlab
SOLVER	linprog
THE ANALYZED BASIN	Chiese's Valley
Number of hydro power plants(HPP's) considered	4 HPPs
INTERVAL STUDY	T= 24 hours
KEY STRENGTHS	
RESTRICTIONS	MODELLING THROUGH
Calculation the optimal generation of hydro plant maximizing their profit	A Hydro Generation block with the specific characteristics of the watershed study was created.
Determine the equilibrium prices for the Italian market	A model for an adequate representation of the market study was used
Influence of transmission constraints and zonal prices on optimal hydro dispatching	A nested algorithm based on the integration of the Hydro Generation block and a model with an adequate representation of the market was created
The effect of a nested algorithm to maximize social welfare of the system	Nested algorithm was applied to a real basin in the Chiese river (Northern Italy) with high frequency of congestions in the Transmission System
CPU time: 4 minutes for hydro generation block	

In the second step, a new two-steps nested algorithm for calculating the optimal energy bids of a set of HPPs, considering the possibility of congestions due to active restrictions in the transmission lines, is developed. The nested algorithm is instrumented on the integration of an adequate representation of the market (based on [19]) and an adequate optimization of the considered hydro plant operation in the basin (based on the model presented in the previous stage of the research, [20]). The Italian market representation was performed in collaboration with researchers of the Energy Department, Polytechnic of Milan, Italy. The hydro model was improved and adapted to the characteristics of the studied basin. Human consumption and environmental flows are not considered, because they are not applicable in this basin. A significantly improvement in CPU time, relative to the hydraulic model of the previous stage, is reached. For this, a successive linear algorithm is developed, reducing the computational effort related to solve large nonlinear optimization problems. The algorithm was applied to the basin of Chiese River (Northern Italy) wanting to analyse the high frequency of congestions in the Italian Transmission System and the influential position of hydro plants in the region. Results were partially published of in the paper "Optimal scheduling of a hydro basin in a pool-based electricity market with consideration of transmission constraints", Electric Power Systems Research, Elsevier, 2016, http://www.sciencedirect.com/science/article/pii/S0378779615003193.

TABLE 1.3: THIRD STAGE

THIRD STAGE	
SUPPORT	GAMS
SOLVER	CONOPT
THE ANALYZED BASIN	Guadalquivir basin
Number of hydro power plants(HPP's) considered 18 HPPs	14 HPP, traditional hydropower plants
	2 HPP, run-of-river hydropower plants
	2 HPP, human consumption without turbines
INTERVAL STUDY	T= 72 hours
KEY STRENGTHS	
RESTRICTIONS	MODELLING THROUGH
To develop a versatile model with short cpu time and simple application to any basin.	The model is implemented in a commercial solver, CONOPT under GAMS.
To search for realistic and representative results	The number of coordinated hydro power plants is increased, until 18 HPP's.
Greater profitability and coordination of resources and structures.	The reservoirs used only for supply are included in the coordinated management.

Realistic representation of the morphology of reservoirs.	Equations relating to height, volume and performance reserve are included.
To represent management restrictions.	Normative values of environmental flows are included.
	Typical values for human consumption are considered.
Long travel times in the basin.	The horizon is increased to 72 hour.
Scarcity and high variability of resources.	200 average influx scenarios, based on historical data, are considered.
CPU time: 2 minutes to run 200 scenarios.	

This step aims to provide a tool for the coordinated management of a large basin with ecological restrictions, human consumption, governmental regulation on water resource allocation, different technical characteristics of hydropower plants, high variability of resources and wanting the maximum hydropower production profits. The developed tool is versatile, solved in a commercial solver, widely available and proven (CONOPT, in GAMS) [21]. In order to obtain representative results of the basin, a larger number of hydro power plants is considered, including reservoirs without electric generation. The nonlinear model of relationships between height, reserve volume and performance is represented by successive linear approximation curves, achieved without using binary variables in the formulation. The extension of Guadalquivir basin requires an extended horizon of 72 hours, for short time optimization. Also, the variability of resources in this horizon requires using statistical analysis, based on historical data. The computation time for 200 scenarios is approximately 2 minutes. The mathematical model is presented in “On the operational optimization of large hydrological basins”, Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2016, http://dx.doi.org/10.1109/SPEEDAM.2016.7525998 (indexed by IEEE Xplore) and statistical and optimization results are partially included in the paper “Hydropower Scheduling of a Basin with Stochastic Inflow and Heavy Ecological and Human Restrictions in a Mediterranean Environment”, submitted for publication.

1.3 Thesis structure

Chapters 2, 3 and 4 have been written as independent articles with its own abstract, introduction, notation and bibliography, and can be independently read. Each one corresponds to results obtained sequentially in the development of this thesis, and these have been published or submitted to international journals.

In Chapter 2, first step of the research in Guadalquivir basin is developed, as presented in Table 1.1. In Chapter 3, the Chiese basin is analysed, with the characteristics included in Table 1.2. Chapter 4 presents an improved management tool for Guadalquivir basin, as presented in Table 1.3. Conclusions of the research and proposed further works are included in Chapter 5.

1.4 References

[1] N. B. Harmancioglu, F. Barbaros and C. P. Cetinkaya. Sustainability issues in water management. Water Resour. Manage. 27(6), pp. 1867-1891. 2013.

[2] W. W. Yeh. Reservoir management and operations models: A state-of-the-art review. Water Resour. Res. 21(12), pp. 1797-1818. 1985. . DOI: 10.1029/WR021i012p01797.

[3] R. G. Evans and E. J. Sadler. Methods and technologies to improve efficiency of water use. Water Resour. Res. 44(7), 2008.

[4] A. Singh. An overview of the optimization modelling applications. Journal of Hydrology 466–467(0), pp. 167-182. 2012. . DOI: http://dx.doi.org/10.1016/j.jhydrol.2012.08.004.

[5] A. J. Wood and B. F. Wollenberg. Power Generation, Operation, and Control 2012.

[6] G. Steeger, L. A. Barroso and S. Rebennack. Optimal bidding strategies for hydro-electric producers: A literature survey. Power Systems, IEEE Transactions On 29(4), pp. 1758-1766. 2014.

[7] I. F. García-Tejero, V. H. Durán-Zuazo and J. L. Muriel-Fernández. Towards sustainable irrigated mediterranean agriculture: Implications for water conservation in semi-arid environments. Water Int. 39(5), pp. 635-648. 2014.

[8] European Small Hydropower Association (ESHA). (). Small Hydropower roadmap. Condensed research data for the UE-27. DOI: http://streammap.esha.be/fileadmin/documents/Press_Corner_Publications/SHP Roadmap_FINAL_Public.pdf.

[9] J. I. Pérez-Díaz and J. R. Wilhelmi. Assessment of the economic impact of environmental constraints on short-term hydropower plant operation. Energy Policy 38(12), pp. 7960-7970. 2010.

[10] K. Bakker. From state to market?: Water mercantilización in spain. Environ. Plann. A 34(5), pp. 767-790. 2002.

[11] W. A. Blomquist, A. Dinar and K. Kemper. Comparison of institutional arrangements for river basin management in eight basins. World Bank Policy Research Working Paper (3636), 2005.

[12] J. Chang, T. Bai, Q. Huang and D. Yang. Optimization of water resources utilization by PSO-GA. Water Resour. Manage. 27(10), pp. 3525-3540. 2013.

[13] Intergovernmental Panel on Climate Change, (IPCC). (). Fifth Assessment Report - Impacts, Adaptation and Vulnerability.

[14] J. P. Parra, J. C. L. Hernández and M. D. F. Fernández. La agricultura del sureste: Situación actual y tendencias de las estructuras de producción en la horticultura almeriense. Mediterráneo Económico (2), pp. 262-282. 2002.

[15] S. R. Downward and R. Taylor. An assessment of spain's programa AGUA and its implications for sustainable water management in the province of almería, southeast spain. J. Environ. Manage. 82(2), pp. 277-289. 2007.

[16] A. Bhat and W. Blomquist. Policy, politics, and water management in the guadalquivir river basin, spain. Water Resour. Res. 40(8), pp. - W08S07. 2004. . DOI: 10.1029/2003WR002726.

[17] V. A. Barber, G. P. Juday and B. P. Finney. Reduced growth of alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature 405(6787), pp. 668-673. 2000.

[18] C. Lyra and L. R. M. Ferreira. A multiobjective approach to the short-term scheduling of a hydroelectric power system. Power Systems, IEEE Transactions On 10(4), pp. 1750-1755. 1995. . DOI: 10.1109/59.476038.

[19] A. Berizzi, C. Bovo, M. Delfanti, E. Fumagalli and M. Merlo. Simulation of a bid-based dispatch subject to inter-zonal transmission constraints. Presented at Power Tech Conference Proceedings, 2003 IEEE Bologna. 2003, .

[20] G. Hermida and E. D. Castronuovo. On the short-term optimisation of a hydro basin with social constraints. Computational Water, Energy, and Environmental Engineering 2(01), pp. 9. 2013.

[21] A. S. Drud. CONOPT—A large-scale GRG code. ORSA Journal on Computing 6(2), pp. 207; 207-216; 216. 05.

Chapter 2.

On the Short-Term Optimisation of a Hydro Basin with Social Constraints

Abstract— **In this chapter, an optimisation problem for calculating the best energy bids of a set of hydro power plants in a basin is proposed. The model is applied to a real Spanish basin for the short-term (24-hour) planning of the operation. The algorithm considers the ecological flows and social consumptions required for the actual operation. One of the hydro plants is fluent, without direct-control abilities. The results show that the fluent plant can be adequately controlled by using the storage capacities of the other plants. In the simulations, the costs related to the social consumptions are more significant than those due to the ecological requirements. An estimate of the cost of providing water for social uses is performed in the study.**

Contents

2.1 Introduction

Nowadays, the utilisation of water for electricity production is conditioned by many constraints. In Spain, primarily the Kyoto Agreements and the proposals of the European Commission to 2020 must be considered. The European Commission have specified a goal of 20% of the final energy consumption delivered from renewable sources by 2020 [1]. In Spain, 38.6% of the electricity generation comes from renewable resources, mainly from hydro (17.4%) and wind (16.6%) generation [2]. Because electricity generation has to compensate for other non-renewable energy consumptions, electricity production must increase its share of renewable generation. Hydro production is a mature renewable technology that can help reach the ambitious objectives proposed by the European Commission by 2020.

In addition, the exceptionally variable weather conditions of the past few years, most likely due to climate change, complicate the management of water for electricity production. The scarcity and the high variability of water resources have recently reduced the profits in several zones [3-6].

Many studies have been performed to calculate the optimal operation of a hydro basin. In long-term planning, Soares and Carneiro [7] consider the operation planning of a hydrothermal power system in Brazil. The paper highlights the importance on the control of the head hydro power plants (HPPs) in the basin. Granville et al. [8] consider the stochastic characteristics of the problem, including a representation of the market. The solution algorithm is based on stochastic dual dynamic programming. Cheng [9] applies particle swarm optimisation and dynamic programming for a large scale hydro system in China. Oliveira, Binato and Pereira [10] present two techniques: the extension of a binary disjunctive technique and screening strategies for planning studies in Brazil and Bolivia. Fosso et al. [11] give an overview of the planning tool used in Norway for long, medium and short horizons. Kanudia and Loulou [12] propose a stochastic version of the extended market allocation model for a hydro system in Québec, Canada.

In medium- and short-term planning, Habibollahzadeh and Bubenko [13] compare different mathematical methods: Heuristic, Benders and Lagrange methods for hydroelectric generation scheduling in the Swiss system. Castronuovo and Peças Lopez [14] describe economic profits of the coordination of wind and hydro energies. Zhao and Davison [15] analyse the inclusion of storage facilities in a hydro system, demonstrating the sensitive dependences between some of the parameters of the hydroelectric facility, the expected prices and water inflows. Pousinho, Mendes and Catalão [16] propose a mixed-integer quadratic programming approach for the short-term hydro scheduling problem, considering discontinuous operating regions and discharge ramping constraints. Simopoulos, Kavatza and Vournas [17] propose a decoupling method, dividing the hydrothermal problem into hydro and thermal sub-problems, which are solved independently. A Greek system is analysed in the study. Diniz and Piñeiro Maceira [18] use a four-dimensional piecewise linear model for the generation of a hydro plant as a function of storage, turbined and spilled outflows. Shawwash, Thomas and Denis Russell [19] discuss the optimisation model used in the British Columbia hydro system for hydrothermal coordination.

Most of the available reports about the optimal programming of hydro generation have been published in countries with abundant water Norway [11], Brazil [10], Canada [15], USA [19]. In the algorithms reported by these studies, the restrictions on the social use of water and the ecological minimum flows are either minimally considered or not considered at all, aiming at improving the utilisation of the abundant resource in a strictly economical environment. In Spain, the focus of the present study, ecological flows and social uses of water must be considered for the optimal utilisation of the resource. Pérez-Díaz and Wilhelmi [20] want to assess the economic impact of environmental constraints in the operation of a short-term hydropower plant. For that purpose, a revenue-driven daily optimisation model based on mixed-integer linear programming is applied to calculate the optimal operation of a HPP in the northwest area of Spain. In a more recent paper, Pérez-Díaz et al. [21] propose adding a pumping capability to improve the economic feasibility of an HPP project, always fulfilling the environmental constraints imposed on the operation of the hydropower plant.

This chapter presents an optimisation algorithm for calculating the optimal energy bids of a set of HPPs, including the economic objectives for energy generation and the regulations concerning the use of water in the region. The algorithm is applied to the upper Guadalquivir Basin, an area with scarce resources and variable flows, over a 24-hour horizon. Four HPPs are considered in the analysis. Three of them have storage capacity and the other one is run-of-the-river, without directly controllable alternatives. All of the plants are operated jointly with a unique owner or dispatcher (as in current practical operation). Actual data from real power plants and markets are considered in this study, including the travel times of the water (TTW) between the HPPs. The results show that the fluent plant can be controlled to achieve optimal operation by using the upstream HPPs.

Moreover, an estimate of the costs of providing water for social uses (as a function of reductions in profits from selling the electricity produced in the market) is made in this study.

2.2 Rules applicable to the Hydro Generation

2.2.1 Regulations Concerning the Use of Water for Electricity Generation.

The Water Framework Directive [22] establishes a European Community framework for water protection and management. The objectives of this regulation are the prevention and reduction of pollution, promotion of sustainable water use, environmental protection, improvement in aquatic ecosystems and floods and drought mitigation. This norm was adapted to Spanish regulations by [23]. In this directive, the priorities regarding the use of water are fixed. Electricity generation is third in the order of precedence, after the use of water by the population and irrigation requirements. Additionally, this norm specifies the requirement of a Hydrological Plan for each basin or hydrological zone. In [24], the hydro regulations for the Andalucia region (the area considered in this study) are specified. The Guadalquivir Hydrographic Confederation (http://www.chguadalquivir.es) is the organisation designed to control the Guadalquivir basin. This organisation's website features historical data regarding affluences and other hydro information. The minimum levels of flows (ecological flows) are also specified for several points of the river.

2.2.2 The Daily Energy Market

In Spain, the electricity market has been deregulated since 1997 (Electricity Industry Act, [25]). Some renewable productions have special incentives for their production (Royal Decree 661/2007) [26]. However, large or pre-existing hydro plants must auction their production in the conventional market without renewable bonuses and, practically, without special market regulation. This is the situation faced by the plants addressed in the present study.

The Spanish energy market is organised into the following sub-markets: futures market, daily market and several intra-daily markets. More than 95% of energy transactions and more than 80% of the economic volume are traded in the daily market [27]. There are also other markets that can affect hydroelectric production, such as the reserve and restriction management. For clarity, in this work, only daily market participation will be considered.

In the daily market, producers and consumers make their offers, in terms of energy quantity and prices for each hour of the D+1 day. The Market Operator oversees the buying and selling of bids using a simple cassation model [28,29]. The present chapter presents a method to calculate the optimal bids for energy over a 24-hour horizon of the hydro plants in the basin, assuming that the expected prices in these hours are known:

2.3 Mathematical formulation

2.3.1 Flow chart

In Fig. 2.1, the flow chart of the algorithm is presented.

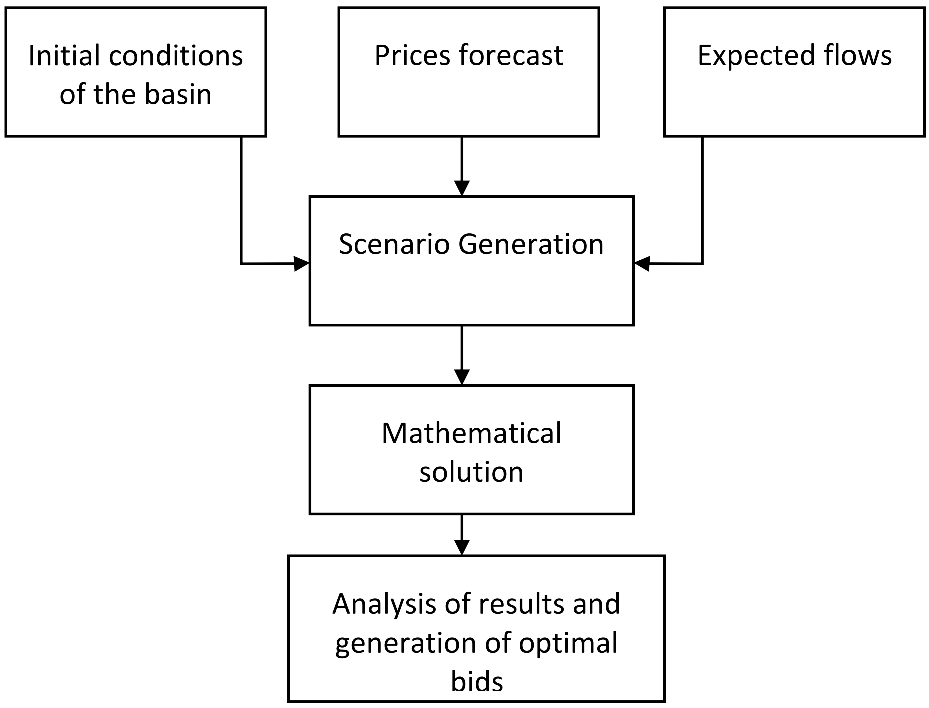


Fig. 2.1. Flow chart of the proposed algorithm

The initial conditions of the basin (level of stored water in the reservoirs, current flows, etc.) are known at the beginning of the study. Moreover, the expected flows in the analysed period can be considered known or estimated. The expected flows are depending also of the medium term planning for the operation of the basin. In the present study, an estimation of the prices in the market, for all the hours of the next day operation, is required. This prediction can be obtained from forecasting tools, outside the scope of the present study. With the knowledge of the initial condition, the price forecast and the expected flows, a scenario can be developed. In the present analysis, a determinist approach is used. However, the present method can be easily extended for considering uncertainties in the prices and/or in the expected flows, by solving many probable scenarios.

When the probable scenario is determined, the optimal solution for the operation in the hydro plants in the basin must be calculated. In the present case, ecological and social constraints are also included in the analysis. In the next section, a fully representation of the optimization problem is provided. After the calculation, the optimal flows of waters and the power and energy optimal bids are obtained. For achieving the profits presented in the analysis, it is considered that all the presented bids are accepted in the market, by offering the hydro production at low prices.

2.3.2 Mathematical representation

The best operation of hydro plants in a basin can be calculated from the solution of an optimisation problem. In this problem, the restrictions to the operation are represented as mathematical constraints. The formulation of the problem is described by eq. (2.1)-(2.15).

$$\text{Max.} \sum_{i=1}^{nr+nwr} \sum_{t=1}^{T} P_{i,t} C_t \tag{2.1}$$

$$\text{s.t.} \quad V_{i,t} = V_{i,t-1} + V_{i,t}^{AF} + V_{i-1,t} - V_{i,t}^{T} - V_{i,t}^{C} - V_{i,t}^{D} \qquad i=1, \ldots, nr \tag{2.2}$$

$$V_{i,t}^{AF} + V_{i-1,t} - V_{i,t}^{T} - V_{i,t}^{C} - V_{i,t}^{D} = 0 \qquad i=1, \ldots, nwr \tag{2.3}$$

$$V_{i-1,t} = \sum_{\alpha i} \left(V_{i-1,\ t-t_v}^{T} + V_{i-1,t-t_v}^{D} \right) \quad i=1, \ldots, (nr+nwr) \tag{2.4}$$

$$V_{i,\ 1} = V_{i,\ 1}^{SP} \qquad i=1, \ldots, nr \tag{2.5}$$

$$V_{i,T} = V_{i,T}^{SP} \qquad i=1, \ldots, nr \tag{2.6}$$

$$P_{i,t} - \eta . V_{i,t}^{T} . g . h_{i,t} = \qquad i=1, \ldots, (nr+nwr) \tag{2.7}$$

$$h_{i,t} = k_{0,i} + k_{1,i}\left(V_i^U + V_i^0\right) + k_{2,i}(V_i^U + V_i^0)^2 + k_{3,i}\,(V_i^U + V_i^0)^3 \quad i=1, \ldots, (nr+nwr) \tag{2.8}$$

$$\sum_{t=1}^{T} V_{i,t}^{C} \geq V_i^{CTmin} \qquad i=1, \ldots, (nr+nwr) \tag{2.9}$$

$$V_i^{Cmin} \leq V_{i,t}^{C} \leq V_i^{Cmax} \qquad i=1, \ldots, (nr+nwr) \tag{2.10}$$

$$V_{i,t}^{T} + V_{i,t}^{D} \geq V_i^{ECmin} \qquad i=1, \ldots, (nr+nwr) \tag{2.11}$$

$$0 \leq V_{i,\ t} \leq V_i^{max} \qquad i=1, \ldots, nr \tag{2.12}$$

$$0 \leq V_{i,t}^{T} \leq V_i^{Tmax} \qquad i=1, \ldots, nr \tag{2.13}$$

$$0 \leq V_{i,t}^{D} \leq 99 \qquad i=1, \ldots, nr \tag{2.14}$$

$$0 < h_{\ i,t} < h_i^{max} \qquad i=1, \ldots, nr \tag{2.15}$$

$$t=1, \ldots, T$$

where the variables indicate the following: $P_{i,t}$, the active power injection to the grid of hydro plant *i* at hour *t*; $V_{i,t}$, the useful volume stored in the reservoir of the hydro plant *i* in the period *t*; $V_{i-1,t}$, the affluence into reservoir *i* at period *t*, coming through the river from upstream plant (or plants); $V^{T}_{i,t}$, the turbined volume at hour *t* by plant *i*; $V^{D}_{i,t}$, the deviated (spilled) volume at hour *t* by plant *i*; $V^{C}_{i,t}$, the output water consumption for social uses delivered by plant *i* at hour *t*; and $h_{i,t}$, the height of reservoir *i* at hour *t*. The following are the parameters in the optimisation formulation: C_t, the expected market price of hour *t*; $V^{AF}_{i,t}$, the individual affluence into reservoir *i* at period *t*, not considering the flows coming through the river from the previous plant; t_V, the TTW between the considered HPPs; $V^{SP}_{i,1}$ and $V^{SP}_{i,T}$, the specified volumes at the beginning and at the end of the horizon (respectively) by plant *i*; η_i, the average efficiency of the hydro plant *i*; g, the acceleration of gravity; $k_{0,i}$, $k_{1,i}$, $k_{2,i}$ and $k_{3,i}$, the coefficients relating volume and height at reservoir *i*; V_i^{U}, the unused volume for electricity generation of reservoir *i*; V_i^{CTmin}, the minimum daily requirements of water for social uses in hydro plant *i*; V_i^{Cmin} and V_i^{Cmax}, the minimum and maximum (respectively) hourly requirements of water for social uses, in plant *i*; V_i^{ECmin}, the minimum (ecological) volume to be maintained in the river downstream of reservoir *i*; V_i^{max} and V_i^{Tmax}, the maximum useful reserve and capacity of production (respectively) of hydro plant *i*; and h_i^{max}, the maximum height at plant *i*. In the equations, *nr* is the number of hydro plants with reservoirs, *nwr* is the number of fluent hydro plants (without reservoir), *αi* is the set of hydro plants upstream from the reservoir *i* and *T* is the number of discretisation steps.

The goal of the optimisation problem (2.1)-(2.15) is to calculate the optimal production of coordinated hydro plants in a basin in *T* periods and considering the expected prices in the market (2.1). Equality constraints (2.2) and (2.3) express the energy balances in the hydro plants with and without a reservoir, respectively. When the hydro plant has storage capacity (2.2), the useful volume in the reservoir can be increased by the individual affluence (rain, tributaries, etc.) and the flows coming from the immediately upstream hydro plants. Additionally, the energy stored in these plants can be reduced by electricity generation and social consumption. When large inflows enter the reservoir, a portion of the water can be deviated by using the spill way to preserve the security of the plant's operation. The amounts of useful energy at the reservoirs at the beginning and end of the programming horizon (2.5)-(2.6) are pre-specified quantities. The hydro production efficiency for power production is expressed by using a third-order polynomial equation (2.7)-(2.8), as a function of the height. In hydro reservoirs with large nonlinear relationships between the height and the stored water (equation 2.7), partial approximations by using third-order polynomial equations for each level of the reservoir can be adopted. In the present formulation, the social requirements for water are represented as minimum daily consumptions (2.9) and restrictions on hourly water flows (2.10).

The operation of the hydrological system requires maintaining the minimum ecological levels of water flows into the basin (2.11). In eq. (2.12)-(2.15), the maximum capacities of the equipment of the hydro plants are expressed.

In the present analysis, the algorithm is solved by using Matlab [30]. Equations (2.1)-(2.15) constitute a large nonlinear optimisation problem requiring (T (7nr+6nwr)) variables, (4T (nr+nwr)+2nr) equality restrictions and (T (16nr+14nwr)) inequality constraints.

2.4 The Test Case

The proposed optimisation problem (2.1)-(2.15) is applied to water management in the upper basin of the Guadalquivir River, Spain (Fig. 2.2).

Fig. 2.2. Geographical Position of the Guadalquivir Basin and Relevant Hydro Power Plants. [31]

Fig. 2.2 shows a map of the headwater of the Guadalquivir River.

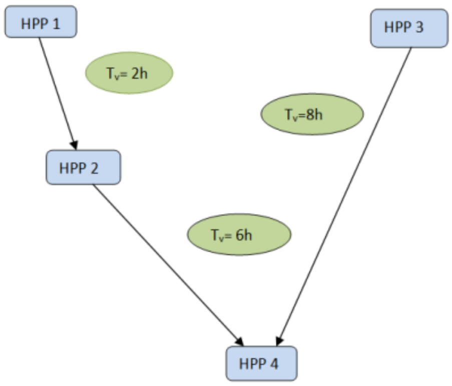


Fig. 2.3. Spatial Distribution of the Reservoirs in the Upper Guadalquivir Basin

Fig. 2.3 shows a schematic representation of four hydro power plants (HPPs). Three of them have reservoirs (HPP 1, Doña Aldonza; HPP 3, Guadalmena; and HPP 4, Marmolejo), and the other (HPP 2, Pedro Marín) is run-of-the-river. The TTW between the plants is shown in the diagram as T_v.

In the present analysis, typical prices in the Daily Market in March 2011 (a month with medium hydro production) in Spain are used to simulate the optimal operation of the hydro system (Fig. 2.4). The acceleration of gravity, g, is 9.81 m/s^2.

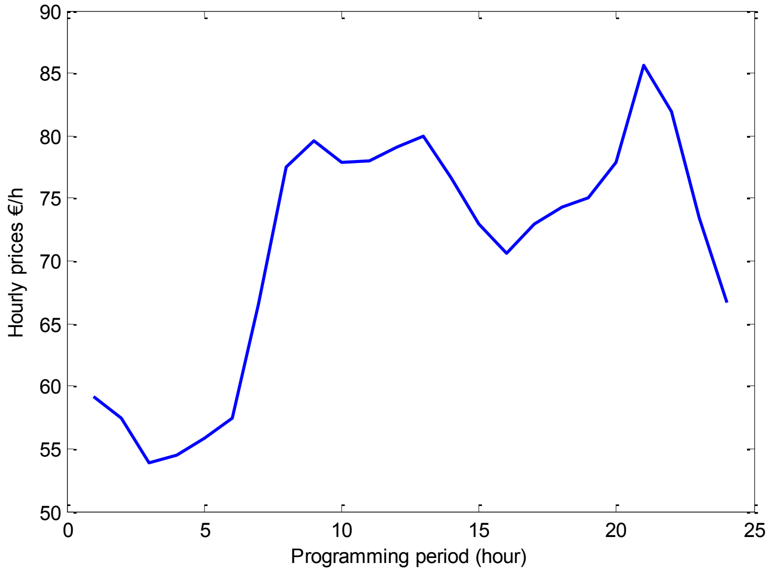


Fig. 2.4. Typical Spanish Next-Day Market Prices in March 2011

To analyse the effect of the constraints on electricity production, several cases are considered:

- ***Case A:***

  base case, in which social consumptions and ecological flows are not represented. Therefore, the optimisation problem is solved without considering equations (2.9)-(2.11).

- ***Case B:***

ecological flows are not considered. The optimisation problem is solved without equation (2.11). In this case, the social consumptions are included in the formulation.

- ***Case C:***

social consumptions are not applied. The optimisation problem is solved without equations (2.9) and (2.10). In this case, the ecological flows are included in the formulation.

- ***Case D:***

solution of the optimisation problem (2.1)-(2.15), considering both social consumptions and ecological flows.

In all of the cases, the same flow (7.944 Hm^3/day, the average flow of March 2011) is considered. The same flow (3.972 Hm^3/day in each HPP) is injected at the heads of the basin and uniformly distributed over 24 hours (0.1655 Hm^3/hour in each HPP). For simplicity in the analysis, no individual affluences ($V^{AF}_{i,t}$) in HPPs 2 and 4 are considered.

For this sample basin, assuming 24 hours of operation and hourly discretisation, the formulation described by (2.1)-(2.15) implies 648 variables, 390 inequality constraints and 1488 inequality restrictions.

2.5 Results

2.5.1 Base Case, without Social Consumption and Ecological Flows

In Fig. 2.5, the optimal production of the four hydro plants is shown.

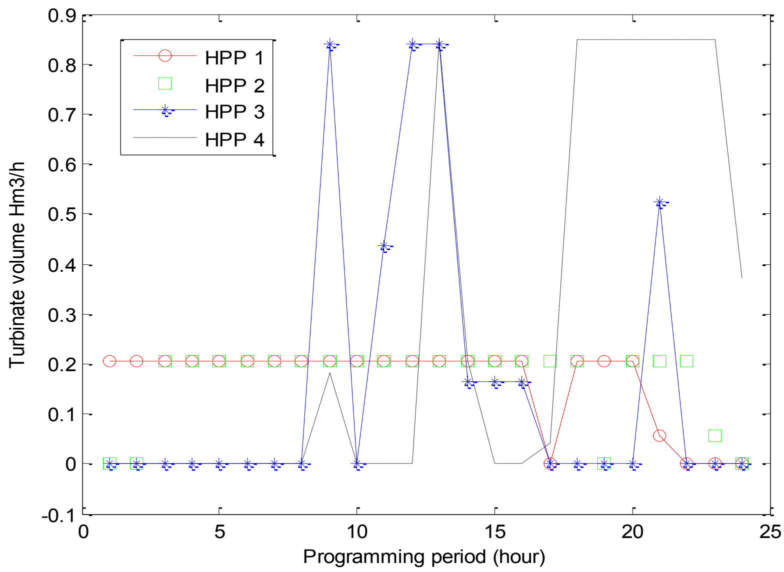


Fig. 2.5. Production in the Four Hydro Plants, Case A

The hydro plants at the head of basin (HPPs 1 and 3) put the resources into circulation, if possible, during the high-price periods in the morning. However, the behaviour of these two plants is quite different due to the TTW between the plants in the basin and the type of plants downstream. The production of HPP 1 is limited by the capacity of the run-of-the-river HPP 2 located downstream. In this scheme, all of the water entering HPP 2 is turbined, obtaining the maximum possible profit in the combined operation. HPP3, with a controllable power plant downstream (HPP 4), generates electricity during the early hours of the day at the highest prices and full capacity. The resources coming from HPP 2 and HPP 3 reach HPP 4 in time to be turbined at full power during the hours of maximum daily price. A small quantity of water is turbined by HPP 3 at the hour of the maximum price of the day, hour 21, without reaching HPP 4 during the daily horizon.

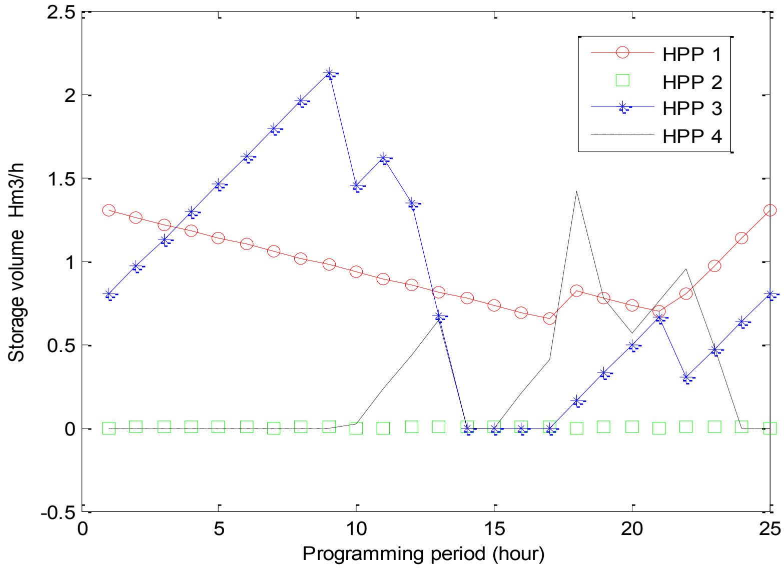


Fig. 2.6. Energy Storage in the Hydro Plants, Case A

As shown in Fig. 2.6, hydro plants HPP 1 and HPP 3 (at the heads of the basin) use the water stored at the beginning of the day to increase production during the first hours. The inflows in the heads in the evening help recover the specified final values of stored energy at the end of the day. As expected, HPP 2 has no storage capacity. HPP 4 utilises its storage capabilities to wait for higher prices to sell its production in the market.

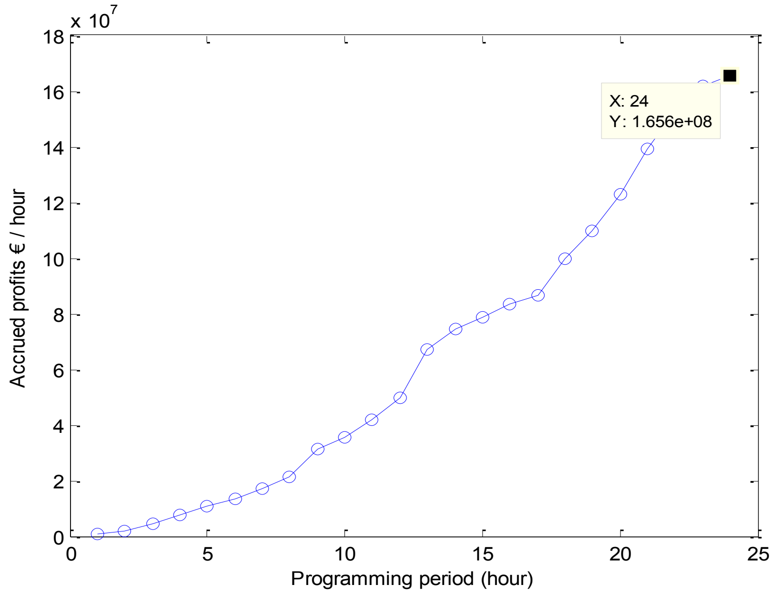


Fig. 2.7. Incremental Profits in the Basin, Case A

The reduced storage capacity of HPP 2 distributes the profits throughout the entire programming period (Fig. 2.7). A higher generation capacity in the plants would centralise the revenue only at the peaks of the price curve. The profit of the joint operation is 165.6 M€.

2.5.2 Optimal Operation Considering only Social Consumption

In this case, the effect of social consumption is studied. Social-consumption values are required in all of the plants.

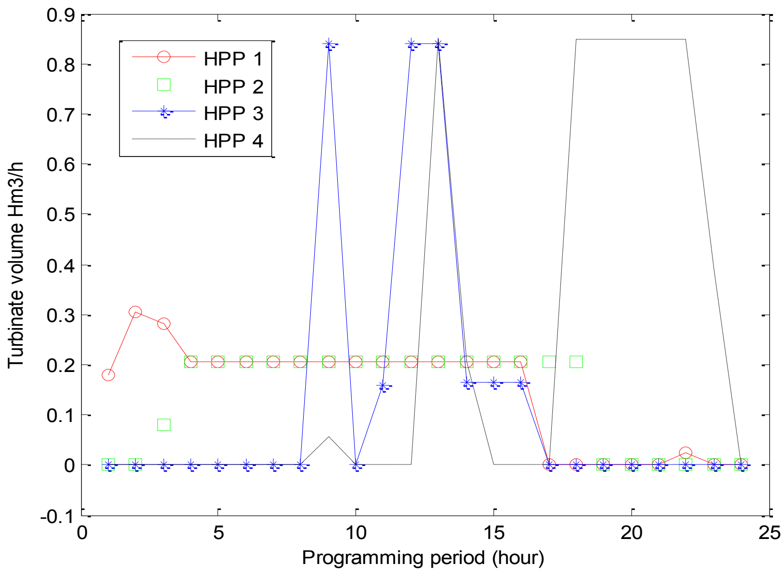


Fig. 2.8. Production in the Hydro Plants, Case B

Fig. 2.8 shows that at the beginning of the day HPP 1 turbines more than the maximum generation capacity of HPP 2, delivering water for social consumption to HPP 2 and HPP 4. This period has the lowest prices of the day. In the other head plant (HPP 3), social requests are supplied using water with less economic efficiency, eliminating HPP 3 generation at hour 21 (Fig. 2.5). Fig. 2.9 shows the delivery of water for social uses for the four hydro plants.

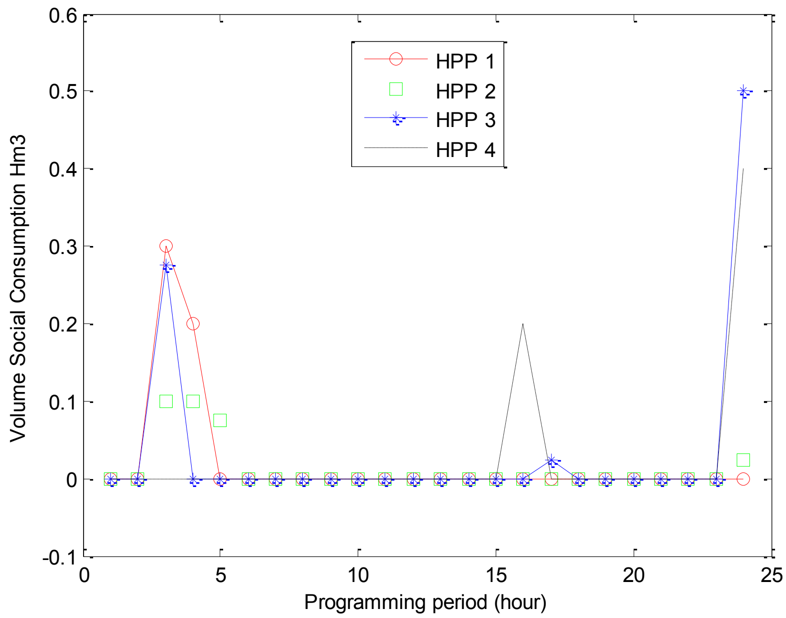


Fig. 2.9. Social Consumption, Case B

The upstream plants, HPPs 1, 2 and 3, transfer the volumes for social consumption at the beginning of the day, the period with lowest prices. HPP 4, without individual inflows, must yield to this restriction along the following minima of the price curve (hours 16 and 24). HPP 3, with the largest social consumption, also uses the minimum price at hour 24 to fulfil the social requirements.

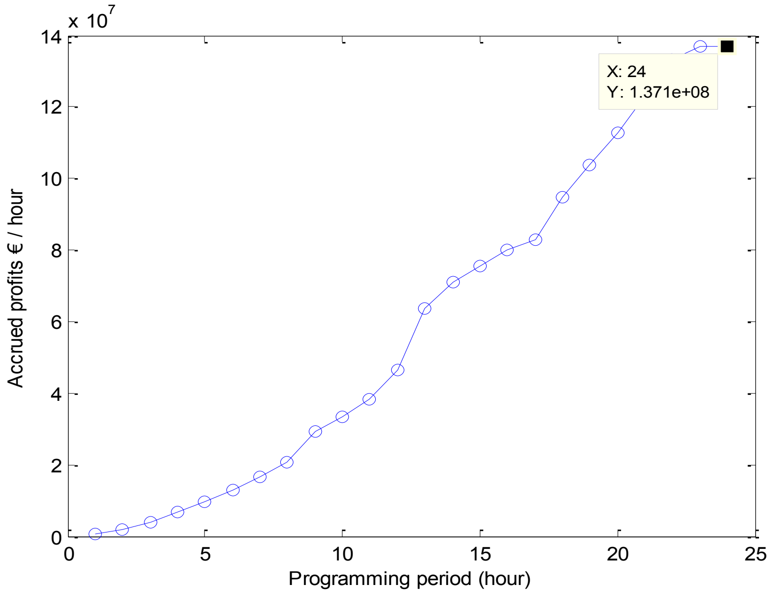


Fig. 2.10. Incremental Profits in the Basin, Case B

The profile of incremental profits is similar, considering (Fig. 2.10) or without considering (Fig. 2.7) social consumption. However, the final profits are different. When considering social requirements, the total revenue is 137.09 M€, 17.20% lower than without human consumption in the basin.

2.5.3 Optimal Operation with only Ecological Constraints

In this case, the individual impacts of the environmental restrictions (minimum flows in the river) on the profits are analysed. In the present simulations, this restriction can only be imposed at the head plants (HPPs 1 and 3). A constant value of 16 m^3/s for each plant is considered. With this value, the minimum ecological flows in all of the basins can be maintained [32], considering TTW. In Fig. 2.11, the optimal productions are shown.

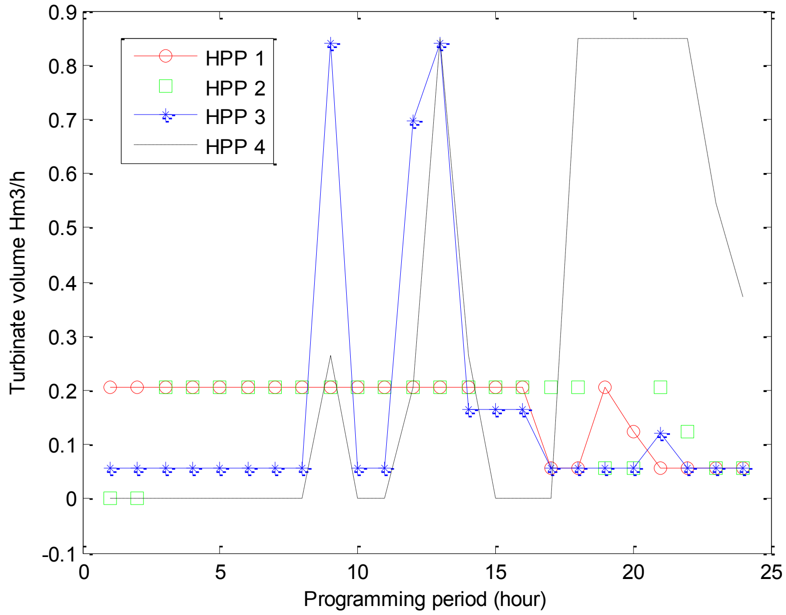


Fig. 2.11. Production in the Hydro Plants, Case C

Fig. 2.11 shows that the two head plants (HPPs 1 and 3) generate electricity at all hours of the day. As in Case A, the generation of HPP 1 is restricted by the limited capacity of HPP 2, and HPP 3 mainly generates electricity during the first high-price periods of the day.

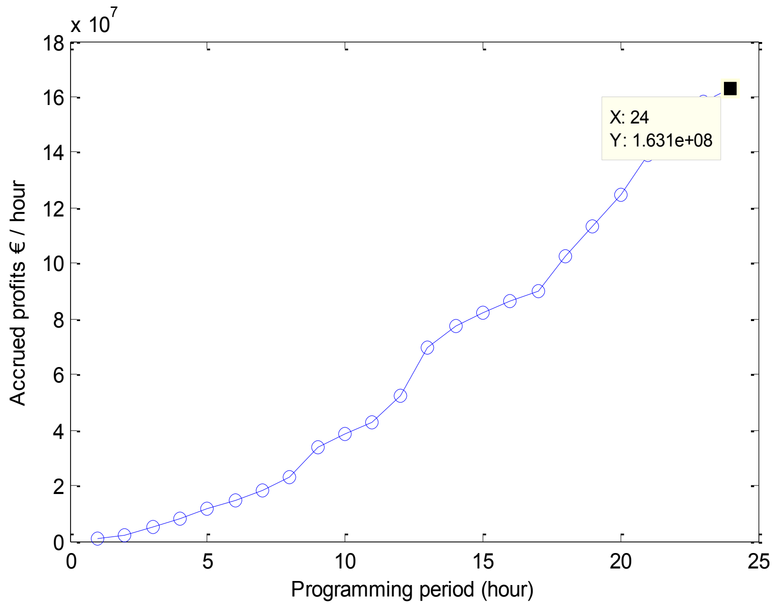


Fig. 2.12. Incremental Profits in the Basin, Case C

The ecological restrictions (minimum flow at all hours) make the slope of income almost constant (Fig. 2.12). The profile of the volume turbined becomes flatter, and therefore, there are fewer resources for producing at the hours of maximum price. The optimal profit in this case reaches 163.14 M€ (1.5% less than that without ecological restrictions). In the present simulations, the restrictions on minimum flows in the river do not significantly reduce the profit of operation. It must be stressed that these restrictions are not consumptive; they only change the generation times of head HPPs 1 and 3. However, the increase in the amount of ecological flow can reduce the total profits.

2.5.4 Optimal Operation with Social Consumption and Ecological Constraints

In this case, the effects of the two types of constraints (social consumption and minimum flows) are analysed.

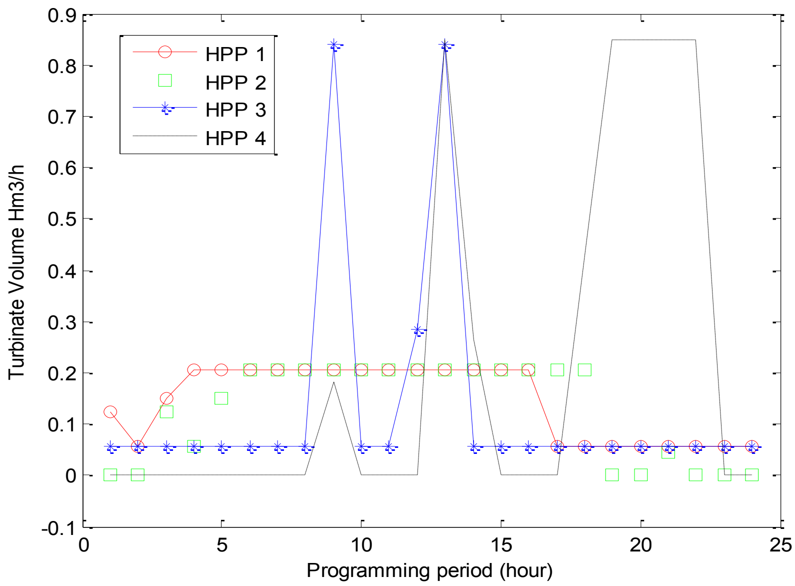


Fig. 2.13. Production in the Hydro Plants, Case D

In this case (Fig. 2.13), the optimal profiles of generation are similar to those observed in Case B (Fig. 2.8). However, some differences must be highlighted. First, the ecological minimum flows require generation at HPPs 1 and 3 during all periods. The distribution of social consumption is also dissimilar (Fig. 2.14).

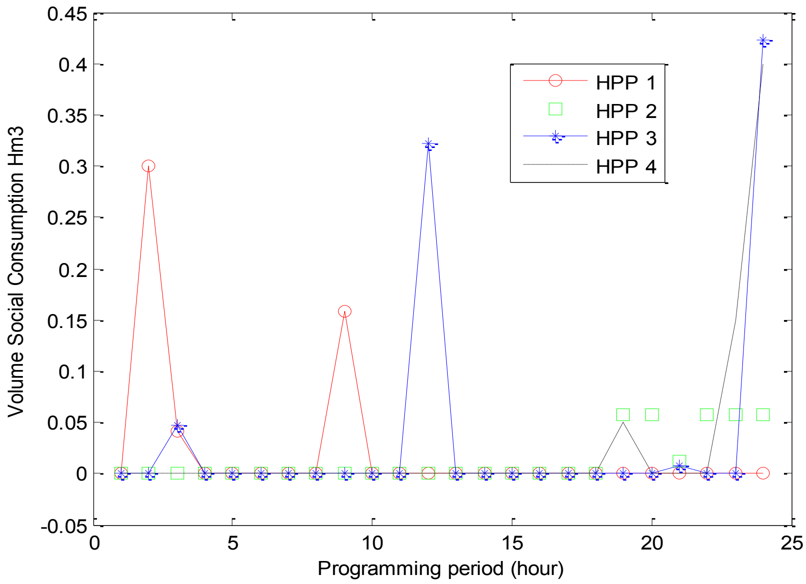


Fig. 2.14. Social Consumptions, Case D

In Case B (with social consumption but without considering ecological restrictions, Fig. 2.9), the volumes for social consumption are assigned to hours 2 to 5 in HPPs 1 and 2. The ecological flow requirement shifts the delivery of HPP 1 to hours 2 and 7 and the release of HPP 2 to the end of the day (hours 19 to 24). In HPP 3, delivery for social consumption is increased at hour 19 and eliminated at hour 24. HPP 4 continues to provide for social consumption at the end of the day (hour 24) but shifts to small delivery from hour 16 to 15. These changes optimise the utilisation resources, increasing the combined profit of the operation. However, the optimal income in this case is 129.90 M€, 21.54% less than that of the base case (without social restrictions and ecological constraints).

2.5.5 Comparison of the Analysed Cases

As previously discussed, the economic results of the previous section depend on the type of restrictions added to the base case. Minimum flows in the river can be maintained without a loss of resources, only changing the time of generation. However, the social uses of water are consumptive constraints, extracting resources from the basin. Moreover, the economic results are a function of the amount of available resources. Therefore, three different scenarios are compared here: dry, medium and wet scenarios, for the two types of restrictions. The medium value coincides with the previous affluence (7.94 Hm^3/day). For comparison purposes, all of the results are obtained by maintaining the data previously used, in particular, the price profile shown in Fig. 2.3.

- ***Results considering only Ecological Constraints***

In the present simulations, the ecological requirements of Table 2.1 (1.6 m^3/s in HPPs 1 and 3) are maintained. However, the effect of the ecological constraints is evaluated in three different situations of affluence.

TABLE 2.1: COSTS OF ECOLOGICAL REQUIREMENTS FOR DIFFERENT INFLOWS

Flow in HPPs 1 and 3 (Hm^3/day)	Income, Case A. (M€)	Income, Case C. (M€)	Income Gap. (M€)	Relative Ecological Costs, (€/Hm^3)	Relative Ecological Cost, (€/Hm^3)
12.47	228	227	1.4	112,549	507,646
7.94	166	163	3	305,253	877,073
3.42	80	67	13	3,801,169	4,947,837

In Table 2.1, the first column shows the total inflow in the basin injected in head HPPs 1 and 3. The second and third columns show the optimal incomes obtained without considering or including the ecological constraints (eq. (2.9)-(2.11)), respectively. The economic difference between the two previous cases is represented in the fourth column. In the fifth column of the table, the relative cost of the ecological constraints, for each Hm^3 of inflow in the head HPPs, is calculated. Finally, the sixth column shows the relative cost of the ecological constraints, for each Hm^3 of minimum flow requested at the head HPPs of the basin. In this Table, it can be seen that the cost of maintaining the ecological constraints depends on the amount of resources injected to the basin. In Fig. 2.15, the curve of variation in the ecological cost (EC) as a function of the affluence is presented.

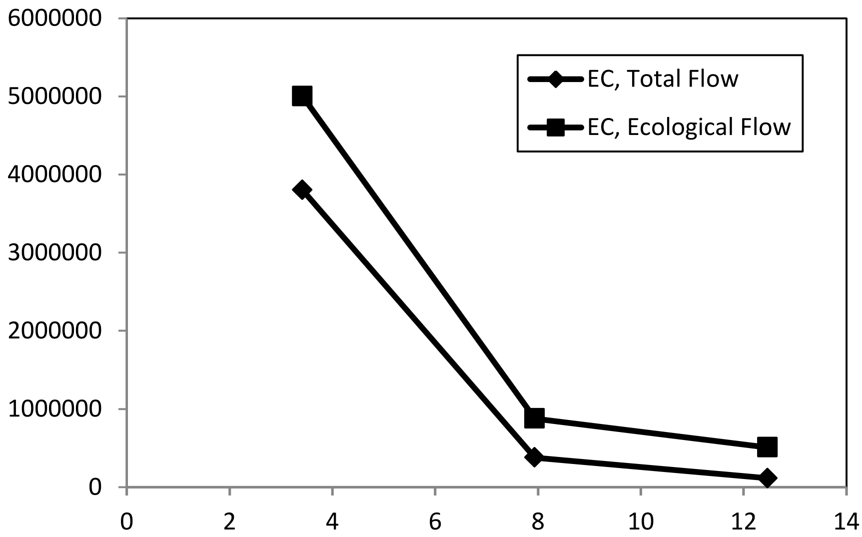


Fig. 2.15. Cost of Ecological Requirements for Different Inflows

As shown in Table 2.2 and Fig. 2.15, the cost of maintaining the ecological requirements is far more important in dry scenarios. In fact, maintaining the same ecological flow of 3.42 Hm^3/day is relatively ten times more expensive than maintaining a flow of 12.47 Hm^3/day.

- ***Results Considering only Social Consumptions***

In the present section, the effect of social consumption in the three previous scenarios of affluence is considered.

TABLE 2.2: SOCIAL CONSUMPTION COSTS FOR DIFFERENT INFLOWS

Flow in HPPs 1 and 3(Hm^3/day)	Income, Case A. (M€)	Income, Case B. (M€)	Income Gap. (M€)	Relative Social Consumption Cost M€/Hm^3)	Relative Social Consumption Cost (M€/Hm^3)
12.47	228	208	20	2	9
7.94	166	137	29	4	13
3.42	80	38	42	12	19

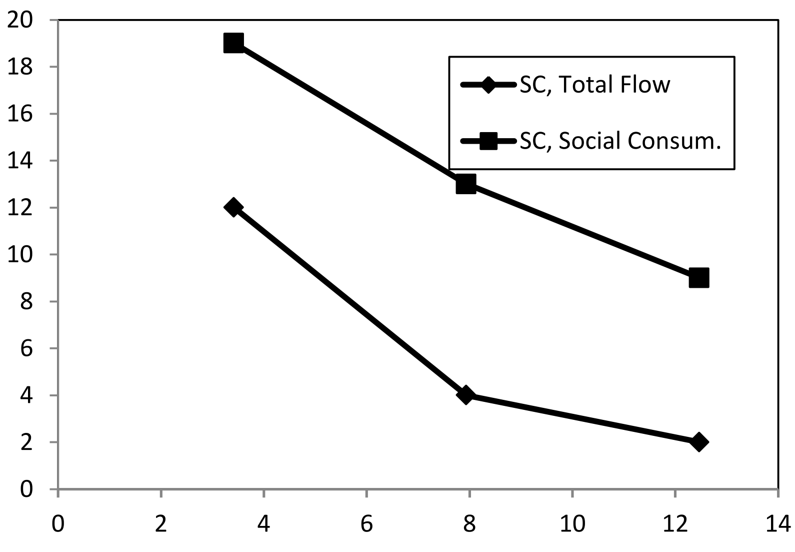


Fig. 2.16. Social Consumption (SC) Costs for Different Inflows

Table 2.2 has the same structure as Table 2.1 but considers the costs of water delivered for social consumption. According to the two tables, the costs of water allocated for social uses are larger than those of maintaining the ecological constraints. In fact, for the medium scenario, the reduction in profit due to the social uses of water is 967% greater than the decrease in revenue due to the ecological constraints. Social uses extract resources from the basin; the ecological constraints only request a modification in the profile of generation, but the resource remains in the river.

In Fig. 2.16, the relative social consumption costs for the three scenarios of affluence are shown. The curve SC, Social Consum., shows the cost of delivering 1 Hm^3 of water from the basin for social uses in the simulated scenarios. The values of this curve can be used to calculate the price of water allocated for human use in the basin as a function of the profits lost in electricity generation

2.6 Conclusion

This chapter presents an optimisation method to calculate the optimal operation of a basin with both controllable and non-controllable hydro power plants. This program considers both social and ecological restrictions, assessing the economic weight of each of them in the management of resources.

The algorithm allows for control over the actions of fluent HPPs, modifying the operation of controllable HPPs. The method calculates the maximum profit electricity generation in the daily power market, considering ecological constraints and the social use of water.

The study of different inflow states shows that in this case the relative value of the social consumption of water is larger than that of maintaining ecological flows in the basin. Moreover, initial evaluations of the costs of providing water for social uses are performed. The proposed algorithm can be easily extended to consider other operational restrictions on the hydro systems.

2.7 References

[1] European Parliament and of the Council, Directive 96/92 of December 19, 1996. Concerning common rules for the internal market in electricity and repealing Directive 96/92/EC. Available: http://www.cne.es/cne/doc/legislacion/Directiva96_92.pdf.

[2] The Spanish Electric System 2010 (in Spanish). Red Eléctrica de España (REE). Madrid, Spain, 2011.

[3] R. Sternberg. Hydropower: Dimensions of social and environmental coexistence. Renewable Sustainable Energy Reviews 12(6), pp. 1588-1621. 2008.

[4] M. Markoff and A. Cullen. Impact of climate change on pacific northwest hydropower. Climate Change 87(3/4), pp. 451-469. 2008.

[5] H. I., T. D. and H. T. A comparison of stochastic and deterministic downscaling methods for modeling potential groundwater recharge under climate change in East Anglia, UK: Implications for groundwater resource management. Hydrogeol. J. 17(7), pp. 1629-1641. 2009.

[6] M. Marie, B. François, K. Stéphane and L. Robert. Adaptation to climate change in the management of a Canadian water-resources system exploited for hydropower. Water Resources Management 23(14), 2009.

[7] S. Soares and A. A. F. M. Carneiro. Optimal operation of reservoirs for electric generation. IEEE Transactions on Power Delivery 6(3), pp. 1101-1107. 1991.

[8] S. Granville, G. C. Oliveira, L. M. Thome, N. Campodonico, M. L. Latorre, M. V. F. Pereira and L. A. Barroso. Stochastic Optimization of Transmission Constrained and Large Scale Hydrothermal Systems in a CompetitiveFramework . Proceedings of the Power Engineering Society General Meeting, 2003, IEEE. 2003.

[9] C. Cheng, S. Liao, Z. Tang and M. Zhao. Comparison of particle swarm optimization and dynamic programming for large scale hydro unit load dispatch. Energy Conversion and Management 50(12), pp. 3007-3014. 2009.

[10] Gerson C. Oliveira, Silvio Binato, and Mario V. F. Pereira. Value-based transmission expansion planning of hydrothermal systems under uncertainty. IEEE Transactions on Power Systems 22(4), pp. 1429. 2007.

[11] O. B. Fosso, A. Gjelsvik, A. Haugstad, B. Mo and I. Wangensteen. Generation scheduling in a deregulated system. the norwegian case. IEEE Transactions on Power Systems 14(1), pp. 75-81. 1999.

[12] A. Kanudia and R. Loulou. Robust responses to climate change via stochastic MARKAL: The case of Québec. Eur. J. Oper. Res. 106(1), pp. 15-30. 1998.

[13] H. Habibollahzadeh and J. A. Bubenko. Application of decomposition techniques to short-term operation planning of hydrothermal power system. IEEE Transactions on Power Systems 1(1), pp. 41-47. 1986.

[14] E. Castronuovo and J. A. P. Lopes. Optimal operation and hydro storage sizing of a wind-hydro power plant. International Journal of Electrical Power Energy Systems 26(10), pp. 771-778. 2004.

[15] G. Zhao and M. Davison. Optimal control of hydroelectric facility incorporating pump storage. Renewable Energy 34(4), pp. 1064-1077. 2009.

[16] H. M. I. Pousinho, V. M. F. Mendes and J. P. S. Catalão. Scheduling of a hydro producer considering head-dependency, price scenarios and risk-aversion. Energy Conversion and Management 56(0), pp. 96-103. 2012.

[17] D. N. Simopoulos, S. D. Kavatza and C. D. Vournas. An enhanced peak shaving method for short term hydrothermal scheduling. Energy Conversion and Management 48(11), pp. 3018. 2007.

[18] A. L. Diniz and M. E. P. Maceira. A four-dimensional model of hydro generation for the short-term hydrothermal dispatch problem considering head and spillage effects. IEEE Transactions on Power Systems 23(3), pp. 1298-1308. 2008.

[19] Z. Shawwash, K. Thomas, K. Siu, and S. O. Dinis Russell. The BC hydro short term hydro scheduling optimization model. IEEE Transactions on Power Systems 15(3), pp. 1125. 2000.

[20] Juan I. Pérez-Díaz, José R. Wilhelmi. Assessment of the economic impact of environmental constraints on short-term hydropower plant operation. Energy Policy 38(12), pp. 7960. 2010.

[21] J. I. Peréz-Díaz, R. Millán, D. García, I. Guisández and J.R. Wilhelmi. Contribution of regulation reservoirs considering pumping capability to environmentally friendly hydropower operation. Proceedings of the 6th. Dubrovnik Conference on Sustainable Development of Energy Water and Environment Systems, September 25 Dubrovnik, Croatia. 2011.

[22] European Parliament and of the Council, Directive 2000/60 october 28. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000, Establishing a Framework for Community Action in the Field of Water Policy. Available: http://www.madrid.org/rlma_web/html/web/FichaNormativa.icm?ID=296.

[23] Government of Spain, Ministry of the Presidency. Royal Legislative Decree 1/2001, July 20, Water Act (in Spanish). Available: http://www.boe.es/boe/dias/2001/07/24/pdfs/A26791-26817.pdf.

[24] Consejeria de Medio Ambiente. Junta de Andalucia. Royal Decree Law 1/2001, July 20 of 2011.Available: http://www.juntadeandalucia.es/medioambiente/ .

[25] CNE, Comisión Nacional de Energía. Royal Decree Law 54/1997, of November 27. Law of the Electric System (in Spanish). Available: http://www.cne.es/cne/doc/legislacion/NE_LSE.pdf.

[26] Government of Spain, Ministry of the Presidency. Royal Decree 661/2007, of May 25th, Establishing the Regulation of the Activity of the Electric Power Production in the Special Regime (in Spanish). Available: http://www.cne.es.

[27] J. M. Yusta Loyo. The electric demand in January 2011 (in Spanish). Available: http://www.unizar.es/jmyusta/wp-content/uploads/2011/01/CONTRATACION-SUMINISTRO-ELECTRICO-Enero-2011.pdf.

[28] OMEL-OMIL. Results of the Iberian Market, 2011. Available: http://www.omel.es/inicio/mercados-y-productos/mercado-electricidad/diario-e-intradiario/mercado-diario.

[29] J. Martínez-Crespo, J. Usola and J. L. Fernández. Security-Constrained Optimal Generation Scheduling in Large-Scale Power Systems. IEEE Transactions on Power Systems 21(1), pp. 321-332. 2006.

[30] MathWorks. MATLAB, The Languages of Technical Computing. Version 7.10.0.499 (R2010a). 2010.

[31] Government of Spain, Ministry of Environment. Guadalquivir's description, 2011 (in Spanish). Available: http://www.chguadalquivir.es/opencms/portalchg/laDemarcacion/guadalquivir/breveDescripcion/.

[32] Confederación Hidrográfica del Guadalquivir. Ecological flows 2011 (in Spanish). Available: http://www.chguadalquivir.es/opencms/portalchg/marcoLegal/planHidrologicoCuenca/.

Chapter 3.

Optimal Scheduling of a Hydro Basin in a Pool-Based Electricity Market with Consideration of Transmission Constraints

Abstract— **The effect of flexible hydropower management on prices is a topic widely studied in research and economic analysis. However, the influence of transmission constraints and zonal prices on optimal hydro dispatching has not been highly considered in the literature. In the present study, an iterative algorithm for calculating the optimal bids of hydro plants in a basin is proposed, considering the fundamental influence of these plants in regions when transmission lines are congested and can affect zonal prices. The results show the efficiency of the algorithm and modifications in positioning of hydro plants in the market.**

Contents

3.1 Introduction

The optimal planning of hydro producers is crucial in many power systems due to the flexible characteristics of these plants. Hydro plants produce electricity at almost null variable cost and have good controllability abilities, allowing for increased renewable source participation in the generation mix. However, the optimal planning of these plants presents significant challenges due to the technical interrelationships between plants in the basin and the influence of these producers on the electricity market.

Many studies have been performed to calculate the optimal operation of a hydro basin. In medium and short-term planning, Habibollahzadeh and Bubenko [1] applied different mathematical alternatives (Heuristic, Benders and Lagrange methods) for obtaining optimal hydroelectric generation scheduling in the Swiss system. Zhao and Davison [2] analyzed the inclusion of storage facilities in a hydro system, demonstrating the sensitivity of parameters of the hydroelectric facility, expected prices and water inflows. Castronuovo and Peças Lopez [3] described economic profit resulting from the coordination of wind and hydro energies. Pousinho, Mendes and Catalão [4] proposed a mixed-integer quadratic programming approach for a short-term hydro scheduling problem that considered discontinuous operating regions and discharge ramping constraints. Simopoulos, Kavatza and Vournas [5] proposed a decoupling method, dividing the hydrothermal problem into hydro and thermal sub-problems, which were solved independently; a Greek system was analyzed in the study. Diniz and Piñeiro Maceira [6] used a four-dimensional piecewise linear model for the generation of a hydro plant as a function of storage, turbined and spilled outflows. Shawwash, Thomas and Denis Russell [7] discussed the optimization model used in the British Columbian hydro system for hydrothermal coordination. Perez-Díaz and Wilhelmi [8] assessed the economic impact of environmental constraints in the operation of a short-term hydropower plant. A revenue-driven daily optimization model based on mixed-integer linear programming was applied to calculate the optimal operation of a hydro power plant (HPP) in the northwest area of Spain. Perez-Díaz et al. [9] propose adding a pumping capability to improve the economic feasibility of a HPP project, always fulfilling the environmental constraints imposed on the operation of the hydropower plant. Martins, Azevedo and Soares [10] propose a novel nonlinear model for medium-term hydro-thermal scheduling with transmission constraints. In this work, the IEEE Reliability Test System [11] and the Brazilian power system are used to test the proposed method. In [12], Fujisawa et al. use the Ward equivalent and DC power flow to calculate the optimal medium-term hydro-thermal scheduling of a basin.

Obtaining an adequate representation of hydro plants integrated in a basin for using in market studies is also a present challenge. Conejo et al. [13] proposed a method for calculating the self-scheduling of a hydro generating company in a pool-based electricity market. The market prices were assumed as known and the authors used a mixed-integer linear programming model for representing the nonlinear relationship between the power produced, water discharged, and head of the reservoir plants. Borghetti et al. [14] extended the analysis for a pumping storage hydro plant, also considering a fixed price for all the hours. Simoglou, Biskas and Bakirtzis [15] calculated the optimal self-scheduling of a power company with a dominant role in both the production and retail sectors of an electricity market. Mixed integer linear programming formulation was used for the representation of the plant. Angarita and Usaola [16] analyzed the problem of the combined offers of hydro and wind units to obtain the maximum profit in a joint operation. Market prices were previously known for the analysis, and the hydro plant was represented by using power and energy restrictions. Catalão et al. [17] considered a detailed nonlinear representation of a cascaded hydro system, calculating the optimal operation for specified prices in the market. Kardakos, Simoglou and Bakirtzis [18] calculate the optimal offering strategy problem of a strategic producer with sufficient number of both thermal and hydro generating units to take advantage of its strategic position. A bi-level formulation is used in the solution of this problem.

In most previous studies, the representation of the market is simplified, aiming more to improve the hydro plant modeling. However, because the schedule of hydro plants can affect market prices, a better model that includes other market participants' behavior is required. Many representations of day-ahead markets have been used in literature. In particular, the electricity market is characterized by a highly concentrated ownership structure together with an inelastic demand and limited transmission capacities, which makes it particularly sensitive to the abuse of market power. Hoobs, Metzler and Pang [19] have identified four primary distinct approaches for addressing questions concerning market power in electricity markets, namely: ex-post analyses of existing markets, market concentration analyses, laboratory experiments and modeling. Generally, it is acknowledged that these approaches cannot fully take into account the special characteristics of electricity markets such as structural, behavioural and market design factors that are related to market power. Therefore, oligopoly models have been typically used for market power analysis in electricity markets, as the special characteristics of electricity markets can explicitly be incorporated into oligopoly models. Ventosa et al. [20] have identified three main trends of electricity market modeling, namely optimization models, equilibrium models and simulation models. Equilibrium models have been extensively used for power market analysis as they are robust and flexible and have the potential to apply to very large systems. A detailed survey on equilibrium power market models can be found in [21] and [22]. Equilibrium models differ in many ways, including market mechanisms simulated, modeling of the electric network and the type of strategic interaction or game assumed. The results of equilibrium market models highly depend on the type of interaction assumed among rival firms and other players. The types of strategic interactions assumed in literature on power market modeling include the

Bertrand and Cournot strategies [23][24], collusion, Stackelberg, General Conjectural Variations (CVs), supply function equilibria (SFE) [25][26] and conjectured supply function (CSF) [27][28]. Ruiz and Conejo [29] propose a method to determine the best bid strategy for a power producer in a pool-based electricity market with endogenous formation of prices. Uncertainties and congestions are considered in the analysis.

This chapter presents an iterative algorithm for calculating the optimal energy bids of a set of HPPs in the day-ahead market, taking into account the possibility that congestions and market splitting take place. This study presents a new two-step nested algorithm that, starting from an optimization of hydro plants in a basin and based on a given electricity price, finds the optimal bid to maximize hydro generator profit. This bid is submitted to the electricity market simulation and the new market prices are found, taking into account a suitable market model including transmission constraints. The procedure is iterated until an equilibrium point is found. The nested algorithm is based on the integration of an adequate representation of the market (based on [30]) and an adequate optimization of the considered hydro plant operation in a basin (based on [31]). The algorithm was applied to a real basin in the Chiese river (Northern Italy) and evaluated using real Italian market data of October 2012. For some hours of the day, transmission congestions in the grid system restrict the flows between the Northern and other regions. Therefore, the price in the Northern region is different from that of the other Italian regions during these hours. When the market splits in regional markets, hydro plants are in the condition of influencing the zonal market price in the Northern region. The results show the efficiency of the algorithm, reaching convergence in only five iterations in most cases.

3.2 Hydro Generation

Hydro plants in a basin cannot be considered as independent producers in the market, because the availability of energy in one of the plants depends on the ability to store water, proper water inflows and the water delivered by upper hydro plants into the same basin. Moreover, the water delivered by upper hydro plants is available for production in the lower hydro plant after a determined travel time between the plants.

Therefore, the hydro plants in a basin cannot be adequately aggregated into one equivalent, large hydro plant. Water flowing between hydro plants cannot be used for production until it reaches the next reservoir, changing the energy availability hourly. Additionally, water in the upper power reservoirs has an inner value higher than in lower ones, because it can be used to produce energy in more hydro plants. It should also be noted that the relationship between produced energy and water is a nonlinear mathematical expression, depending on the height and shape of the reservoir.

In the present study, the best operation of hydro plants in a basin is obtained by the solution of an optimization problem [31], where restrictions to the operation are modelled as mathematical constraints and prices are considered fixed values. The formulation of the problem is described by eq. (3.1)-(3.15).

$$\text{Max.} \sum_{i=1}^{nr+nwr} \sum_{t=1}^{T} \left(C_t \cdot P_{i,t} \right) \tag{3.1}$$

s.t. $V_{i,t} = V_{i,t-1} + V_{i,t}^{AF} + V_{i-1,t} - V_{i,t}^{T} - V_{i,t}^{C} - V_{i,t}^{D}$ *i=1, ..., nr* (3.2)

$V_{i,t}^{AF} + V_{i-1,t} - V_{i,t}^{T} - V_{i,t}^{C} - V_{i,t}^{D} = 0$ *i=1, ..., nwr* (3.3)

$V_{i-1,t} = \sum_{\alpha i}\left(V_{i-1,t-t_v}^{T} + V_{i-1,t-t_v}^{D}\right)$ *i=1, ..., (nr+nwr)* (3.4)

$V_{i,1} = V_{i,1}^{SP}$ *i=1, ..., nr* (3.5)

$V_{i,T} = V_{i,T}^{SP}$ *i=1, ..., nr* (3.6)

$P_{i,t} - \eta_i \cdot V_{i,t}^{T} \cdot g \cdot h_{i,t} = 0$ *i=1, ..., (nr+nwr)* (3.7)

$h_{i,t} = k_{0,i} + k_{1,i}\cdot\left(V_{i,t}\right) + k_{2,i}\cdot\left(V_{i,t}\right)^2 + k_{3,i}\cdot\left(V_{i,t}\right)^3 + k_{4,i}\cdot\left(V_{i,t}^{T}\right) + k_{5,i}\cdot\left(V_{i,t}^{T}\right)^2$ *i=1, ..., (nr+nwr)* (3.8)

$\sum_{t=1}^{T} V_{i,t}^{C} \geq V_i^{CT\min}$ *i=1, ..., (nr+nwr)* (3.9)

$V_i^{C\min} \leq V_{i,t}^{C} \leq V_i^{C\max}$ *i=1, ..., (nr+nwr* (3.10)

$V_{i,t}^{T} + V_{i,t}^{D} \geq V_i^{EC\min}$ *i=1, ..., (nr+nwr)* (3.11)

$0 \leq V_{i,t} \leq V_i^{\max}$ *i=1, ..., nr* (3.12)

$0 \leq V_{i,t}^{T} \leq V_i^{T\max}$ *i=1, ..., nr* (3.13)

$0 \leq V_{i,t}^{D} \leq 99$ *i=1, ..., nr* (3.14)

$0 \leq h_{i,t} \leq h_i^{\max}$ *i=1, ..., nr* (3.15)

t=1, ..., T

where the variables are the following: $P_{i,t}$, the real power injection into the grid of hydro plant *i* at hour *t*; $V_{i,t}$, the useful volume stored in the reservoir of the hydro plant *i* in the period *t*; $V_{i-1,t}$, the inflow into reservoir i at period *t*, coming through the river from upstream plant (or plants); $V^{T}_{i,t}$, the turbined volume at hour *t* by plant *i*; $V^{D}_{i,t}$, the deviated (spilled) volume at hour *t* by plant *i*; $V^{C}_{i,t}$, the output water consumption for social uses delivered by plant *i* at hour *t*; and $h_{i,t}$, the net head of reservoir *i* at hour *t*. The following are the parameters in the optimization formulation: C_t, the expected market price at hour *t*; $V^{AF}_{i,t,}$ the individual affluence into reservoir *i* at period *t*, not considering the flows coming through the river from the previous plants; t_V, the travel time between the considered hydro plants; $V^{SP}_{i,1}$ and $V^{SP}_{i,T}$, the specified volumes at the beginning and end of the horizon (respectively) by plant *i*; η_i, the average efficiency of the hydro plant *i*; g = 9.81 m/s^2, the acceleration of gravity; $k_{0,i}$, $k_{1,i}$, $k_{2,i}$ and $k_{3,i}$, the coefficients relating volume and net head at reservoir *i*; $k_{4,i}$ and $k_{5,i}$, the coefficients relating turbined volume and net head at reservoir *i*; V^{CTmin}_i, the minimum daily requirements of water for social use in the hydro plant *i*; V^{Cmin}_i and V^{Cmax}_i, the minimum and maximum (respectively) hourly requirements of water for social use in plant *i*; V^{ECmin}_i, the minimum (ecological) water flow to be kept in the river downstream of reservoir *i*; V^{max}_i and V^{Tmax}_i, the maximum useful reserve and capacity of production (respectively) of hydro plant *i*; and h^{max}_i, the maximum net head at plant *i*. In the equations, *nr* is the number of hydro plants with reservoirs, *nwr* is the number of run-of-river hydro plants (without reservoirs), *αi* is the set of hydro plants upstream the reservoir *i* and T is the number of discretisation steps.

The goal of problem (2.1)-(2.15) is to calculate the optimal production of coordinated hydro plants in a basin in T periods, considering expected prices in the market (2.1). The expected prices are obtained from the market representation described in Section 3.3.

Equality constraints (2.2) and (2.3) express the energy balances in the hydro plants with and without a reservoir, respectively. When the hydro plant has storage capacity (2.2), the useful volume in the reservoir is increased by both individual affluence (rain, tributaries, etc.) and flows coming from hydro plants immediately upstream. On the other side, the energy stored in these plants can be reduced by electricity generation and social consumption. When large inflows enter the reservoir, a portion of the water can be deviated by using the spill way to preserve security of the plant. The amount of useful energy in the reservoirs at the beginning and end of the programming horizon (2.5)-(2.6) are pre-specified quantities. The hydro power production is expressed in (2.7) as a function of gravity, average efficiency, turbined volume and net head. The latter is calculated in (2.8), as function of useful volume at the reservoir and turbined water. Coefficients $k_{0,i}$, $k_{1,i}$, $k_{2,i}$, $k_{3,i}$, $k_{4,i}$ y $k_{5,i}$ mainly express the relationship between useful volume, turbined volume and net head at the hour. The efficiency in hydro plants depends on both head and water flow, [32]. In the present formulation, an average efficiency value for each plant is considered in (2.7). The efficiency variation is integrated in the coefficients of (2.8), allowing the adequate calculation of the net head. In hydro reservoirs with large nonlinear relationships between the head and stored water, partial approximations for each level of the reservoir can be adopted, changing parameters of (2.8) as function of the useful volume in the reservoir and the head. In the present case, the social requirements for water are represented as minimum daily consumption (9) and restrictions on hourly water flows (10). The operation of the hydrological system requires keeping the minimum ecological levels of water flows into the basin (11). In eq. (3.12)-(3.15), the maximum equipment capacities of the hydro plants are expressed.

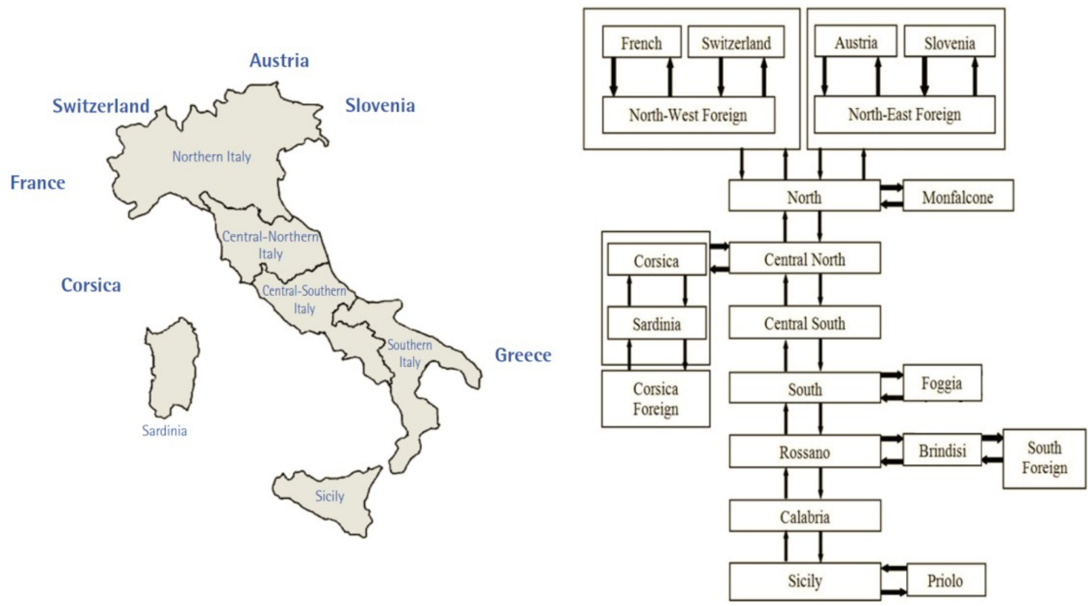
Equations (2.1)-(2.15) make a large nonlinear optimization problem requiring (T (7*nr*+6*nwr*)) variables, (4T (*nr*+*nwr*)+2*nr*) equality constraints and (T (16*nr*+14*nwr*)) inequality constraints. For the sake of simplicity, in the present formulation integer variables (used for representing start-ups and shutdown costs) are not considered. However, these variables can be easily included in the model, when necessary.

3.3 The Market Representation

The Italian electricity market is a real physical market, where the schedules of electricity injection and withdrawal into and from the grid are defined under economic merit-order criterion. The Italian Power exchange (Ipex) is a voluntary market organized in function of a Spot Electricity market and a Forward Electricity market. In particular, the Spot Electricity market consists of the Day-Ahead Energy market (MGP, in Italian), Intra-Day Energy markets and Ancillary Services markets.

In the MGP, participants submit offers/bids where they specify the quantity and minimum/maximum price at which they are willing to sell/purchase. Bids/offers are accepted under the economic merit-order criterion and taking into account transmission capacity limits between zones. For each hour, the Marginal Clearing Price (MCP) is given by the intersection of the cumulative demand and supply curves. Intra-Day markets allow market participants to modify the schedules defined in the MGP by submitting additional supply offers or demand bids. Finally, in the Ancillary Services market, the Italian Transmission System Operator (TSO) procures ancillary resources.

The MGP hosts most of the electricity sale and purchase transactions. Presently, over 200 thermal power plants (of more than 40 GW capacity) belonging to different companies are in operation in the Italian electricity market. In addition, the Italian power system consists of hydroelectric capacity of more than 20 GW, mostly in the Northern region. The particular geographic characteristics of the country and location of generations and demand may cause transmission congestions. To deal with congestions, the Italian electricity market is divided into a number of areas that define critical sections where congestions are considered more probable (zonal model, Fig. 3.1.a and 3.1.b).



(a) (b)

Fig. 3.1. Virtual and geographical zones of the national transmission grid

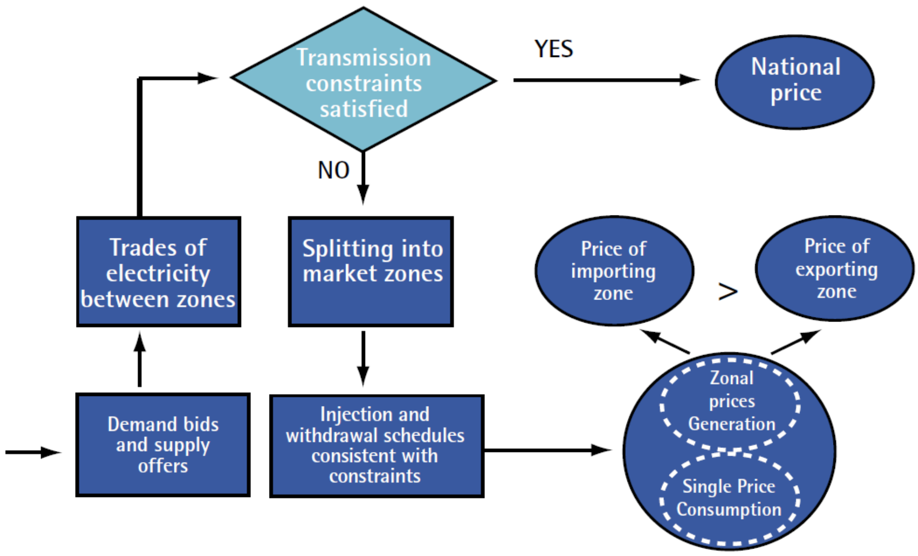


Fig. 3.2. Zonal price algorithm

A particular feature of the Italian market is that all accepted demand bids are valued at a national single price; this price is equal to average price across geographical zones, weighted on the quantities purchased in each zone. Instead, the seller bids are valued at the marginal clearing price of the zone they belong to.

Due to the high frequency of congestions in the Transmission System, the algorithm used to find the market solution has to take into account the zonal transmission constraints. In particular, an unconstrained electricity market model is first solved. When all power flows among critical interfaces are lower than the maximum values, the solution is accepted. Otherwise, a constrained market model is solved where total social welfare is maximized subject to energy balance constraint and inter-zonal transmission limits. Calculation of local market prices is performed by using an iterative algorithm, represented in Fig. 3.2.

The general formulation of the optimization problem is expressed as follows (the mathematical algorithm used is fully described in [30][33]):

$$MAX \left(\sum_{i=1}^{nl} PQ_i \cdot pr_{p,i} - \sum_{j=1}^{ng} SQ_j \cdot pr_{s,j} \right) \tag{3.16}$$

$$\text{s.t.} \sum_{i=1}^{nl} PQ_i = \sum_{j=1}^{ng} SQ_j \tag{3.17}$$

$$\underline{PF}_{r,s} \le PF_{r,s} \le \overline{PF}_{r,s} \ (18)\ 0 \le PQ_i \le \overline{PQ}_i \tag{3.19}$$

$$0 \le SQ_j \le \overline{SQ}_j \tag{3.20}$$

where PQ_i is the quantity that customer i is willing to purchase; $pr_{p,i}$ is the purchase price of customer i; SQ_j is the quantity that seller j is willing to sell; $pr_{s,j}$ is the offer price of generator j; $PF_{r,s}$ is the flow on the interface between areas r and s, computed using fixed coefficients given in advance; $\underline{PF}_{r,s}$ and $\overline{PF}_{r,s}$ are the minimum and maximum flow limits on the interface between areas r and s; $\overline{PQ}_i$ is the upper bound of PQ_i; $\overline{SQ}_j$ is the upper bound of SQ_j, n_l and n_g are, respectively, the number of buyers and sellers, respectively. In the model adopted in this chapter, the demand is assumed fixed due to its very low elasticity in the Italian market. According to this assumption, the market model is the same as the single auction model and the national single price can be computed ex-post after the closing of the market and it is not a variable of the optimization problem.

Writing the Karush–Kuhn–Tucker (KKT) conditions and analyzing the meaning of the Lagrangian multiplier associated to the balance equality constraint and the transmission inequality constraints, it is possible to compute electricity price for each market zone as follow:

$$pr_k = \lambda + \sum_{m=1}^{NT} \underline{\mu_m} \frac{\partial TR_m}{\partial Q_{v,k}} - \sum_{m=1}^{NT} \overline{\mu_m} \frac{\partial TR_m}{\partial Q_{v,k}}$$

where pr_k is the price in area *k*, λ is the Lagrangian multiplier associated to the balance constraint, $\underline{\mu_m}$ and $\overline{\mu_m}$ are respectively the Lagrangian multipliers associated to the maximum and minimum limit for the interface *m*, $\frac{\partial TR_m}{\partial Q_{v,k}}$ is the sensitivity of the transit on interface *m* w.r.t. a withdrawal in area *k*, NT is the number of zonal interfaces. In particular, if a zonal approach is adopted and the zonal structure is radial, $\frac{\partial TR_m}{\partial Q_{v,k}}$ can be equal to 1, -1 or zero because the equation that represents the transit on an interface is linear w.r.t. the independent variable of the optimization problem. If the transits never reach their limits, the energy price is given by the Lagrangian multiplier of the balance constraint ($\underline{\mu_m}$ and $\overline{\mu_m}$ are equal to zero). In the presence of an active transit constraint, different zonal prices appear. In particular, the zone that exports energy has an energy price lower than the importing zone.

In the pool market model, the energy (produced or withdrawn) is priced at the zonal price; therefore, due to the difference of the zonal prices, the Power Exchange collects a congestion rent (CR), equal to:

$$CR = TTC \cdot (pr_i - pr_e) \tag{3.21}$$

where *TTC* is the active limit ($|\underline{PF}_{r,s}|$ or $|\overline{PF}_{r,s}|$), pr_i is the energy price in the import zone and pr_e is the price in the export zone ($pr_i > pr_e$). The congestion revenue represents the economic value of the transmission service. In the case that all power flows between two different market zones are lower than maximum values, the transmission resources are sufficient and the energy prices are the same in each zone, therefore CR is equal to zero. If the power flow between two zones reaches the maximum value, from the economic point of view, this means that there is a lack of transmission resources. When economic value of the transmission service is other than zero, the GME collects the CR from the market. This mechanism implicitly allocates the transmission resources.

3.4 The Nested Algorithm

Representations of the market and HPPs are integrated in a nested algorithm, which carries out alternate iterations of models described in Sections 3.2 and 3.3. Iterations are stopped when both models are at the equilibrium: this guarantees that the HPP considered maximizes its profits taking into account the interactions with the market mechanism and the other market players. In Fig. 3.3, the flow chart of the algorithm is presented.

In the *Initialization* block of Fig. 3.3, initial estimates for the price at each hour of the day are obtained by means of a market simulation performed according to (3.16)-(3.20). In this simulation, all competitors in the Italian market submit prices for purchasing or selling energy and the quantities of energy they are willing to sell or buy. For the initial simulation, the considered HPP plants in the Chiese river offer fixed values of energy (obtained from historical production data) at very low prices, to be sure they will be dispatched. The other market participants are assumed both to bid according to their historical behavior (which is known) and irrespective of the strategy of the considered HPPs. The solution of equations (3.16)-(3.20) allows calculation of the starting guess of the market, in terms of quantities and prices, as well as possible congestions.

This initial market solution is used for the first iteration of the cycle in Fig. 3.3, in the *Hydro Generation* block, where a first guess of the optimal schedule of the HPP hydro plants is determined, solving optimization problem (3.1)-(3.15). The optimal HPP hourly schedules are identified according to the above mentioned prices as well as the overall HPP profit. In the *Hydro Generation* block, hourly prices are considered fixed quantities; in the first iteration they are computed in the *Initialization* block, while in following iterations they are determined by the *Market Simulation* block. In the *Market Simulation* block, the HPP bids the so-determined optimal quantities again at a zero price, and this results in an updated market outcome (quantities and prices for each market participant) and, accordingly, updated power system operating conditions (in particular, congestions). After each *Hydro Generation* calculation, the difference in the profits of the HPPs in consecutive iterations is assessed and, if this difference is lower than a tolerance δ, the nested algorithm is stopped.

At the convergence, the hourly dispatching profile is both the solution of the electricity market for each hour and the optimum for the considered set of HPPs, because it maximizes their profits. Therefore, the nested algorithm can effectively determine and assess the bidding strategy of the HPPs into the market, including in the strategy all the effects related to the transmission constraints and their impact on zonal prices.

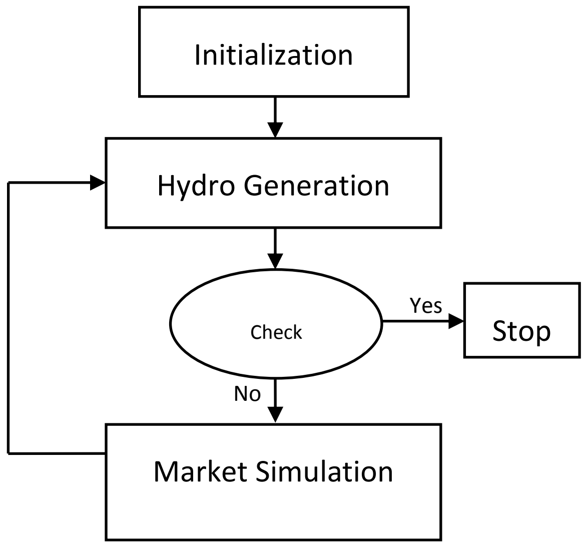


Fig. 3.3 Flow chart of the proposed algorithm

3.5 The Test Case

The proposed nested optimization problem is applied to water management in four HPPs of the Chiese river of Daone Valley, North of Italy. In Fig. 3.4, a schematic representation of the hydro plants and their reservoirs is presented. The travel times between the reservoirs are also included in the diagram.

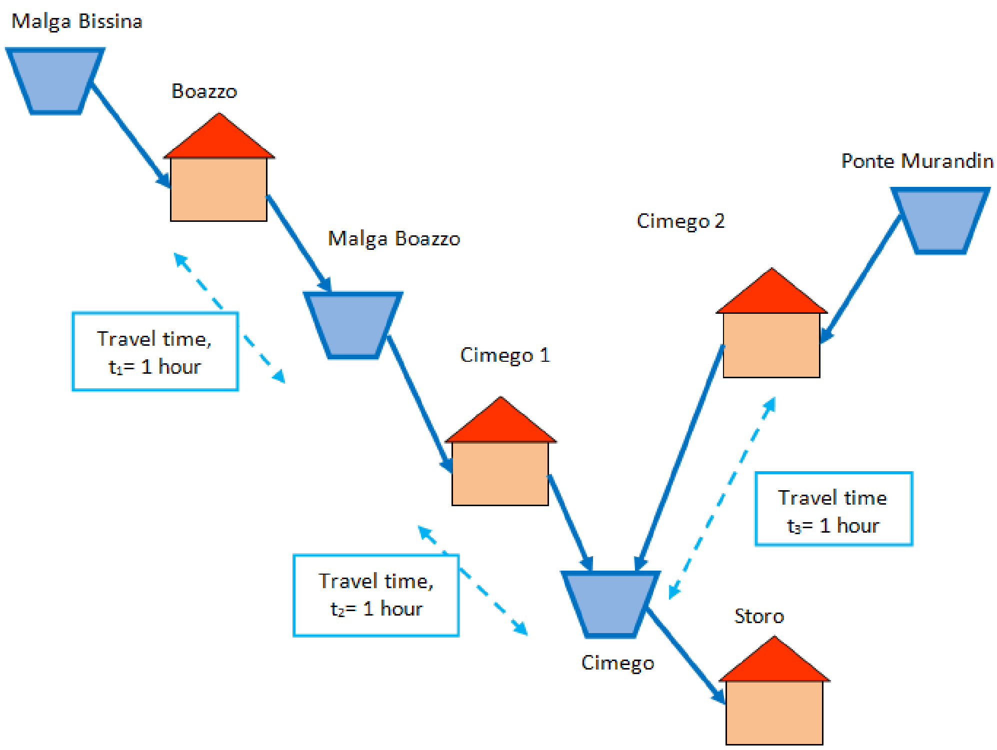


Fig. 3.4. The Alto Chiese Basin and Relevant Hydro Plants [34]

The HPPs Boazzo, Cimego 1, Cimego 2 and Storo have installed capacities of 95,220, 9.2 and 20 MW, respectively. The reservoirs Bissina, Boazzo, Pontemurandin and Cimego have maximum useful storage capacities of 60045, 11690, 288 and 250 dam^3, respectively. In the present simulation, typical hydro data from October 2012 (a month with medium hydro production) were used, considering a constant affluence of 6,745 m^3/s in the reservoir of Bissina and 1,867 m^3/s in the reservoir of Pontemurandin.

The basin is included in the Northern region of Italy shown in Fig. 3.1. In general, a unique price is calculated in the *Market simulation* block for all the electrical regions in one specified hour. However, when transmission constraints between electrical regions become active, the market prices in these regions are different.

In the present analysis, the market simulation is carried out the complete Italian market. However, only the prices and congestions in the Northern region (the area of the studied HPPs) are significant for the hydro schedule calculation. It must be highlighted that in congested hours, the HPPs action can affect the price in the region and, therefore, prices in neighboring areas as well.

Simulation results for the week from the 13th to 19th of October 2012 (from Monday to Sunday; 168 hours) are shown to take into account the effect of storage between consecutive days. Accordingly, the hourly productions and costs of each power plant and also hourly load demands of different zones in the mentioned week were taken from historical data published by GME [35] and transmission limits were obtained from the TSO [36]. A tolerance $\delta = 0.33\%$ of the total profit in the considered HPPs was assumed

3.6 Results

Selected results are presented in order to highlight properties of the proposed algorithm. It is important to first check the convergence features of the iterative algorithm. In Fig. 3.5, the required iterations of the algorithm depicted in Fig. 3.3 are shown.

In Fig. 3.5, the differences between the aggregated HHP's profit (Diff) in two successive iterations of the algorithm are depicted. It is worth noticing that, like in this case, in all the studies carried out the convergence was reached in at most five iterations. The main differences are obtained in the second iteration, due to variation between profits obtained with prices from the *Initialization* block (Fig. 3.3) and those calculated with data from the *Market Simulation* block.

In Fig. 3.6, the evolution of prices in the week and for the iterations of the algorithm is shown.

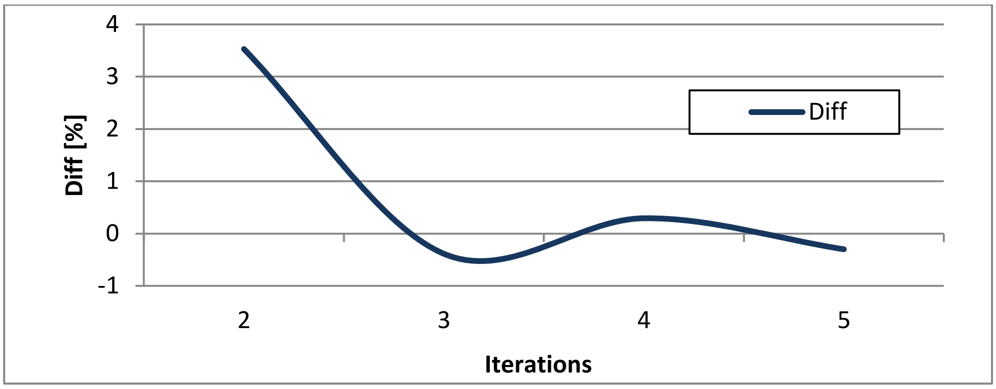


Fig. 3.5. Convergence of the Nested Algorithm

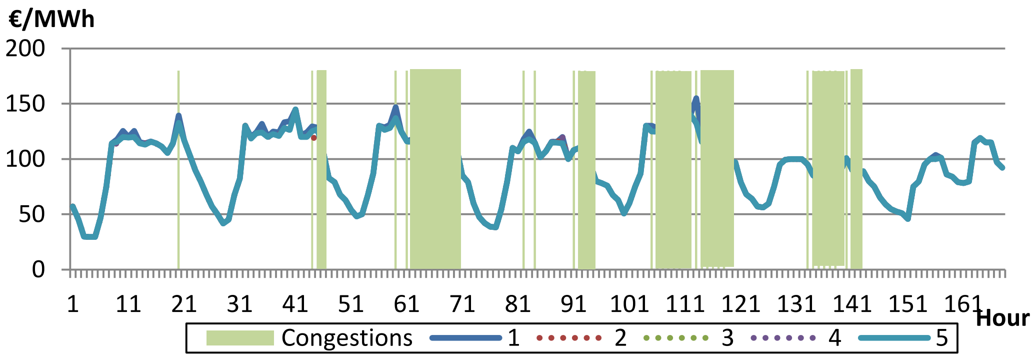


Fig. 3.6. Market Prices in the 5 Iterations

In Fig. 3.6, the prices obtained in the *Initialization* block (first iteration) and in the *Market Simulation* block (other iterations) are depicted. In particular, first and last iterations are depicted as continuous lines and intermediate results as dotted lines. As expected, the prices present 7 consecutive patterns for the 7 days of the week. The prices are higher in the 5 weekdays than in the weekend. Differences in prices between iterations are mainly present in the peak hours of weekdays. In these hours, congestions between the North and Central-North regions of the country can occur. In Fig. 3.6, the hours with congestions and therefore different prices in the North and Central-North regions are highlighted. In the hours with transmission congestion, the considered HPPs significantly affect the zonal price. In these hours, the optimization process takes advantage of congestions. It must be highlighted that the algorithm does not modify the hours with congestions, because these hours were mainly determined by the profile of the loads and transmission limits. The average prices are reduced by the action of the algorithm from 95.01 €/MWh in the first iteration to 93.85 €/MWh at the convergence, due to the interaction between market and HPP's behavior simulations. The decrease is mainly due to reductions in prices during peak periods. The average highest price (computed on hourly prices greater than 100 €/MWh) is reduced from 119.48 €/MWh to 117.21 €/MWh, 2% of decrease, at the convergence.

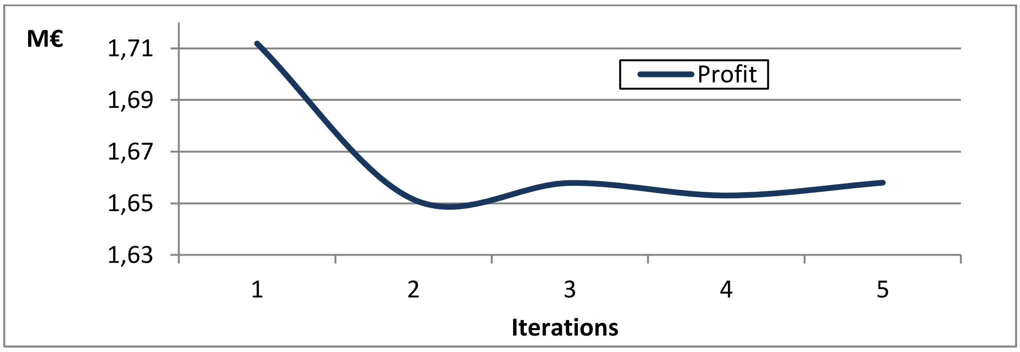


Fig. 3.7. Aggregated Profit of the Hydro Plants in the 5 Iterations

In Fig. 3.7, the aggregated profit of considered HPPs, is shown for each iteration. The HPP profit at first iteration (1.71 M€) is larger than the obtained in the convergence of the algorithm (1.66 M€). The *Hydro Generation* block calculates the optimal generation of hydro plant maximizing their profit (eq.

(3.1)-(3.15)), as function of prices and productions. The market simulation determines the equilibrium prices for the Italian market. The interaction between the two blocks results in the convergence to the value of 53.90 k€ for the studied hydro plants, as it is shown in Fig. 3.7.

In Fig. 3.8, the aggregated production of the 4 HPPs is depicted for each iteration to convergence.

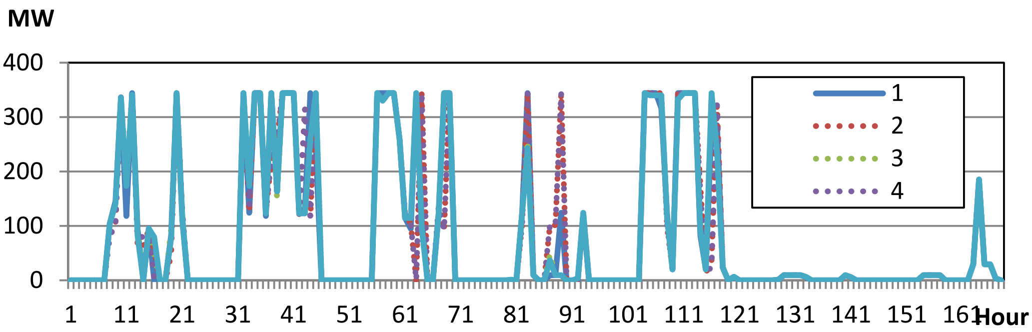
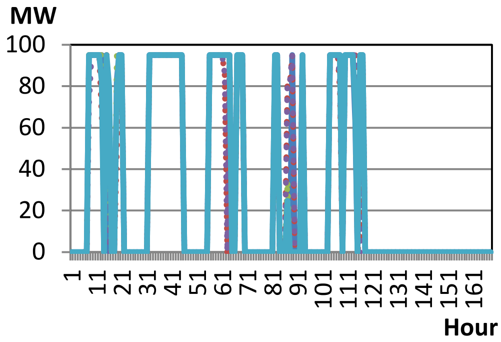
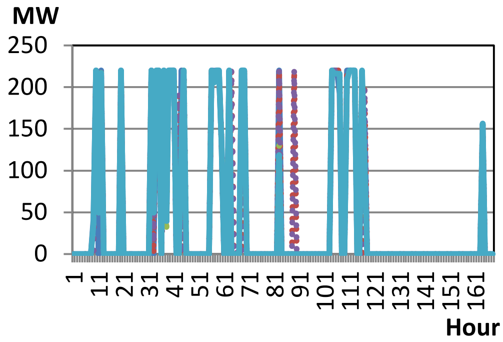


Fig. 3.8. Aggregated Production of the HPPs in the 5 Iterations

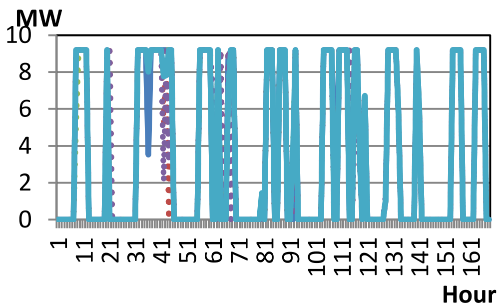
In Fig. 3.8, the hydro system produces to its limit (344.2 MWh) in the high price periods during the first days, reducing production during the weekend. The inflows in the weekend were mainly used to reach the specified value of storage at the end of the simulation (constraint (3.6) of the hydro model). The main difference in the productions of the HPPs between iterations occurred during days 2-5. In Fig. 3.9, evolution of the production of individual HPPs are shown.



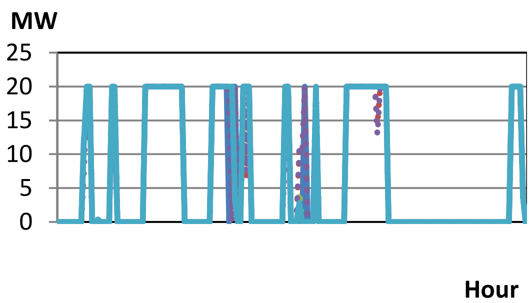
(a) Boazzo



(b) Cimego 1



(c) Cimego 2



(d) Storo

Fig. 3.9. Productions in the HPPs in the 5 Iterations

Fig. 3.9 shows that for most hours, the optimization algorithm yielded that the best profit changing in the iterations was the production between the two branches of the hydro system (HPPs Cimego 1 and Cimego 2 are allocated in different affluents of the Cimego reservoir). This was mainly performed during hours with congestions between North and Central-North areas, in which the influence of the optimization significantly affect market prices. As an example, in hour 110 the production of Cimego 1 is modified between iterations 1 to 5 from 220 MW to 208.58 MW (the other productions remain the same at that hour), resulting in a reduction of the initial market price from 150 €/MWh to 125.16 €/MWh. This reduction can be seen as an initial cut in the almost plain production of the HPP plants (Fig. 3.8) and of Cimego 1 (Fig. 3.9.b) in this period. Also, the algorithm modifies the HPP production in hours without congestion (see, e.g. power variations in Boazzo and Cimego 1 at hour 89, Figs. 3.9.a and 3.9.b) looking for the optimal solution. In Fig. 3.10, storage activity in the four HPPs is depicted at the convergence of the algorithm (iteration 5).

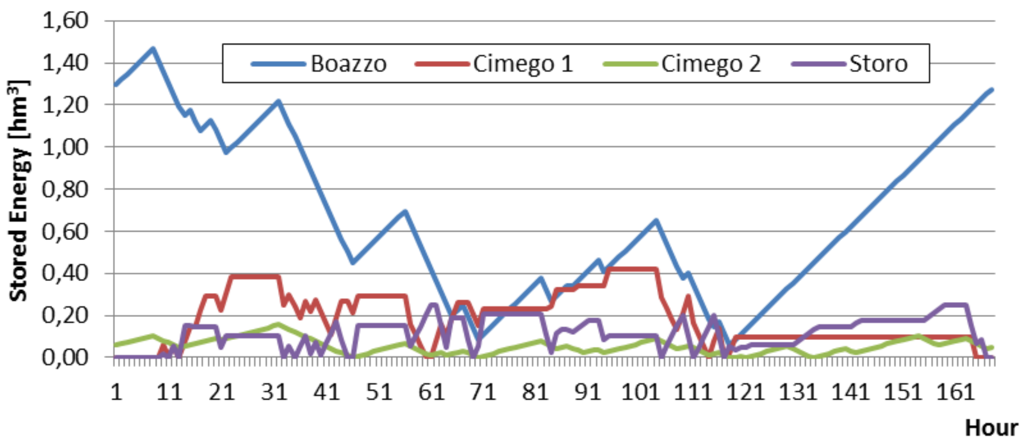


Fig. 3.10 Stored energy in the reservoirs of the HPPs, iteration 5

The HPP of Boazzo, in the head of one of the branches of the system, uses its large storage capacity to control the injection of water into its branch using both the water affluence during the day and the energy available in the reservoir at the beginning of the simulation to produce more energy during weekdays. It must be stressed that the two HPPs Boazzo and Cimego 1 (this latter downstream of Boazzo in the same branch of the system) almost empty reservoirs at the end of the high price period on Friday. The Boazzo HPP uses affluence during the weekend to reach the specified level at the end of the simulation. The HPP of Cimego 2 is in the second branch of the hydro system and has little storage capacity. Therefore, the optimization action results in changing production during each day, this power plant needs to produce every day during peak hours.

3.7 Conclusion

This chapter presents an iterative optimization method to calculate the optimal operation of a basin with hydropower plants that sell energy to the market, taking into account equilibrium of the market. The hydropower plants have dissimilar storage capacities and installed capacities, with production depending on the structure of the hydro system and its management. The hydro plants are included in an area with frequent congestion problems with the other areas of the power system. The hydro plants are considered influential in the region, but not as influential considering the complete national power system.

The proposed algorithm is based on successive iterations of the strategy of the hydro producer in order to maximize its profit and the complete simulation of the electricity market, taking into account transmission constraints. The solution is provided by the equilibrium point of this iterative procedure.

HHP optimization is aimed to increase profits by modifying water flows of the river and corresponding hydro plant generation during congestion hours. Market Simulation block defines the equilibrium point of the market, taking into account the behavior of all market participants.

HHP optimization wants to increase profits by modifying water flows of the river and corresponding hydro plant generation during congestion hours. Market Simulation block wants to maximize the social welfare of the system. The algorithm changes the production of plants for obtaining the best equilibrium point, resulting in a decrease of the average market price in the zone. The modifications are due mainly in the hours with congestions, where zonal prices are different, and in peak hours of workdays. In the simulated case, the action of the HPP cannot modify the number of hours or timing of these hours with congestions. The algorithm performed a multi-day optimization (e.g., on a weekly basis) to take advantage of HPP storage abilities and difference in prices during the week. The convergence of the process is very fast, requiring 5 iterations of a nested algorithm with a master-slave structure.

3.8 References

[1] H. Habibollahzadeh and J. A. Bubenko. Application of decomposition techniques to short-term operation planning of hydrothermal power system. IEEE Transactions on Power Systems 1(1), pp. 41-47. 1986.

[2] G. Zhao and M. Davison. Optimal control of hydroelectric facility incorporating pump storage. Renewable Energy 34(4), pp. 1064-1077. 2009.

[3] E. Castronuovo and J. A. P. Lopes. Optimal operation and hydro storage sizing of a wind-hydro power plant. International Journal of Electrical Power Energy Systems 26(10), pp. 771-778. 2004.

[4] H. M. I. Pousinho, V. M. F. Mendes and J. P. S. Catalão. Scheduling of a hydro producer considering head-dependency, price scenarios and risk-aversion. Energy Conversion and Management 56(0), pp. 96-103. 2012.

[5] D. N. Simopoulos, S. D. Kavatza and C. D. Vournas. An enhanced peak shaving method for short term hydrothermal scheduling. Energy Conversion and Management 48(11), pp. 3018. 2007.

[6] A. L. Diniz and M. E. P. Maceira. A four-dimensional model of hydro generation for the short-term hydrothermal dispatch problem considering head and spillage effects. IEEE Transactions on Power Systems 23(3), pp. 1298-1308. 2008.

[7] Z. Shawwash, K. Thomas, K. Siu, and S. O. Dinis Russell. The B.C. hydro short term hydro scheduling optimization model. IEEE Transactions on Power Systems 15(3), pp. 1125. 2000.

[8] Juan I. Pérez-Díaz, José R. Wilhelmi. Assessment of the economic impact of environmental constraints on short-term hydropower plant operation. Energy Policy 38(12), pp. 7960. 2010.

[9] J. I. Perez-Díaz, R. Millán, D. García, I. Guisández and J.R. Wilhelmi. Contribution of regulation reservoirs considering pumping capability to environmentally friendly hydropower operation. Proceedings of the 6th. Dubrovnik Conference on Sustainable Development of Energy Water and Environment Systems, September 25 Dubrovnik, Croatia. 2011.

[10] L. S. A. Martins, A. T. Azevedo and S. Soares, Nonlinear Medium-Term Hydro-Thermal Scheduling With Transmission Constraints, (2014), IEEE Transactions on Power Systems, vol. 29, no. 4, July 2014.

[11] C. Grigg, P.Wong, P.Albrecht, R. Allan,M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S.Haddad, S. Kuruganty, W. Li,R.Mukerji, D. Patton, N. Rau, D. Reppen, A. Schneider, M. Shahidehpour, and C. Singh, “The IEEE reliability test system-1996. A report prepared by the reliability test system task force of

the application of probability methods subcommittee," (1999), IEEE Trans. Power Syst., vol. 14, no. 3, pp. 1010–1020, 1999.

[12] C. H. Fujisawa, L. S. A. Martins, A. T. Azevedo and S. Soares, "Equivalent networks for medium-term hydro-thermal scheduling with variable head cascaded reservoirs and transmission constraints," (2014), Power Systems Computation Conference (PSCC), Wroclaw, Poland, Aug. 2014.

[13] A.J. Conejo, J.M. Arroyo, J. Contreras, Villamor, F.A. Self-Scheduling of a Hydro Producer in a Pool-Based Electricity Market. IEEE Transactions on Power Systems 17(4), pp. 1265-1272. 2002.

[14] A. Borghetti, C. D'Ambrosio, A. Lodi and S. Martello. An MILP Approach for Short-Term Hydro Scheduling and Unit Commitment With Head-Dependent Reservoir. IEEE Transactions on Power Systems 23(3), pp. 1115-1124. 2008.

[15] C. K. Simoglou, P. N. Biskas and A. G. Bakirtzis. Optimal Self-scheduling of a Dominant Power Company in Electricity Markets. Electrical Power and Energy Systems 43, pp. 640–649. 2012.

[16] J. M. Angarita and J. G. Usaola. Combining Hydro-Generation and Wind Energy. Biddings and Operation on Electricity Spot Markets. Electric Power Systems Research 77, pp. 393–400. 2007.

[17] J. P. S. Catalão, S. J. P. S. Mariano, V. M. F. Mendes and L. A. F. M. Ferreira. Scheduling of Head-Sensitive Cascaded Hydro Systems: A Nonlinear Approach. IEEE Transactions on Power Systems 24(1), pp. 337-346. 2009.

[18] E.G. Kardakos, C.K. Simoglou, A.G. Bakirtzis, "Hydrothermal Producer Offering Strategy in a Transmission-Constrained Electricity Market: An MPEC

Approach", Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2014 IEEE PES, October 2014, Istanbul, Turkey.

[19] B.F. Hobbs, C.B. Metzler, and J-S Pang, "Strategic gaming analysis for electric power systems: An MPEC Approach" IEEE Transactions on Power Systems, vol. 15, no. 3, pp 638-645, May. 2002.

[20] M. Ventosa, A. Baillo, A Ramos and M. River, "Electricity market modeling trends", Energy Policy, vol. 33, pp 897-913, 2005

[21] CJ. Day, B.F. Hobbs, and J.S. Pang, "Oligopolistic competition in power networks: A conjectured supply function approach," IEEE Transactions on Power Systems, vol. 17, no. 3, pp 597-607, Aug. 2002.

[22] R.Baldick, "Computing the Electricity Market Equilibrium: Uses of market equilibrium models," Power Systems Conference and Exposition, Altanta, GA, 29 October 29- 1 November 2006.

[23] A.M.A.K Abeygunawardana, C. Bovo, A. Berizzi, “Implications of CO2 prices on the generation capacity expansion in the Italian electricity market,” 45th International Universities Power Engineering Conference (UPEC), Cardiff, Wales, 2010, Aug. 31-Sept. 3.

[24] A.M.A.K. Abeygunawardana, C. Bovo, M. Gholami, A. Berizzi, “Generation Capacity Expansion with CO2 Emission and Transmission Constraints in an Oligopolistic Market,” Research Journal of Applied Sciences, Engineering and Technology 6(23), 2013.

[25] A.M.A.K Abeygunawardana, C. Bovo, A. Berizzi, “Market Power Analysis in the Italian Electricity Market using a Supply Function Equilibrium Model,”

Proceedings of the 44th International Universities Power Engineering Conference (UPEC), Glasgow, United Kingdom, 2009, 1-4 September.

[26] A.M.A.K Abeygunawardana, C. Bovo, A. Berizzi, “Analysis of impacts of carbon prices on the Italian electricity market using a supply function equilibrium mode,” (2009), Proceedings of the 9th WSEAS/IASME International Conference on Electric Power Systems, High Voltages, Electric Machines, POWER '09, Genova, Italy, 2009, October 17-19.

[27] A.M.A.K Abeygunawardana, A. Berizzi, C. Bovo, M. Innorta, "A Conjectural Supply Function model for the Italian Electricity market", 43rd International Universities Power Engineering Conference. Padova, Italy, 2008, September 1-4.

[28] AM.A.K. Abeygunawardana, A Berizzi, C. Bovo, M. Innorta, "Impacts of European Union Emissions Trading in Italian Power sector", International Conference on Energy Security and Climate Change. Bangkok, Thailand, 2008, August 6-8.

[29] C. Ruiz, A. J. Conejo, "Pool Strategy of a Producer With Endogenous Formation of Locational Marginal Prices", IEEE Trans. Power Syst., vol. 24, no. 4, November 2009, pp. 1855 - 1866.

[30] A. Berizzi, C. Bovo, M. Delfanti, E. Fumagalli, M. Merlo, Simulation of a bid-based dispatch subject to inter-zonal transmission constraints, Proceedings of the IEEE Bologna Power Tech Conference, 2003, Bologna, Italy, 23-26 June.

[31] Gloria Hermida, Edgardo D. Castronuovo. On the Short-Term Optimisation of a Hydro Basin with Social Constraints. Computational Water, Energy, and Environmental Engineering, 2(1), pp. 9–20. 2013.

[32] E. C. Finardi and E. Luiz da Silva, "Solving the Hydro Unit Commitment Problem via Dual Decomposition and Sequential Quadratic Programming," (2006), IEEE Trans. Power Syst., vol. 21, no. 2, pp. 835-844, May 2006.

[33] "Market splitting auction algorithm" and "Uniform purchase price auction algorithm", available on www.mercatoelettrico.org.

[34] www.hydrodolomitienel.it and www.enel.it

[35] Data of transactions on the Italian electricity market, available: www.mercatoelettrico.org

[36] Statistical data on Italian electricity market published by Italian TSO (Terna SpA), available on www.terna.it (in Italian).

Chapter 4.

Hydropower Scheduling in a Basin with Stochastic Inflow and Heavy Ecological and Human Restrictions

Abstract— **The optimal coordination among all basin reservoir system characteristics requires the use of computer modeling tools. These provide the information needed for the rational management of a basin, allowing profits to be maximized whilst meeting all necessary legal, social, and environmental requirements. This study proposes a novel management tool that allows economic profitability to be increased while satisfying all European and local regulations, consumption requirements, rights of use, and environmental flows in the Guadalquivir Basin of southern Spain. This is an area characterized by low water availability and high variability. A set of 200 stochastic scenarios is created to model these conditions. The results demonstrated the robustness of the model and the validity of the statistical methods for application in short-term studies in which a large chain of reservoirs must be operated under dry conditions and onerous operational constraints. The statistical behavior of the different variables in the reservoirs is shown to vary across the basin, reflecting the available storage capacity, the ecological constraints, and the water travel time.**

Contents

4.1 Introduction

Over the last several decades, annual water consumption in developed countries has steadily increased. In [1] it is noted that, with increasing water demand of cities and modern agricultural techniques, the amount of water required often exceeds that available. Author [2] observes that irrigation now underpins at least 40% of worldwide food and fiber supply. Overall, irrigation remains a necessary factor in global prosperity and growth. Water supply is likely to be affected by climate change, and a number of studies have highlighted the potential negative impacts. In [3], it is presented a series of observable effects arising from climate change, and in [4] it is explored the negative impact on groundwater reserves. According to [5], future studies on the management of water resources need to focus on the optimal management of resources, in addition to the political and economic problems of basin management.

Spain is considered to be one of the countries within the European Union (EU) that is most vulnerable to climate change and its consequences [6]. Several studies have suggested that both water demand management and water supply management are necessary to allow adaptation to the changing environment and the associated uncertainty of water resource availability [7].

The EU legislation for watershed management, such as the European Water Framework Directive (WFD) [8], requires considerable economic and coordination efforts. Author [9] develops the decision support system known as the MULINO project, to support the implementation of the WFD. In [10], the WFD is characterized as an environmental law that uses economics to achieve its objectives. The WFD itself recognizes that water management requires economic analysis.

Several recent studies have investigated different elements of ecosystem accounting and presented initial guidelines for the same. Ecosystem accounting may provide an appropriate framework for achieving the goals of the WFD. Many entities have used the MULINO project to advance the System of Environmental–Economic Accounting (SEEA) to SEEA Experimental Ecosystem Accounting. In [11], some examples that demonstrated how ecosystem accounting can support sustainable development are provided. Following [12], an internationally adopted SEEA could be used to measure the interaction between the economy and the natural environment. However, while the proposed method can account for the depletion of natural resources, it does not consider environmental degradation.

The WFD has substantially changed European legislative approaches toward water management. Its objectives are to prevent the deterioration of aquatic ecosystems and improve their status by promoting the sustainable use of water. To achieve these objectives, the WFD requires member states to develop management plans for all their river basins. Studies have been conducted on the impact of the economic tools of WFD in real environments in Greece, Italy and northern Spain. The results from Greece suggest that the use of water pricing as a single way of controlling irrigation is an ineffective approach to the reduction of water consumption [13]. In Italy, although the implementation of the directive resulted in a minor reduction in water use, it is associated with a sharp decrease in farm incomes and employment [14]. In the Douro region of Spain, a study of three different crops shows no significant reduction in water consumption until prices reached levels at which farm incomes and agricultural employment are negatively impacted [15].

The current study focuses on the Guadalquivir River in southern Spain. This basin is currently operated under river basin management plans enacted by the Hydrographic Confederation of the Guadalquivir River (CHG) [16]. Draft laws, regulations, plans, and programs are openly available on the CHG website. The hydrological basin plans meet the requirements of the WFD. The River Basin Management Plan (Art. 41.1. TRLA) [17] establishes priority criteria for the different uses of the river, weighs the compatibility of these different uses, and sets priorities accordingly. The CHG establishes that "environmental flows will be designed to meet the objectives of the operating systems in a coordinated manner, with the single goal of supplying the population" [18]. A current key challenge in basin management is to meet the growing demand for dwindling resources while complying with these regulations.

Because of their short start-up time, hydropower plants are used to respond to imbalances in power demand and supply caused by an unpredicted change in demand or unplanned shutdown of generation units. However, several studies [19, 20] have demonstrated the negative impact of abrupt changes in the output of hydropower plants on river flow. These studies have concluded that human activities often affect the environment in ways that exceed the environment's capacity to adjust. Lower limits are often set on water flows (called ecological flows). However, rapid fluctuations in discharge rates do not necessarily influence the water flows, and may actually be beneficial to the flora and fauna of the basin in some cases [20]. In [21], it is developed an approach to quantify the effect of human actions, in terms of changes in ecological flow regimes. In basins with strong ecological restrictions, regulations can produce significantly suboptimal outcomes. The forgone profits of hydro-operators and the potential environmental impact of ramping rate restrictions should be considered [22]. The latter arises from the need to bring alternative sources, including conventional power generation, into play. Several studies have examined the impact of such restrictions on power generation. Economic benefits arising from different ecological flows are studied in [23]. The way in which ramping restrictions affect generation, thereby limiting production during peak periods, is analyzed in [24]. In [25], it is concluded that such restrictions might force turbines to operate with inappropriate flows or at head values outside their design range, reducing the overall plant efficiency and increasing the risk of cavitation and mechanical vibration. In the Guadalquivir Basin, the requirements for ramping and water use are imposed by the CHG.

The short-term optimal scheduling of hydropower generation has been extensively studied using optimization models. Optimal operating procedures are needed in the planning of complex water resource systems, to ensure the optimal use of the available resources. Mathematical models developed for optimization of hydropower operation are reviewed in [26, 27]. A multi-objective approach for the short-term scheduling of a hydroelectric power system is also formulated in [28]. The study shows that two companies in free competition but that are able to negotiate can achieve greater energy gains and reduce energy waste. The results are compared with those from an approach in which the management system benefits a single company. The study demonstrates that greater individual benefits can be achieved in striving for common benefits. The importance of the control of the heads of the hydropower plants, when optimizing the complete hydropower system, is also highlighted [29]. A comparative analysis of the results from linear and nonlinear programming (NLP) models is presented in [30]. They conclude that the NLP model is more complex and accurate compared with competing models, and it is particularly suited to the establishment of guidelines for real-time operation. Short-term studies of a hydropower systems using NLP approaches and considering head dependency are conducted in [31, 32]. They conclude that the NLP model has many advantages over a linear model, because it allows more accurate representation of the characteristics of hydroelectric power generation. Approaches for the management of water resources using NLP, genetic algorithms and linear programming are studied in [33]. They conclude that NLP provides faster and more accurate analysis than genetic algorithms. In [34], a mixed-integer model to solve the short-term hydropower scheduling problem is used. This model optimizes the water time delay, which is the time required for discharged water from an upstream reservoir to reach its downstream reservoir. They conclude that the model accurately describe the coupling of hydraulic and electrical factors in cascaded hydropower stations. Four scenarios are considered in [21], with three objectives: maintaining ecological flow, attaining water supply, and optimizing hydropower generation. In each scenario, each of the different objectives are optimized, while the other objectives are treated as target constraints.

Planning and scheduling models are reviewed in [35], highlighting the greater efficiency of stochastic models. All mathematical models include system parameters that are uncertain by their nature, and this uncertainty are explicitly considered. Because of the relatively short time horizon of short-term studies, in general all system parameters are often assumed to be deterministic. However, the solution obtained can be completely impractical if the uncertainties are considered, and that even a small perturbation may make the optimal schedule unworkable [36]. In typical stochastic programming models, the number of scenarios increases exponentially, as the number of uncertain parameters increases. This effect limits the utilization of stochastic models in practical applications in which a large number of parameters are uncertain [37]. Therefore, in the literature NLP is not frequently applied to stochastic multi-reservoir systems, because of the large computational resources that are required [38].

This study investigates in this way, using NLP and by applying strong operational constraints. Monte Carlo simulations are used in the representation of uncertainties associated with water flows in short-term NLP studies, with time-series modeling flows and production to be determined. For the case of the Guadalquivir River, the study addresses the self-scheduling problem of a hydro basin with 18 plants. The operation of this basin is strongly constrained by ecological and social restrictions and by the irregularity and scarcity of the water inflow. The model considers the specific features of the different hydropower plants, the spatial–temporal coupling between reservoirs, the actual travel time between reservoirs, and the stochastic nature of the inflows. The head of each reservoir is represented by a piecewise linear approximation related to the morphology of the reservoir, without requiring the use of integer variables. Time-series scenarios of water inflows are calculated, and an optimized daily operation strategy is determined in each scenario. The results show that the statistical distribution of the main variables changes across the basin, reflecting differences between the types of hydropower plants, travel times, ecological constraints, human consumption and storage capacities. Significant variations in the statistical distribution of the main variables for optimal basin operation are observed. The simulations also show that uncertainty about the economic profit is larger than that related with the water inflow. This increase in the uncertainty is likely due to nonlinearities in the model and the extension of the basin.

4.2 The Basin

Several previous studies have analyzed the implementation of the WFD in Spain and its economic impact. Three studies published in 2000 and 2011 analyze the impact of water pricing on three irrigated areas in Spain [10, 39, 40]. All the three studies conclude that the use of the price mechanism alone fail to significantly reduce agricultural water consumption. In [41], it is claimed that current water pricing policies fail to convey the correct message about the responsible use of water resources. An increase in water prices results in higher costs for the farmer, reduced profits, and ultimately land abandonment [42]. In southern Spain, the supply–demand imbalance is especially difficult to resolve for the context of increasing water consumption and scarcity [43]. Water resources are under severe pressure, and the margin between available water supply and the demand is decreasing. Guadalquivir Basin management is historically associated with a management style that stresses on economic development [44, 45]. As a result, this region has been extensively studied. Following [41], the current lack of sustainability of water resources in the Guadalquivir system is attributable to several factors, including obstacles to the adoption of more efficient technology, limited incentives for reducing water use, an unsuitable institutional framework, weak enforcement of environmental policies, and differences in the degree to which environmental concerns are integrated into sectoral policies. An improvement in water-use efficiency could be key to mitigating water shortages and reducing environmental problems. The modernization of irrigation methods has a rebound effect and investigating is an urgent scientific task, [46]. The rebound effect suggests that an increase in the efficiency with which a resource is used tends to increase (rather than decrease) the rate of consumption of that resource. In 2012, the European Commission identified this effect as a potential barrier to reducing water use [47]. However, a reduction in the irrigated area might be inevitable in the region, with implications for the regional economy and level of employment of the Andalusia region, [43]. In Spain, irrigated agriculture plays an important role in economic development, with irrigated land comprising approximately 23% of the total agricultural surface area, generating 57% of total yield and accounting for 60%

of agricultural employment [42]. Some authors conclude that political solutions to the management of water resources in Spanish basins have focused on increasing the water supply and modernizing hydro-developments, notwithstanding claims of radical change [45, 48]. In [49] the same problems are reported and in [50] the lack of communication between those actors affected and the relevant authorities is highlighted.

The irregularity and scarcity of water supply is another important characteristic of this region Guadalquivir Basin, Andalusia, in the of southern Spain. The mean annual flow in the basin is 596 mm; however, this average value changes significantly over space and time. In the areas of lower elevation, on the eastern side of the basin, the average annual precipitation is below 300 mm, whereas at the mountain summits it is approximately 1,000 mm. Evapotranspiration works in the opposite way: the rates are highest in the valley and lowland areas and lowest at the summits. Annual precipitation ranges from 300 mm to 1,000 mm, and years with extremely high or low precipitation tend to cluster together, compounding the effect of droughts and floods. The seasonal variability in water supply is also significant. Precipitation is highest during winter, with peak rainfall between November and March, whereas summers are typically dry, with long periods of almost zero precipitation and high levels of evapotranspiration. Winter storms can be deluges; several areas in the basin have experienced rainfall rates of 150–200 mm within 24 h, equivalent to almost half the average annual precipitation [51].

The variability of precipitation presents challenges for flood control and drought protection in the Guadalquivir Basin. Over the past century, water resource management has been focused on the regulation of river and tributary flows for both flood control and water supply. Reservoirs have been constructed to control droughts, reduce scarcity and manage torrential storms.

Several studies have considered the impact of climate change on hydropower generation. Most of them [52-55] have concluded that droughts and increased variability reduce the benefits of hydropower. This effects present an important challenge to the regional economy.

The increase in temperature due to climate change [51] is expected to decrease the water resources available in the basin [56]. To address this consequence, the potential expansion of the number of reservoirs in the basin is studied by [57], it is concluded that nearly all the economically viable enclaves are already in use. Labadie [58] states that as the construction of new water storage projects tapers off, the focus should be switched to improving operational effectiveness, in order to maximize the contribution of the existing reservoirs.

In the basin area, competing water uses must be considered: water supply, hydropower generation and flood control. These objectives must be balanced while complying with legal contracts and respecting traditions of water allocation and use. Unfortunately, these restrictions could mean that many reservoirs fail to provide sufficient economic returns to justify their investment or maintenance costs [59].

This study addresses the scheduling problem of the upper basin of the Guadalquivir River in southern Spain, analyzing 18 cascaded plants along several parallel tributaries of the river (Fig. 4.1) and considering social and environmental constraints, scarcity, flood control, and the stochastic characteristics of the water inflow. All plants in the area are considered. Three types of reservoirs are observed: a) those used for human consumption with no electricity generation, b) traditional hydropower plants (HPPs), and c) run-of-river hydropower plants. The first type is used to provide irrigation for land and urban consumption. Traditional HPPs are located next to reservoirs, whereas run-of-river plants have negligible capacity to store. In total, 18 water reservoirs are considered: 14 with conventional hydropower generation, 2 with run-of-river hydropower generation, and other 2 only used for human consumption (irrigation and urban water uses). From the short-term planning point of view, this basin presents challenges because of the large number of HPPs along the parallel routes of the main course. Moreover, the large travel times between the first and final reservoir (at least 50 h) required the optimization algorithm to model a period larger than 24 h.

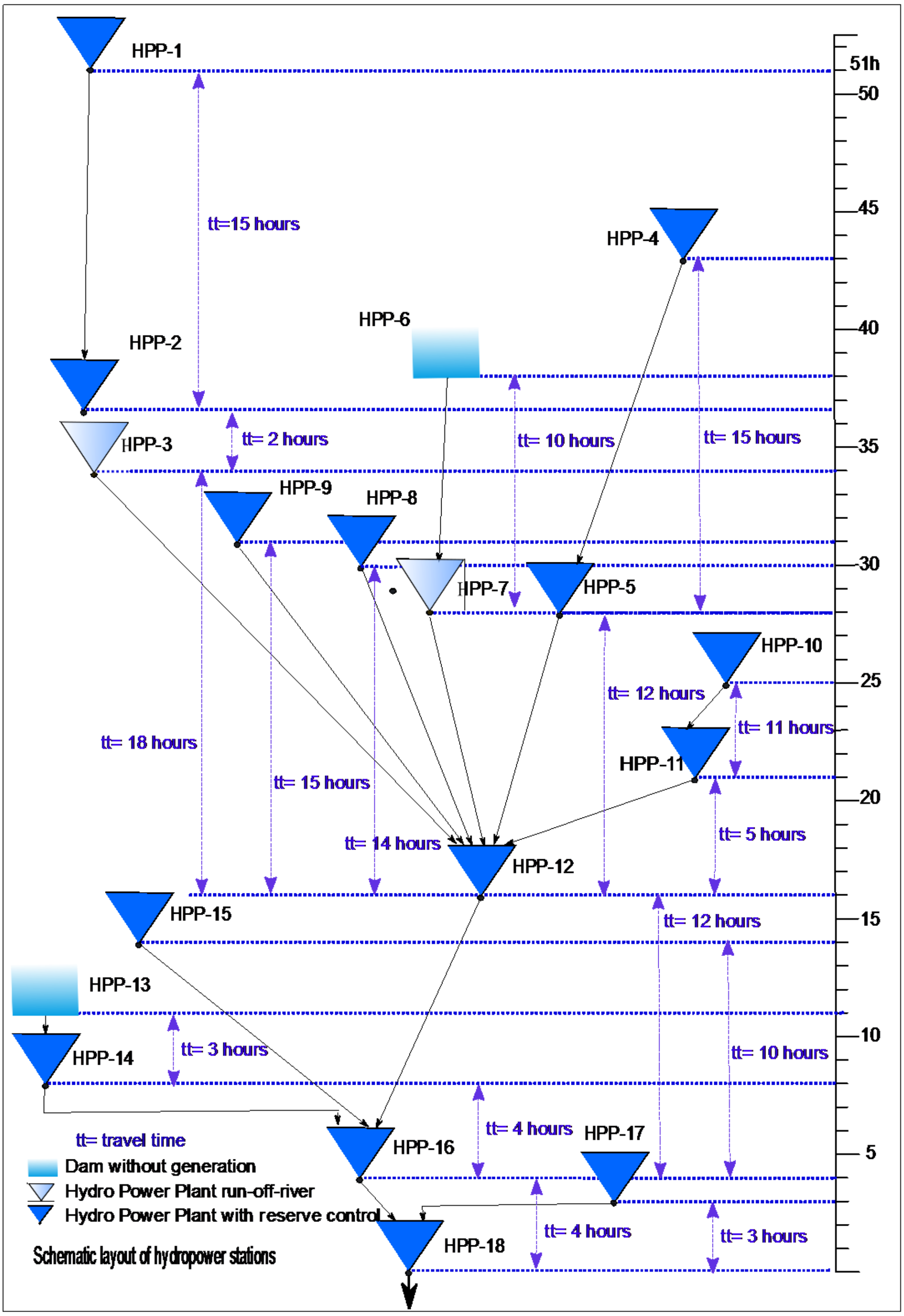


Fig. 4.1. Schematic layout of hydropower stations in upper Guadalquivir basin

In addition to the plants specifically dedicated to supply for human consumption, most traditional HPPs provide water for irrigation and urban uses. Spanish law establishes that water needs for ecological uses should be set out in the respective basin plans. The specific ecological values determined by the CHG for the basin are used in this study.

4.3 The Short-term Hydro-optimization Model

This chapter presents the nonlinear model of the basin. The basin is operated in the day-ahead electricity market to supply energy in a coordinated manner. Many owners operate in the basin; in this study, it is assumed that the offers made the best option for all the owners within the basin, and that the owners are price-takers (who lack the power to set the market price).

In a hydro basin where hydropower plants are connected both in series and in parallel, the release from an upstream plant contributes to the inflow of the downstream plants in several ways, establishing a spatial–temporal coupling between reservoirs. Head-dependency, coupled with the cascaded hydraulic configuration, increases the complexity and dimensionality of the problem.

The proposed formulation for the upper Guadalquivir Basin is generic and can be applied to any other basin in which there are strong restrictions on use.

4.3.1 The objective function

The goal of the optimization process is to derive the optimal operation of the coordinated hydropower plants in the basin for T periods, assuming that the expected hourly prices in the market are known. The natural influx or rainfall is assumed to be low and unpredictable. Two hundred scenarios are generated based on the real average values for flow and uncertainty. In the present case, the average inflow is derived from a historical series. Infiltration and evaporation effects are neglected; however, they can be included if necessary [60]. Because the basin is large, simulations are run over an horizon of 3 days. However, only the first 24 h are used to determine the hydropower plant operation for the following day.

The objective function to be maximized can be expressed as

$$\begin{aligned} Max \sum_{t=1}^{T}\sum_{i=1}^{nr} C_t M \eta_{i,t} g\, v_{i,t}^{T} h_{i,t} + \sum_{t=1}^{T}\sum_{i=1}^{nwr} C_t M \eta_i h_i g\, v_{i,t}^{T} + \\ \sum_{t=T}^{T}\sum_{i=1}^{n} C_{i,Te}^{\exp} v_{i,t} - \sum_{t=1}^{T}\sum_{i=1}^{nr}\sum_{j=1}^{nt} ks_{even_{j,i,t}} - k1v7 - k2v8. \end{aligned} \tag{4.1}$$

The first and second terms of Eq. (4.1) represent the profit maximization of traditional HPP and run-of-river plants. They use the expected market price C_t ($/MWh) and the power output of the unit. The power output is expressed as a product of the net efficiency of each plant $\eta_{i,t}$, the net head $h_{i,t}$, the water flow rate through the turbine $v^{T}_{i,t}$ in each time period t, a conversion factor M, and the gravity g. The net efficiency $\eta_{i,t}$ varies with the net head of each hydropower plant (Fig. 4.2), whereas the net head $h_{i,t}$ has a nonlinear dependency on the stored water in the reservoir. The third term in Eq. (4.1) represents, in simplified form, the future value of the water stored in the reservoir. The fourth term adds a penalty factor to avoid errors into the calculation of the head in periods when the water volume through the turbine is zero. The last two terms of the objective function are penalty factors for environmental flow and human consumption, allowing the algorithm to converge in low inflow situations. The terms used in the equations are defined below.

M	Conversion factor of water discharge from (Hm^3/h) to (m^3/s) and the conversion of power (MW) into energy (MWh). Note that time periods of 1 h are considered.
$\eta_{i,t}$	Net efficiency of the hydropower plant *i*.
$v_{i,t}^{T}$	Water volume flowing through the turbine of plant *i* at hour *t*.
g	Gravitational acceleration (m/s^2).
$h_{i,t}$	Net height at plant *i* at hour *t*
C_t	Expected electricity market price at hour *t* [€/MWh].
$v_{i,T}$	The useful volume stored in the reservoir of hydropower plant *i* at the end of the period $T = t$.
$C_{i,Te}^{\text{expected}}$	The future value of the water.
k	Coefficient of the penalty factor.
$S_{odd\_j,i,t}$	Odd slack variables.
n	Total number of hydropower plants, including conventional, run-of-river, and human consumption.
nr	The number of conventional hydropower plants, i.e., with reservoirs.
nwr	The number of hydropower plants without regulated reservoirs.

nt	Total number of sections linearized in the head/volume-stored curve (Fig. 4.2).
T	Total stages (h).
k1, k2	Penalty factors for environmental flow and human consumption.

k2 = 10 * k1 v8 has a larger penalty factor than v7.

The objective function is formulated as a quadratic equation with respect to the net water head and water discharge. The first and second terms in Eq. (4.1) can be rewritten as

$$\sum_{t=1}^{T}\sum_{i=1}^{nr+nwr} 0.5C_tM\ \eta_{i,t}g\left[\left(v_{i,t}^{T}+h_{i,t}\right)^2-\left(v_{i,t}^{T}\right)^2-\left(h_{i,t}\right)^2\right].$$

The other terms in Eq. (4.1) are linear expressions.

When price uncertainties are considered, the above formulation can be used to calculate the optimal operation in each scenario, using Monte Carlo simulation.

The optimal result is subject to equality and inequality constraints. These constraints are discussed in the following subsection.

4.3.2 Equality constraints

- ***Net efficiency***

Net efficiency varies with the net head in a linear way [61]:

$$\eta_{i,t}=\eta_i^0+\alpha_i h_{i,t}.$$

The parameter αi is given by:

$$\alpha_i = \left(\eta_i^{max} - \eta_i^{min}\right) / \left(h_i^{max} - h_i^{min}\right),$$

where η_i^{max} and η_i^{min} are the maximum and minimum performance indexes for each hydropower plant, respectively.

- ***The curve head/water stored***

The head and water level in a reservoir have a nonlinear relationship, and several approaches have been taken to represent this relationship. In [62], the head dependency on discontinuous operating regions and discharge ramping constraints in two cascaded hydropower systems with up to seven cascaded reservoirs is considered. Nonlinearity between the specific head level and the actual hydropower generated can be approximated using a two-segment linear curve with breakpoints at the full gate position, the best efficiency positions, and a point representing the minimum flow [63]. Also, the nonlinearities of the relationships between the power produced, the water discharged, and the head of the reservoir can be represented using the discretization of a set of nonconcave curves [34].

The electrical power, net head ans turbine water discharge can be obtained using a so-called under-relaxed iterative procedure, where the net head is successively updated until convergence is achieved, [64]. The sucessive iterations are then used to build the input–output curves. An enhanced linearization technique to represent a mixed-integer model of the head effect is presented in [65], adopting a specialized approximation methodology for the three-dimensional relationship between power production, water volume and flow. In other studies, the same approach is followed, requiring integer variables to change from one section to another of the piecewise linear curve.

The here proposed formulation also uses linearization by parts. However, integer variables are not required, when using slack variables and a penalty factor. When modeling the upper Guadalquivir Basin, 18 HPPs are represented over a period of more than 50 h. The head/water curve for each HPP within each hour is represented by several linearized parts. Therefore, in previous approaches, many integer variables are needed, requiring large computational times and causing convergence problems. The use of complementary variables in a continuous approach allows a simple and accurate representation of the variation of the reservoir head curve with the stored water at each reservoir.

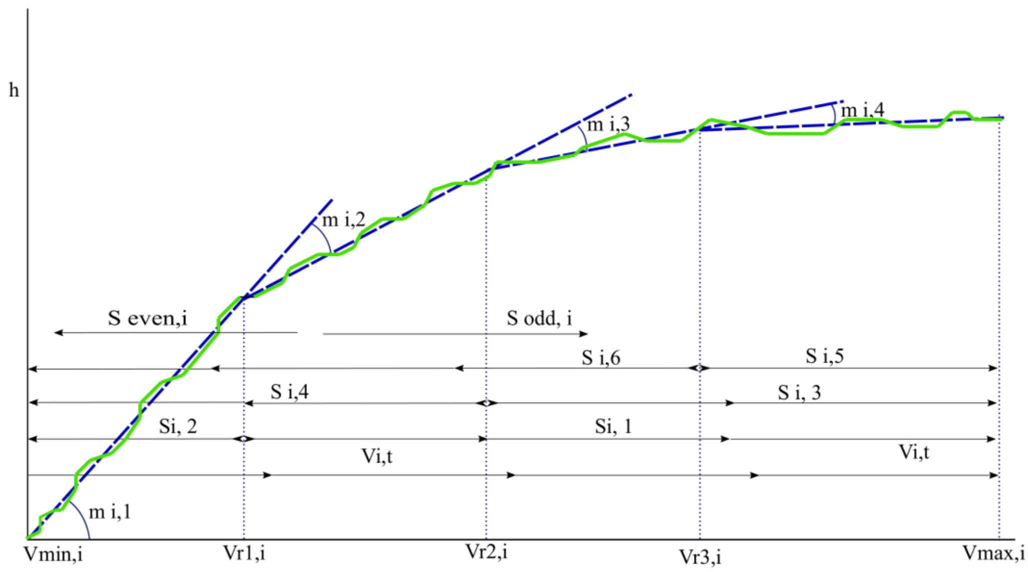


Fig. 4.2. Piecewise linear head/volume stored curve

In Fig. 4.2, the green curve represents the relationship between the accumulated water and the head in a traditional HPP, depending on the morphology of the reservoir. In present approach, this curve is discretized by parts. The following equations represent the linearized curve:

$$h_{i,t} = f\left(v_{i,t}\right) = h_i^{\min} + m_{i,1} v_{i,t} + \sum_{j=1}^{nt}\left(m_{i,j+1} S_{i,j,t}^{\text{odd}}\right) \quad i=1,...,nr+nwr;\ nt=1,...,nt \tag{4.2}$$

$$v_{i,t} + S_{\text{even}\_j,i,t} - S_{\text{odd}\_j,i,t} = v_{nt} \tag{4.3}$$

$$\begin{aligned} &S_{\text{even}\_j,i,t} \geq 0 \\ &S_{\text{odd}\_j,i,t} \geq 0 \end{aligned} \tag{4.4}$$

with the following variable definitions:

$h_{i,t}^{\min}$	The minimum head is the difference between the head intake level and the tailrace level
$vr_{i,t}$	Storage of reservoir *i* at the end of stage *t*
$m_{1,i}$	Slope of the first tranche for the dam's hydropower plant *i*

where the slope of the first tranche for the dam's hydropower plant *i* , expressed in the function $v_{i,t}$–h, is:

$$m_{\text{i,j}} = \frac{vr_{j,i} - vr_{j-1,i}}{h_{\text{i,j}} - h_{\text{i,j}-1}},$$

$S_{\text{odd}\_j,i,t}$	Variable slack with an odd index
$vr_{j,i}$ $\quad v_{\min,2,...,}v_{\max}$	Values of the stored volume for each tranche for hydropower plant *i*
nt	Set of indices for the blocks of the piecewise linearization of the head/stored volume curve

The net head varies nonlinearly with the volume of the reservoir, following the green piecewise curve shown in Fig. 4.2. In this case, four parts are used to linearize the nonlinear curve. In Eq. (4.2), the net head is a function of the following factors: a constant initial net head ($h_{i,t}^{\min}$), the initial gradient ($m_{1,i}$) multiplied by the stored volume (second part of Eq. (4.9)), and the differences in gradient in successive parts of the curve $(m_{nt+1} - m_{nt})$ multiplied by complementary variables ($s_{\text{odd}\_j,i,nt}$), measuring the distance at the right side of each $vr_{i,t}$. For example, if

$$vr2,i \le vr_{i,t} \le vr3,i ,$$

$$h_{i,t} = h_i^{\min} + m_{i,1}\ v_{i,t} + \sum_{j=1}^{nt}\left(m_{i,j+1}\ s_{i,j,t}^{\text{odd}} \right) \quad i = 1,\ldots,nr ,$$

where $s_{\text{odd}\_3,i,nt} = s_{\text{odd}\_4,i,nt} = 0$.

The values of the complementary variables, measuring the distances to the left $(s_{\text{even}\_j,i,t})$ and right $(s_{\text{odd}\_j,i,t})$ between $vr_{i,t}$ and the limits vr_{nt}, are obtained using Eq. (4.3). The complementary variables $(s_{\text{even}\_j,i,t})$ are minimized in the objective function, given by Eq. (4.1), using a small penalization factor *k*. In this way, the minimum values of the complementary variables can be calculated. Complementary variables assume nonnegative values through Eq. (4.4). This allows the optimization problem to be solved in a straightforward way, and larger systems with more variables can be represented and analyzed.

As in previous studies, the authors assumed that the net head varies with the discharge at the end of each hour. This assumption is justified when the storage level variations are relatively small, as in the case of study. These small variations are considered in the net head over the following hour.

- ***Water balance in hydropower plants with regulated reservoirs***

The balance equation for hydropower plants with reservoirs considers the state of the reservoir in the previous period, the natural inflow, contributions to the flow through the turbine of water from upstream plants, water spilled and consumed and ecological volumes. The equation is as follows:

$$v_{i,t} = v_{i,t-1} + v_{i,t}^{AF} + v_{i-1,t} - v_{i,t}^{T} - v_{i,t}^{S} - v_{i,t}^{HC} - v_{i,t}^{EF} \qquad \text{i=1...nr} \qquad (4.5)$$

With the following variable definitions:

$v_{i,t-1}$ The useful volume stored in the reservoir of hydropower plant *i* in the period *t*–1

$v_{i,t}^{AF}$ Individual flows into reservoir *i* at period *t*, not considering the flows coming through the river from the previous plants; the predicted water inflow in period *t (t* ϵ *T)* [Hm^3/h]

$v_{i-1,t}$ The flow into reservoir *i* at period *t* through the river from an upstream plant (or plants)

$v_{i,t}^{T}$ The water volume flowing through the turbine at hour *t* at plant *i* [Hm^3/h]

$v_{i,t}^{S}$ The deviated (spilled) water volume at hour t at plant i [Hm^3/h]

$v_{i,t}^{HC}$ The water consumed for human uses delivered by plant i at hour t [Hm^3/h]

$v_{i,t}^{EF}$ The minimum (ecological) volume to be maintained in the river downstream of reservoir i [Hm^3/h]

The water travel times are considered in the formulation, and do not require integer variables.

- ***Water balance in run-of-river hydropower plants***

Run-of-river hydropower plants have a negligible storage capacity. Therefore, in Eq. (4.5), the related terms are discarded, giving Eq. (4.6):

$$v_{i,t}^{AF} + v_{i-1,t} - v_{i,t}^{T} - v_{i,t}^{HC} - v_{i,t}^{S} - v_{i,t}^{EF} = 0 \quad i=1...nwr \tag{4.6}$$

- ***Water balance in human consumption reservoirs***

Reservoirs intended only for human consumption do not have electricity generation capacity. However, they have a storage capacity that allows a more cost-effective use of resources and better flooding control in the basin to be achieved. In these reservoirs, the hydropower generation term is removed from Eq. (4.5), resulting in Eq. (4.7):

$$v_{i,t} = v_{i,t-1} + v_{i,t}^{AF} + v_{i-1,t} - v_{i,t}^{S} - v_{i,t}^{HC} - v_{i,t}^{EF} \qquad i=1...hr\ , \tag{4.7}$$

where *hr* is the number of human reservoirs

- ***Flow into reservoirs from upstream plants***

The flow from upstream plants is given by

$$v_{i-1,t} = \sum_{\lambda i}\left(v^{T}_{i-1,t-t_v} + v^{S}_{i-1,t-t_v}\right) \quad i=1,\ \dots,\ (nr+nwr) \tag{4.8}$$

where $v^{T}_{i-1,t-t_v}$ is the water volume flowing through the turbine at hour (*t–tv*) from the upstream plants, $v^{S}_{i-1,t-t_v}$ is the spilled volume at hour (*t–tv*) from the upstream plants, and λi is the number of hydropower plants upstream of hydropower plant *i*, including the branches upstream of *i*.

Eq. (4.8) models the contribution made by water flow from upstream reservoirs to the water volume flowing through the turbine and the spilled volume considering water travel time. In the case of study, up to six branches flow into a reservoir (at HPP 12).

- ***Constraints from previous period***

The initial reservation status of each reservoir at the start of the simulation period is expressed as:

$$v_{i,1} = v^{\text{Initial\_V}}_{i,1} \quad i = 1 \ldots nr \tag{4.9}$$

where $v_{i,1}$ is the specified volume at the beginning of the horizon in hour 1 for plant *i* and $v^{\text{Initial\_V}}_{i,1}$ is the amount of reserved water at the beginning of period $t = T$ at hour 1.

- ***Long-term constraints***

In the current scenario of irregular and scarce supply, short term planning is strongly linked with medium term planning. To calculate the optimal level in the reservoirs at the end of the simulation period, the program provides two options: a) use of the future value of stored water in Eq. (4.1), or b) pre-specification of the optimal final reserve using Eq. (4.10).

$$v_{i,T} = v_{i,t=T}^{\text{Final\_V}} \qquad i = 1...nr \quad , \tag{4.10}$$

Where

$v_{i,T}^{\text{Final\_V}}$ is the specified amount of water in the reserve at the end of the period $t = T$.

The regulations set stringent long-term values for stored water on a three-year horizon. These values need to be transferred from medium to short term planning.

4.3.3 Inequality constraints

- ***Human consumption***

Rainfall is the driving force of all hydrological processes and is the most important input to any runoff calculation or modeling procedure [66]. What are often perceived as water scarcity problems may actually be water quality problems. One important cause of shortages of clean drinking water is the assumption that water consumption must contain volumes necessary for sanitation. With the current growth of urban populations and the increasing difficulty in finding new water sources, it is necessary to satisfy the growing water demand using new strategies. Urban hydrology is an applied science that develops urban hydrological models based on data collection, calculation, and modeling. It has recently been used to improve the measurement and prediction of urban rainfall [67]. Despite these advances, many important challenges remain. In particular, further studies are needed to improve short-term rainfall prediction, the performance of the technologies used to restore the water balance and the treatment of emerging priority pollutants. This study considered urban water supply, other water uses and the methods available for satisfying water demand in most critical situations.

The costs of human water consumption in the Guadalquivir Basin are calculated in [68] and it is demonstrated their economic significance. Most plants in this basin provide water for human consumption in agricultural, industrial and urban uses. Water consumption is represented as a daily-specified expenditure for each plant. In our simulations, this consumption is assumed to be the same on each one of the three days. However, the consumption can be varied following forecast water demand, as shown in Eq. (4.11). In some simulations, when water inflow is low, human consumption could not be satisfied. To allow the algorithm to converge in these cases, an additional variable, v8, is introduced to minimize the human consumption requirements. Variable v8 is penalized in the objective function by imposing a cost that is larger than the other prices in the function. The water flows for human consumption are also limited by the water pipes, as shown in Eq. (4.12).

$$\sum_{t=1}^{24} v_{i,t}^{HC} \geq v_1^{CH}\text{-v8} \qquad if \quad t \leq 24$$
$$\sum_{t=24}^{48} v_{i,t}^{HC} \geq v_2^{CH}\text{-v8} \qquad if \quad 24 < t \leq 48$$
$$\sum_{t=48}^{72} v_{i,t}^{HC} \geq v_3^{CH}\text{-v8} \qquad if \quad 48 < t \leq 72 \tag{4.11}$$

where $v_1^{CH},\ldots,v_{nd}^{CH}$ are the consumption values each day on the *nd* different days and $v_{i,t}^{HC}$ is the output water consumption for human use delivered by plant *i* at hour *t.*

$$0 \leq v_{i,t}^{HC} \leq v_i^{HC\max} \qquad i = 1 \ldots nr \,, \tag{4.12}$$

where $v_i^{HC\max}$ is the maximum transmission capacity of the water pipes.

- ***Environmental restrictions***

Several studies have highlighted the importance of environmental restrictions on water operation planning and have examined their economic impact on the optimal operation of the system. The revenues of a hydropower plant are very sensitive to the magnitude of these restrictions [25]. Environmental constraints reduce the amount of water available for electricity production and therefore limit the ability of hydropower plants to match demand, reducing the provision of ancillary services [69]. In the Guadalquivir Basin, significant water rights are attached to ecological flows. These are taken into account in the model through minimum water discharge limits and they are applied to both the turbine discharge and the spillage. At times of reduced water inflow, these ecological flows cannot be satisfied. In these cases, the variable v7 allows the algorithm to converge by relaxing the ecological constraints. Variable v7 is included in the objective function, and carries a penalty value larger than the energy price in all periods:

$$v_{i,t}^{T} + v_{i,t}^{S} \geq v_{i,t}^{EF} \text{-v7} \quad i = 1, \ldots, (nr + nwr) . \tag{4.13}$$

4.3.4 Bounds on the variables

Many variables are bound by equipment or operational limits. These restrictions are discussed in the following subsections.

- ***Minimum and maximum water released***

These restrictions are derived as follows:

$$0 \leq v_{i,t}^{T} \leq v_{i}^{T\max} \quad i = 1, \ldots, nr , \tag{4.14}$$

where $v_{i}^{T\max}$ is the maximum production capacity of a hydropower plant *i*.

- ***Maximum and minimum useful reserves***

These limits are derived as follows:

$$0 \leq v_{i,t} \leq v_{i}^{\max} \quad i = 1, \ldots, nr , \tag{4.15}$$

where $v_{i}^{\max}$ is the maximum capacity of a reservoir *i*.

- ***Requirements of spillage***

During torrential storms, spillage is necessary to protect the dam. The flood control and drought protection offered by the dams in the Guadalquivir Basin is modeled as follows:

$$0 \le v_{i,t}^{S} \le v_i^{S\max} \qquad i = 1, \ \ldots \ , \ nr \ , \tag{4.16}$$

where $v_i^{S\max}$ is the maximum spillage capacity of a hydropower plant *i.*

- ***Height limits***

These restrictions are derived as follows:

$$h_i^{\min} \le h_{i,t} \prec \qquad = 1, \ \ldots \ , nr \tag{4.17}$$

4.4 Results and Discussion

This section presents the results for the coordinated reservoir management of the upper and middle basin of the Guadalquivir River. As the model explicitly accounts for the uncertainty of water inflow, 200 scenarios are generated based on the expected average values of the inflows and their uncertainty, representing the margin of the forecast error. For simplicity, only inflows into the basin heads (HPPs 1, 4, 6, 8, 9, 10, 13, 15, and 17) are here considered, and the same inflow curve is used in all the cases. Fig. 4.3 shows the inflow curve in average hourly values and the corresponding standard deviations. A Gaussian distribution is assumed for the average influx and standard deviation at each hour. Forecasts covering longer periods have larger errors, and the standard deviation values therefore increase with time. In the profile, the average inflow has clear hourly differences, with higher values on the first day and at the 60th. hour. The standard deviation slowly increased with the horizon and had a median value of 0.0013 Hm^3/h. The coefficient of variation is defined as the ratio of the standard deviation to the mean value. This coefficient is a measure of the dispersion of the statistical distributions. In this case, the average coefficient of variation for the water inflows is 0.65%, over the first 24 h.

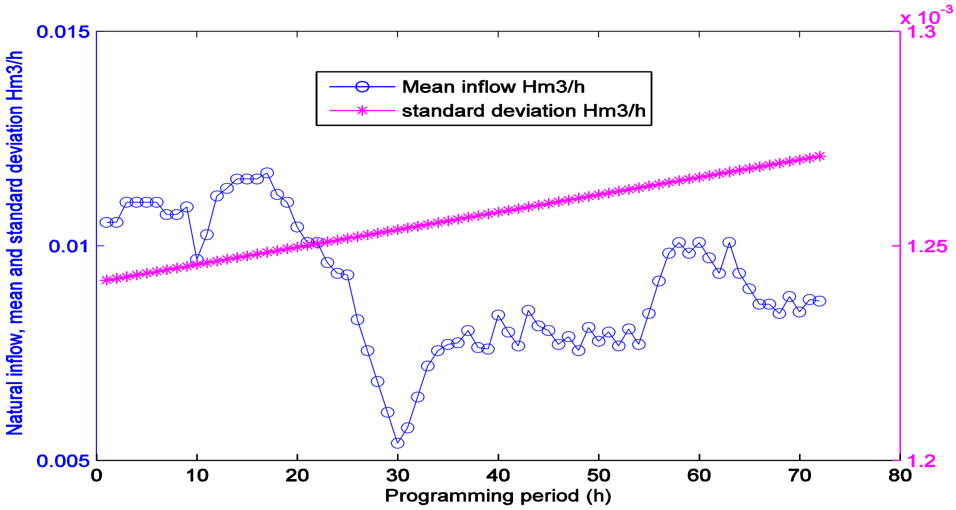


Fig. 4.3. Statistical distribution of water inflow in hydropower plants (HPPs) 1, 4, 6, 8, 9, 10, 13, 15, and 17

In addition to the water inflow data presented in Fig. 4.3, a constant inflow of 0.00576 Hm^3/h is included for HPP 3 over the first 2 hours. HPP 3 is a run-of-river hydropower plant and it has an ecological constraint downstream. This constant value represents the water flowing through the river from HPP 2, released on the previous day.

The system comprises 18 plants in cascade and in parallel tributaries along the upper Guadalquivir Basin. The dates and features of the different hydropower plants, including height, installed power, and reservoir capacity, are obtained from several sources [70-73]. The case of study covers 72 h, requiring

14259 variables and 14329 constraints (of which 3888 are nonlinear) in each scenario. The model is implemented on a standard computer with an Intel Core I5 750 processor and 4 GB of RAM, using CONOPT under GAMS. The computation time for all 200 scenarios is approximately 2 minutes.

To model human water consumption, typical values calculated by the Ministry of Environment of the Junta de Andalucía [74] are used. Ecological flow restrictions are taken from the values specified in the basin water plans [21]. Time-series scenarios are determined before running the Monte Carlo simulations. For each of the 200 scenarios, the optimized daily operation strategy is determined by solving this optimization problem. Typical daily prices in the Spanish market for March 2015 are based on data produced by the Operador del Mercado Ibérico de Energía (OMIE) [75] and used to simulate the optimal coordinated operation of the basin. Fig. 4.4 shows the statistical distributions of the storage levels and the water volumes flowing through the turbine used to produce electricity in each reservoir, obtained from the 200 simulations. For analytical purposes, the price profile in the period is included in the curves of the water volumes flowing through the turbines.

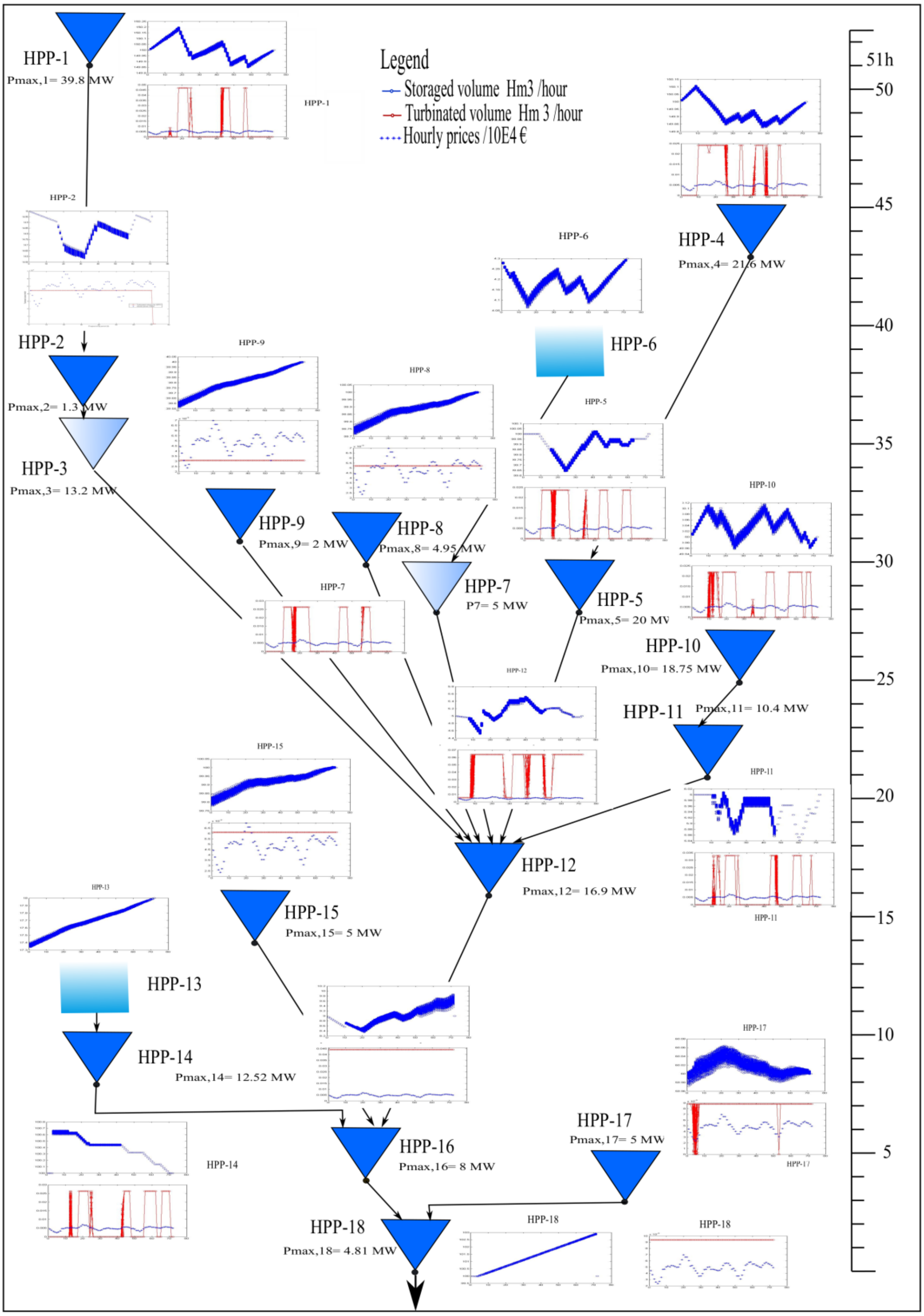


Fig. 4.4. Management of water volume flowing through turbines and stored water volume

From Fig. 4.4, the storage capacity of the hydropower plants, the price profile and the travel times significantly modify the statistical distribution of the inflows. The water flow after the first HPP in each head differs significantly from the inflow, as shown in Fig. 4.3. This difference is also noted between similar hydropower plants. HPP 6 and HPP 13 are supply dams with no electricity generation capacity. From Fig. 4.4, it can be seen that the management of HPP 6 allows profits to be maximized in the downstream plant HPP 7 by using hourly variations. However, HPP 14, downstream from HPP 13, is a hydropower plant with managed capacity. In this case, the discharge from HPP 13 at the beginning of the programming period increases the head of HPP 14, thus improving the efficiency of the generation. Therefore, dams without generation not only help with flood control, but also allow real-time control of water flow in the basin, meeting restrictions, improving generation, and increasing joint profits.

HPPs 8, 9, 15, and 17 behave in a similar way to HPP 13, depleting the reservoir at the beginning of the programming period, to improve the water height (and therefore the generation efficiency) of downstream plants. As the initial and final water levels in the reservoirs have the same value, in these plants the water inflows are used to reach the desired final level (in this case, approximately 50% of the total capacity of the reservoir). In the other plants, inflows and stored water are used to increase production in periods when prices are high, increasing the profitability of the integrated operation.

As expected, differences in scheduling in the 200 scenarios are more evident in the downstream reservoirs. However, these differences are concentrated in the early hours of the simulation for HPPs 8, 9, 13, 15 and 17, and the values are almost stabilized at the end of the simulation.

The management of the volumes of water for human consumption and spillage is presented in Fig. 4.5.

Most HPPs have no spillage, and for these plants, this curve is not represented. As the spilled volumes represent energy that is not available for electricity production, spilling is not generally advantageous. However, as the generation efficiency depends on the water height in the reservoir, it is sometimes convenient to spill water in early hours, as it is shown in the case of some of the upstream reservoirs. The management of spilled volumes in the downstream hydropower plants HPP 16 and HPP 18 is the opposite of that in the upstream HPPs. Discharge only occurs at the end of the programming period, to maintain a higher reserve at all times and to improve generation. This final spilled water is needed to mantain the initial and final water levels in the reservoir. The results demonstrate that better programming can be obtained by modifying the final reserve value, avoiding unnecessary spillage and making use of the existing resources more efficiently.

HPP 2 continuously spills water. The installed power of this plant is $V^{T}_{max} = 0.00445$ Hm^3/h. However, the run-of-river HPP 3, downstream from HPP 2, must maintain an ecological discharge into the basin $V_{ec\_min} = 0.00576$ Hm^3/h without external inflow. Therefore, HPP 2 discharges water to reach the required ecological flow. In this way, legislation affects both the supply priorities and the optimal operation of the plants.

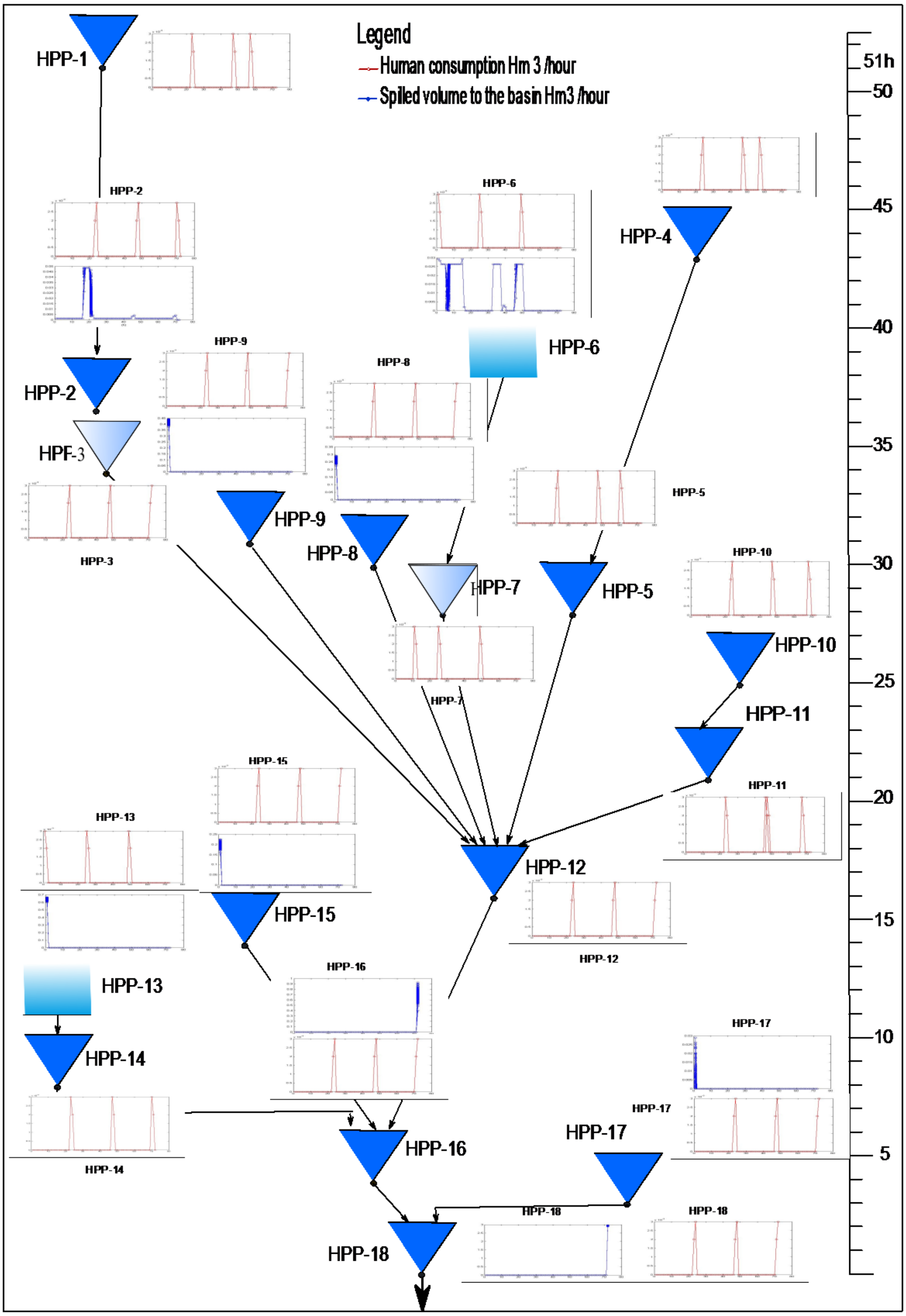


Fig. 4.5. Management of spilled volumes and volumes for human consumption

As shown in Fig. 4.5, the transfer of consumption volumes is performed in two different ways. If a reservoir has no turbines, consumption volumes are assigned at the beginning of each day. If a reservoir has generation capacity, volumes are transferred at the end of each day. This mode of operation allows the plants to operate with a higher level of reserves and to achieve higher performances. To ensure compliance with the specified priorities, it is necessary to verify the operation of the program at the most critical points in the basin. One of the most critical points is HPP 3. This is a run-of-river HPP lacking its own inflow and it must meet restrictions on human consumption and ecological flow. The behavior of this hydropower plant across the 200 scenarios is shown in Fig. 4.6. Both requirements are consistently met in all simulations.

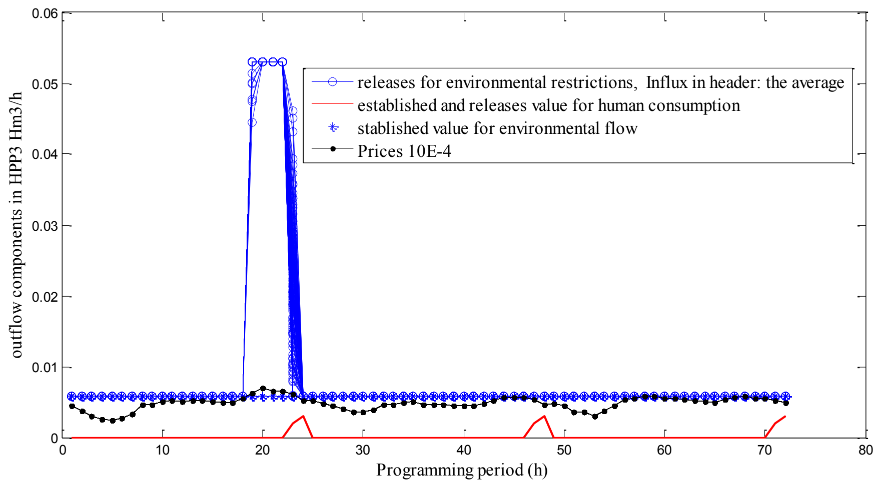


Fig. 4.6. Results of 200 random scenarios for HPP 3

Across the 200 random scenarios, the results demonstrate compliance with the environmental flows and the human consumption volumes in all periods.

The results demonstrate the robustness of the solutions produced by the model, considering the irregular and scarce water supply characteristics of the basin.

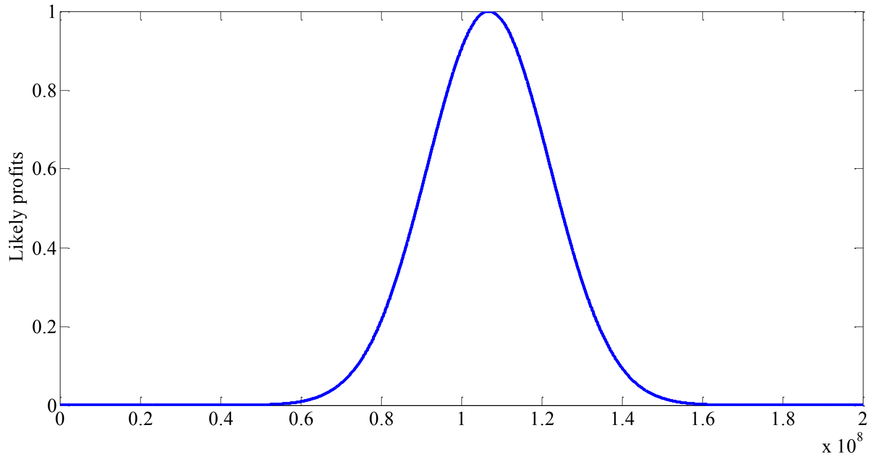


Fig. 4.7. Bell curve of total profit

Fig. 4.7 shows a bell curve of the total profits in the stochastic scenarios. The median value is 1.0685e + 08 €/day, with a standard deviation of 1.5285e + 06 €/day. The coefficient of variation for the profits is 1.4%, which is 115% larger than that for the water inflows (0.65%, see Fig. 4.3). Because of the nonlinear representations in the basin, the uncertainties in the profits are larger than those in the water forecasts.

4.5 Conclusions

In some regions, the consequences of hydropower management for the surrounding ecosystem are sufficiently serious; therefore, restrictions on the water flow are warranted. This is an issue that has received attention in both Spanish and European jurisdictions. The economic and social importance of water in the Guadalquivir Basin has resulted in its overuse. The EU requires resources to be used sustainably. This study aims to provide a tool for the coordinated management of a river basin, ensuring compliance with ecological restrictions, governmental regulations on water resource allocation, technical characteristics of the local hydropower plants and best profitability of the hydropower operators. The results demonstrated that coordinated resource management can allow legal requirements to be met while preserving the ecological, economic, and social benefits of the water management system.

4.6 References

[1] A. Iglesias, L. Garrote, A. Diz, J. Schlickenrieder and F. Martin-Carrasco. Re-thinking water policy priorities in the mediterranean region in view of climate change. Environ. Sci. & Policy 14(7), pp. 744-757. 2011.

[2] R. G. Evans and E. J. Sadler. Methods and technologies to improve efficiency of water use. Water Resour. Res. 44(7), pp. - W00E04. 2008. . DOI: 10.1029/2007WR006200.

[3] V. A. Barber, G. P. Juday and B. P. Finney. Reduced growth of alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature 405(6787), pp. 668-673. 2000.

[4] P. Goderniaux, S. Brouyere, S. Blenkinsop, A. Burton, H. J. Fowler, P. Orban and A. Dassargues. Modeling climate change impacts on groundwater resources using transient stochastic climatic scenarios. Water Resour. Res. 47(12), 2011.

[5] R. M. Saleth. Introduction to special section on river basin management: Economics, management, and policy. Water Resour. Res. 40(8), pp. - W08S01. 2004. . DOI: 10.1029/2004WR003368.

[6] Inter governmental Panel on Climate Change, (IPCC). (2016). IPCC Report Graphics.

[7] X. Wang, J. Zhang, S. Shahid, E. Guan, Y. Wu, J. Gao and R. He. Adaptation to climate change impacts on water demand. Mitigation Adapt. Strat. Global Change pp. 1-19. 2014.

[8] WFD. 32000L0060: Directive 2000/60/EC of the European Parliament and of the Council of 23 October. (2015). 32000L0060: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.

[9] C. Giupponi. Decision support systems for implementing the european water framework directive: The MULINO approach. Environmental Modelling & Software 22(2), pp. 248-258. 2007.

[10] J. Berbel, M. A. Mesa-Jurado and J. M. Pistón. Value of irrigation water in guadalquivir basin (spain) by residual value method. Water Resour. Manage. 25(6), pp. 1565-1579. 2011.

[11] L. Hein, C. Obst, B. Edens and R. P. Remme. Progress and challenges in the development of ecosystem accounting as a tool to analyse ecosystem capital. Current Opinion in Environmental Sustainability 14pp. 86-92. 2015.

[12] P. Bartelmus. Do we need ecosystem accounts? Ecol. Econ. 2015.

[13] B. Manos, T. Bournaris, M. Kamruzzaman, M. Begum, A. Anjuman and J. Papathanasiou. Regional impact of irrigation water pricing in greece under alternative scenarios of european policy: A multicriteria analysis. Reg. Stud. 40(9), pp. 1055-1068. 2006.

[14] G. M. Bazzani, S. Di Pasquale, V. Gallerani, S. Morganti, M. Raggi and D. Viaggi. The sustainability of irrigated agricultural systems under the water framework directive: First results. Environmental Modelling & Software 20(2), pp. 165-175. 2005.

[15] F. A. Ward. Decision support for water policy: A review of economic concepts and tools. Water Policy 9(1), pp. 1-31. 2007.

[16] Ministerio de Agricultura, Alimentación y Medio Ambiente. Confederación Hidrográfica del Guadalquivir, (CHG) Dirección General del Agua. (Diciembre de 2010). Planes Hidrológicos. Available: http://www.famp.es/famp/intranet/documentos/PH/PH%20GUADALQUIVIR/Anejos/Anejo%205%20Caudales%20Ecologicos/Anejo%205%20-%20IMPLANTACION%20REGIMEN%20CAUDALES%20ECOLOGICOS.pdf

[17] Ministerio de Medio Ambiente «BOE» núm. 176, de 24 de julio de 2001 Referencia: BOE-A-2001-14276. (2016). Real Decreto Legislativo 1/2001, de 20 de julio, por el que se aprueba el texto refundido de la Ley de Aguas. - BOE-A-2001-14276-consolidado.pdf.

[18] Ministerio de Agricultura Alimentación y Medio Ambiente, Confederación Hidrográfica del Guadalquivir. (2016). Caudales ecológicos.

[19] M. J. Bradford, G. C. Taylor, J. A. Allan and P. S. Higgins. An experimental study of the stranding of juvenile coho salmon and rainbow trout during rapid flow decreases under winter conditions. N. Am. J. Fish. Manage. 15(2), pp. 473-479. 1995.

[20] G. Berland, T. Nickelsen, J. Heggenes, F. Økland, E. Thorstad and J. Halleraker. Movements of wild atlantic salmon parr in relation to peaking flows below a hydropower station. River Research and Applications 20(8), pp. 957-966. 2004.

[21] H. Wang, E. D. Brill, R. S. Ranjithan and A. Sankarasubramanian. A framework for incorporating ecological releases in single reservoir operation. Adv. Water Resour. 78pp. 9-21. 2015.

[22] S. Niu and M. Insley. On the economics of ramping rate restrictions at hydro power plants: Balancing profitability and environmental costs. Energy Econ 39pp. 39-52. 2013.

[23] D. A. Harpman. Assessing the short-run economic cost of environmental constraints on hydropower operations at glen canyon dam. Land Econ. pp. 390-401. 1999.

[24] B. K. Edwards, S. J. Flaim and R. E. Howitt. Optimal provision of hydroelectric power under environmental and regulatory constraints. Land Econ. pp. 267-283. 1999.

[25] J. I. Pérez-Díaz and J. R. Wilhelmi. Assessment of the economic impact of environmental constraints on short-term hydropower plant operation. Energy Policy 38(12), pp. 7960-7970. 2010.

[26] W. W. Yeh. Reservoir management and operations models: A state-of-the-art review. Water Resour. Res. 21(12), pp. 1797-1818. 1985. . DOI: 10.1029/WR021i012p01797.

[27] A. Singh. An overview of the optimization modelling applications. Journal of Hydrology 466–467(0), pp. 167-182. 2012. . DOI: http://dx.doi.org/10.1016/j.jhydrol.2012.08.004.

[28] C. Lyra and L. R. M. Ferreira. A multiobjective approach to the short-term scheduling of a hydroelectric power system. Power Systems, IEEE Transactions On 10(4), pp. 1750-1755. 1995. . DOI: 10.1109/59.476038.

[29] S. Soares and A. A. Carneiro. Optimal operation of reservoirs for electric generation. Power Delivery, IEEE Transactions On 6(3), pp. 1101-1107. 1991.

[30] M. Barros, F. Tsai, S. Yang, J. Lopes and W. Yeh. Optimization of large-scale hydropower system operations. J. Water Resour. Plann. Manage. 129(3), pp. 178-188. 2003. Available: http://dx.doi.org/10.1061/(ASCE)0733-9496(2003)129:3(178). DOI: 10.1061/(ASCE)0733-9496(2003)129:3(178).

[31] A. J. Conejo, J. M. Arroyo, J. Contreras and F. A. Villamor. Self-scheduling of a hydro producer in a pool-based electricity market. Power Systems, IEEE Transactions On 17(4), pp. 1265-1272. 2002. . DOI: 10.1109/TPWRS.2002.804951.

[32] J. Catalão, S. Mariano, V. Mendes and L. Ferreira. Scheduling of head-sensitive cascaded hydro systems: A nonlinear approach. Power Systems, IEEE Transactions On 24(1), pp. 337-346. 2009.

[33] X. Cai, D. C. McKinney and L. S. Lasdon. Solving nonlinear water management models using a combined genetic algorithm and linear programming approach. Adv. Water Resour. 24(6), pp. 667-676. 2001.

[34] X. Ge, L. Zhang, J. Shu and N. Xu. Short-term hydropower optimal scheduling considering the optimization of water time delay. Electr. Power Syst. Res. 110pp. 188-197. 2014.

[35] P. M. Verderame, J. A. Elia, J. Li and C. A. Floudas. Planning and scheduling under uncertainty: A review across multiple sectors. Ind Eng Chem Res 49(9), pp. 3993-4017. 2010.

[36] X. Lin, S. L. Janak and C. A. Floudas. A new robust optimization approach for scheduling under uncertainty:: I. bounded uncertainty. Comput. Chem. Eng. 28(6–7), pp. 1069-1085. 2004. . DOI: http://dx.doi.org/10.1016/j.compchemeng.2003.09.020.

[37] S. L. Janak, X. Lin and C. A. Floudas. A new robust optimization approach for scheduling under uncertainty: II. uncertainty with known probability distribution. Comput. Chem. Eng. 31(3), pp. 171-195. 2007. . DOI: http://dx.doi.org/10.1016/j.compchemeng.2006.05.035.

[38] J. W. Labadie. Optimal operation of multireservoir systems: State-of-the-art review. J. Water Resour. Plann. Manage. 130(2), pp. 93-111. 2004.

[39] J. Berbel and J. A. Gómez-Limón. The impact of water-pricing policy in spain: An analysis of three irrigated areas. Agric. Water Manage. 43(2), pp. 219-238. 2000.

[40] J. Gómez-Limón and J. Berbel. Multicriteria analysis of derived water demand functions: A spanish case study. Agricultural Systems 63(1), pp. 49-72. 2000.

[41] F. Porta Visa. Hacia la sostenibilidad de los recursos hídricos en el siglo XXI: Un gran reto para los servicios de agua y saneamiento. Revista Del Instituto De Estudios Económicos (4), pp. 147-154. 2001.

[42] I. F. García-Tejero, V. H. Durán-Zuazo and J. L. Muriel-Fernández. Towards sustainable irrigated mediterranean agriculture: Implications for water conservation in semi-arid environments. Water Int. 39(5), pp. 635-648. 2014.

[43] J. R. Diaz, E. Weatherhead, J. Knox and E. Camacho. Climate change impacts on irrigation water requirements in the guadalquivir river basin in spain. Regional Environmental Change 7(3), pp. 149-159. 2007.

[44] A. Bhat and W. Blomquist. Policy, politics, and water management in the guadalquivir river basin, spain. Water Resour. Res. 40(8), 2004.

[45] E. Swyngedouw. Into the sea: Desalination as hydro-social fix in spain. Ann. Assoc. Am. Geogr. 103(2), pp. 261-270. 2013.

[46] J. Berbel, C. Gutiérrez-Martín, J. A. Rodríguez-Díaz, E. Camacho and P. Montesinos. Literature review on rebound effect of water saving measures and analysis of a spanish case study. Water Resour. Manage. 29(3), pp. 663-678. 2015.

[47] European Commission. (2012). A Blueprint to Safeguard Europe's Water Resources, Brussels COM(2012)673/F1 - EN - 1-2012-673-EN-F1-1.Pdf.

[48] W. A. Blomquist, A. Dinar and K. Kemper. Comparison of institutional arrangements for river basin management in eight basins. World Bank Policy Research Working Paper (3636), 2005.

[49] L. del Moral Ituarte, A. Herrera Grao and A. Ramos Garrido. (Octubre de 2014).

Evaluación del primer ciclo de planificación DEMARCACIÓN HIDROGRÁFICA DEL GUADALQUIVIR.

[50] S. Valinia, H. Hansen, M. Futter, K. Bishop, N. Sriskandarajah and J. Fölster. Problems with the reconciliation of good ecological status and public participation in the water framework directive. Sci. Total Environ. 433pp. 482-490. 2012.

[51] Intergovernmental Panel on Climate Change, (IPCC). (2016). Fifth Assessment Report - Impacts, Adaptation and Vulnerability.

[52] M. Markoff and A. Cullen. Impact of climate change on pacific northwest hydropower. Clim. Change 87(3/4), pp. 451-469. 2008.

[53] R. Sternberg. Hydropower: Dimensions of social and environmental coexistence. Renewable Sustainable Energy Reviews 12(6), pp. 1588-1621. 2008.

[54] M. Marie, B. François, K. Stéphane and L. Robert. Adaptation to climate change in the management of a canadian water-resources system exploited for hydropower. Water Resources Management 23(14), 2009.

[55] H. I., T. D. and H. T. A comparison of stochastic and deterministic downscaling methods for modelling potential groundwater recharge under climate change in east anglia, UK: Implications for groundwater resource management. Hydrogeol. J. 17(7), pp. 1629-1641. 2009.

[56] I. Pulido-Calvo, J. C. Gutiérrez-Estrada and D. Savic. Heuristic modelling of the water resources management in the guadalquivir river basin, southern spain. Water Resour. Manage. 26(1), pp. 185-209. 2012.

[57] A. Álvarez Martínez and J. C. Mosquera Feijoo. En españa¿ son necesarias nuevas presas? [are new dams necessary in spain?] . Revista De Obras Públicas Number 3373, 51–55 1998.

[58] N. K. Dubash. World commission on dams. Handbook of Transnational Governance pp. 202-210. 2011.

[59] Agencia Estatal de Meteorología. Gobierno de España. (). (AEMET).

[60] J. P. S. Catalão, H. M. I. Pousinho and V. M. F. Mendes. Scheduling of head-dependent cascaded hydro systems: Mixed-integer quadratic programming approach. Energy Conversion and Management 51(3), pp. 524-530. 2010. . DOI: http://dx.doi.org/10.1016/j.enconman.2009.10.017.

[61] G. W. Chang, M. Aganagic, J. G. Waight, J. Medina, T. Burton, S. Reeves and M. Christoforidis. Experiences with mixed integer linear programming based approaches on short-term hydro scheduling. Power Systems, IEEE Transactions On 16(4), pp. 743-749. 2001.

[62] J. García-González, E. Parrilla and A. Mateo. Risk-averse profit-based optimal scheduling of a hydro-chain in the day-ahead electricity market. Eur. J. Oper. Res. 181(3), pp. 1354-1369. 2007.

[63] A. Borghetti, C. D'Ambrosio, A. Lodi and S. Martello. An MILP approach for short-term hydro scheduling and unit commitment with head-dependent

reservoir. Power Systems, IEEE Transactions On 23(3), pp. 1115-1124. 2008. . DOI: 10.1109/TPWRS.2008.926704.

[64] J. Niemczynowicz. Urban hydrology and water management–present and future challenges. Urban Water 1(1), pp. 1-14. 1999.

[65] T. Fletcher, H. Andrieu and P. Hamel. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. Adv. Water Resour. 51pp. 261-279. 2013.

[66] G. Hermida and E. D. Castronuovo. On the short-term optimisation of a hydro basin with social constraints. Computational Water, Energy, and Environmental Engineering 2(01), pp. 9. 2013.

[67] I. Guisández, J. I. Pérez-Díaz and J. R. Wilhelmi. Assessment of the economic impact of environmental constraints on annual hydropower plant operation. Energy Policy 61(0), pp. 1332-1343. 2013. . DOI: http://dx.doi.org/10.1016/j.enpol.2013.05.104.

[68] Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía. (2016). Inventario de las presas y embalses andaluces.

[69] S.A.I.H.(Sistema Automático de Información Hidrológica) del Guadalquivir(2016). Available: http://www.juntadeandalucia.es/agenciadelagua/saih/DatosHistoricos.aspx.

[70] Comité Nacional Español de Grandes Presas (CNEGP). (2015). Inventario de presas españolas, ficha técnica.

[71] Confederación Hidrográfica del Guadalquivir (CHG), Dirección general del agua. (2016). Confederación Hidrográfica USO ENERGETICO.pdf.

[72] Junta de Andalucía. (2016). S.A.I.H (Servicio Automático de Información Hidrológica) del Guadalquivir. Valores de aportación por embalse.

[73] Ministerio de Agricultura Alimentación y Medio Ambiente. (2016). Disposición 439 del BOE núm. 16 de 2016 - normativaphguadalquiviranexoviird1_2016_tcm7-409221.pdf.

[74] Operador del Mercado Ibérico de Energía, OMIE. (2016). Precios del mercado diario.

Chapter 5.

Conclusions

Abstract— **In this chapter, the final conclusions and contributions from the development of this work are presented. Also, publications derived from this research and future works to enhance the present study are included.**

Contents

5.1 General considerations

European legislation proposes a way to regulate environmental conditions, guarantying water quality and eco-friendly conservation. The application of these policies is strongly conditioned in river basins with scarcity and high variability of resources. Management tools are an aid to controlling resources shortages, while complying with strong restrictions ecological and legal uses. In this thesis, a software tool that simultaneously considers economic optimization and compliance with established priority and ecological restrictions is developed. The management tool is applied to two basins with very different characteristics: Guadalquivir basin, Southern Spain, and Chiese basin, Northern Italy. Optimization problems are used in the modelization of the basins. The research runs the implemented models in commercial solvers (in MATLAB and GAMS), widely available and proven, allowing the diffusion and comparison of the proposed methodology.

5.2 Contributions

The main contributions of this thesis are summarized below:

1. New formulations for the short-term optimization of a hydro basin, including social constraints and ecological flows, are developed. The

models allow obtain best economic profitability while satisfying European and local regulations, consumption requirements, rights of use, and environmental flows in an area with scarce resources.

2. The optimization models can be used to estimate costs for social consumption and environmental flows.
3. A novel study of the influence of transmission constraints and zonal prices on optimal hydro dispatching has been developed, through a nested algorithm based on the integration of the hydro generation block and a market model.
4. The nested algorithm is used to obtain: optimal generation of each hydro plant maximizing their profit and the better equilibrium point for the Italian market.
5. Research has been developed to reduce the computational times in the solution of large hydro systems. A new representation using linear restrictions and without requiring integer variables is obtained, allowing obtaining statistical results with adequate cpu times.
6. The proposed optimization problem runs satisfactorily in a large real basin, with 18 hydro plants of 3 different types, up to 3 convergent flows in the same reservoir and up to 72 hours of horizon.
7. Statistical methods are applied in short-term studies, when a large chain of reservoirs must be operated under very restrictively constraints. Results show the validity of the statistical methods and the influence of the uncertainties in the optimal solution.

5.3 Final Conclusions

The main contributions of this thesis are summarized below:

- After application of the proposed optimization model to two different study systems, it has been observed that the computational burden of the algorithm cannot pose a significant problem in the systems used. Also, no convergence problems have been observed in the solution of the proposed model.
- Given the nonlinear nature of the models, it is not possible to guarantee that the obtained solutions correspond to local or global optimums of the problem. However, the consistency of the solutions over a wide range of cases suggests that global optima are obtained.
- The proposed optimization problem adequately calculates best energy bids of a set of hydro power plants in basins, in an efficient way. The application of the proposed algorithm to consider the ecological flows and social consumptions required for the actual operation can be used as an assessment tool for the managers of the basin.
- Results show that different types of hydro plants (in this case, conventional, fluent and water consumption plants are represented) can be adequately represented in the same optimization problem. Moreover, controlling the management abilities of all plants

(including those without electric generation) can increase the operability in the basins.

- In the basin with stronger operational restrictions (Guadalquivir river), the study of different inflow shows that the social consumption of water has larger economic effect than to maintain the ecological flows in the basin. Initial evaluations of the costs of providing water for social uses are performed in the thesis.
- When the hydro plants have large penetration in the region (e.g., when transmission lines are congested) they can affect zonal prices. The results show that the algorithm changes the production of the plants for obtaining the best equilibrium point, resulting in a decrease of the average market price in the zone.
- Statistical methods are particularly adapted to represent large hydro basins with high travel times in short term studies, due to the uncertainties in the water and market conditions for more than 24 hours.

5.4 Publications

As a result of this research work, results have been reported in various forums. The developed publications are listed below.

Indexed Journals:

2013. Gloria Hermida, Edgardo D. Castronuovo. "On the Short-Term Optimization of a Hydro Basin with Social Constraints". Computational Water, Energy, and Environmental Engineering (CWEEE), 2013 http://dx.doi.org/10.4236/cweee.2013.21002

2016. Edgardo D. Castronuovo, Gloria Hermida, Majid Gholami, Cristian Bovo, Alberto Berizzi. "Optimal scheduling of a hydro basin in a pool-based electricity market with consideration of transmission constraints". Electric Power Systems Research, Elsevier, 2016, http://www.sciencedirect.com/science/article/pii/S0378779615003193.

2016. Gloria Hermida, Edgardo D. Castronuovo. "Hydropower Scheduling in a Basin with Stochastic Inflow and Heavy Ecological and Human Restrictions". Submitted.

International Conferences:

2016. Edgardo D. Castronuovo, Gloria Hermida. "On the Operational Optimization of Large Hydrological Basins". *SPEEDAM 2016*, June 22-24, 2016, Anacapri, Capri, Italia. Indexed by *IEEE Xplore*, doi: http://dx.doi.org/10.1109/SPEEDAM.2016.7525998

National conferences:

2011. Gloria Hermida, Edgardo D. Castronuovo. "On the Optimization of the Short-Term Operation of a Spanish Hydro Basin". *MixGenera, 2011*, University Carlos III de Madrid, http://electrica.uc3m.es/geste/Anteriores/MixGenera_E5.pdf

2012. Gloria Hermida, Edgardo D. Castronuovo. "Short-Term Optimization of the Operation in a Spanish Hydro Basin". Seminary: *Climate change and hydropower*, 2012. Polytechnic University of Madrid.

5.5 Future works

The following works are suggested for future research.

1. To extend the proposed short-term optimization model to all the hydro power plants in the basin of the Guadalquivir River.
2. To include ecological maximum rate restrictions in the model.
3. To explore the effect of wind farms coupled with hydro generation in this basin, with different scenarios of wind generation.
4. To explore the effect of adding pumping stations in Guadalquivir basin.
5. To analyze the effect of solar generation coupled with hydro generation in Spanish and Italian basins.
6. To study the effect of coordination of hydro generation, wind farms, pumping stations and solar generation for a small test case.