Energy efficiency in water distribution systems – A path to an ideal network – AGS' experience

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Abstract
Infrastructure asset management (IAM) gave a step forward in Portuguese water utilities due to recent legal obligations in developing IAM plans. An effort was made by AGS (private operator in 17 water utilities) to achieve a higher level of managing data. Data management was an important hurdle to be overcome in order to accuratly assess performance indicators. An appropriate bridge to be made is the link between IAM methodological processes and current operational management; this link is crucial when alternative solutions are defined in the planning stage and decisions need to be made. In the past, through continuously hydraulic modelling collaborative projects, AGS achieved sufficient maturity in several processes, such as: a) update network's maps, b) link GIS with other information systems, c) profiling consumption demand. Nowadays, concerns related with energy savings are gaining importance; concepts as energy efficiency, reducing carbon footprint and gas emissions should be followed. This paper describes an approach to energy assessment in a real water distribution system (WDS), where performance indicators associated to energy efficiency were computed for three different operational alternatives. Results considering a balance between cost and performance dimensions were assessed.

Keywords
Asset management; water systems modelling; energy efficiency

INTRODUCTION

Water utilities' responsibility to deliver quality and reliable service under a sustainable basis requires an increasingly efficient management and therefore an asset management strategy that ensures high levels of service, safe and reliable drinking-water quality and an appropriate network performance.

In Portugal, IAM gave a step forward with a recent Portuguese decree law (Decreto-Lei n.º194/2009), supported by the National Regulator's (ERSAR) technical guides (Alegre and Covas 2010; Almeida and Cardoso 2010), where water and wastewater utilities serving more than 30,000 inhabitants shall promote the development of IAM plans. This requirement is an important driver towards suitable long term balance between cost, performance and risk at strategic, tactical and operational levels concerning three different perspectives: engineering, information and management (Alegre 2008). In order to achieve this balance, a correct performance assessment of WDS supported on a good knowledge of the assets, reliable network models and adequate measures is essential.

From an IAM perspective, energy assessment is part of the system performance evaluation. Energy is a major concern in water utilities, not only because of its importance in terms of operational costs but also due the need to improve energy efficiency. At the same time, concepts as energy efficiency, reducing carbon footprint and gas emissions that contribute for the greenhouse effect are increasingly becoming a global concern.

The purpose of this paper is to present AGS path along modelling activities and the relation between water systems modelling and strategic asset management methods (Feliciano *et al.*, 2012) regarding energy efficiency. A case study will be presented with the goal to achieve the highest potential energy recovery, using performance indicators (PI) to evaluate energy efficiency. Different alternative solutions and the influence of several consumption scenarios will be analysed, considering performance, operational costs and investments.

AGS PRESENTATION AND PURPOSE

AGS is a Portuguese private operator that manages 14 utilities in Portugal and 3 in Brazil, in concession and public-private partnership contexts. The territorial dispersion is an important factor to promote collaborative projects in order to standardize procedures, methods, tools and engineering processes. AGS has in its headquarters an engineering support team with the main goal of seeking efficiency in the group's utilities. Regarding this goal, AGS supports different research activities and has participated in several National and European RTD projects such as INSSAA (National Initiative for the Development of Simulation Models - Portugal), CARE-W (Computer Aided Rehabilitation of Water Networks) and AWARE-P (Advanced Water Asset Rehabilitation - Portugal).

The initial phase of each concession contract is followed by an implementation stage of different information systems, such as, supervisory control and data acquisition (SCADA), geographical information system (GIS), work orders application, maintenance support system, etc. There is an organisational awareness that projects by themselves do not cover their own costs, meaning that motivations must exist in order to promote the applications' support and their permanent update, in data and information terms. Following this rational, AGS launched a collaborative project for the Group's utilities on water systems modelling (PIMSAA – Programa de Implementação de Modelos de Simulação de Abastecimento de Água). These modelling initiatives, complemented with the recent work developed under the IAM plans, promoted a more sustainable analysis and a "new perspective" in operational management including the approach to energy efficiency.

For AGS, balance between performance and cost, under management's perspective, is one of the IAM concerns. There is therefore a need to cross-relate the performance assessment for each WDS with the operational and capital costs, acknowledging its hydraulic models. One of the successful results of this methodology is the capability to convert the rehabilitation's activities from a traditional like-for-like approach into an 'organic' perspective; saying that rehabilitation decisions among different WDS should be made according proper energy performance assessment (Duarte *et al.*, 2008; Cabrera, 2010) and studied under an adaptive and continuously improving design. This dynamic cycle, about energy efficiency, will drive systems to an ideal network instead of a status quo context.

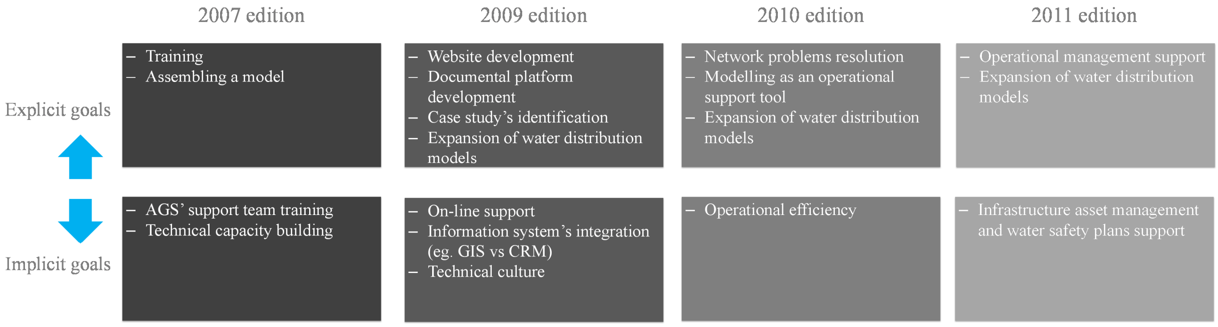
AGS EXPERIENCE - MODELLING

The implementation of technological projects across AGS' utilities and central support services, concerning information systems (IS) such as billing, GIS and SCADA, added to the National Regulator's reporting requirements and the participation in RTD projects, had provided the opportunity to achieve a deep knowledge of available data and to improve operational management.

Between 2003 and 2006, AGS participated, with three concessions, in the referred INSSAA project, the objective of which is to promoting development and use of simulation models in nine

Portuguese water utilities. The project was coordinated by National Laboratory of Civil Engineering (LNEC) and provided know-how to water utilities to plan, develop and implement fully functional, calibrated models of selected network sectors.

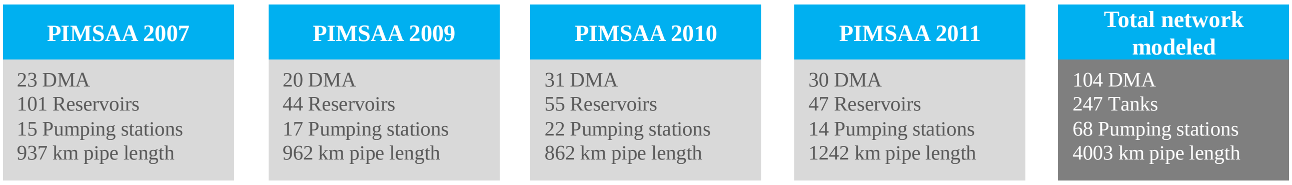
In 2007 AGS started PIMSSA in all its utilities, using INSSAA's methodology. This project promoted data management efficiency and organisational procedures assuring its integration with others IS across the utility. The program main goals were: a) to acknowledge difficulties obtaining data; b) permanent hydraulic formation; c) to promote the linkage between different IS; d) to promote the right knowledge about infrastructures and e) to work systematically in efficiency gains. The program had four editions and included the participation of 14 water utilities. Figure 1 shows explicit and implicit goals of each PIMSAA's edition.



	2007 edition	2009 edition	2010 edition	2011 edition
Explicit goals	– Training – Assembling a model	– Website development – Documental platform development – Case study's identification – Expansion of water distribution models	– Network problems resolution – Modelling as an operational support tool – Expansion of water distribution models	– Operational management support – Expansion of water distribution models
Implicit goals	– AGS' support team training – Technical capacity building	– On-line support – Information system's integration (eg. GIS vs CRM) – Technical culture	– Operational efficiency	– Infrastructure asset management and water safety plans support

Figure 1. PIMSAA's participation and goals.

The direct results from implementing this program were obvious: operational teams from each utility started assembling models and increasingly using modelling as an operational support tool. Figure 2 shows the evolution of water utilities' modelled networks in each edition.



PIMSAA 2007	PIMSAA 2009	PIMSAA 2010	PIMSAA 2011	Total network modeled
23 DMA	20 DMA	31 DMA	30 DMA	104 DMA
101 Reservoirs	44 Reservoirs	55 Reservoirs	47 Reservoirs	247 Tanks
15 Pumping stations	17 Pumping stations	22 Pumping stations	14 Pumping stations	68 Pumping stations
937 km pipe length	962 km pipe length	862 km pipe length	1242 km pipe length	4003 km pipe length

Figure 2. PIMSAA's modelled network.

However, more important than the direct results were the indirect ones. From a strategic level PIMSAA allowed a new holding management approach promoting a technical culture inside the organisation and fulfilling the utilities territorial dispersion gap, allowing knowledge transfer between operational teams from different utilities and AGS' support team. For AGS' utilities, PIMSAA promoted a relevant evolution of the WDS' knowledge, not only from an infrastructural and operational point of view but also in terms of data validation. In technological terms, PIMSAA promoted IS' integration, mainly between GIS, SCADA and billing system.

PIMSAA's results were an important step to improve operational management and to support the development of IAM plans according to the Portuguese decree law obligation. IAM methodology requires a detailed performance diagnosis and an intervention analysis that can be difficult and inefficient without having reliable water distribution models.

STRATEGIC ASSET MANAGEMENT – ENERGY EFFICIENCY

The strategic asset management methodology presented in ERSAR's technical guides requires a more advanced assessment and knowledge of the systems. At a tactical level district metering areas (DMA) should be prioritized and in each one intervention's alternatives should be analysed in order to identify the best solution. In this level hydraulic models are key to support operational activities and to assess the best decisions.

Studying energy efficiency in gravitational systems is not very usual, although pressure reducing valves installation reflects inefficient energy performance.

To analyse energy efficiency three indices presented by Duarte *et al.* (2008) and Cabrera *et al.* (2010) were used. These measures are based on the concepts of minimum energy and energy in excess (Alegre 1992). Table 1 and Table 2 present the different types of hydraulic power in a water supply system and the indices defined to assess energy performance.

Table 1. Hydraulic power's types in a water supply system

Name	Definition
Hydraulic power	$P_e = \gamma \,.\, Q \,.\, H$ in which P_e = hydraulic power (W); γ = water volumetric weight (9800 Nm^{-3}); Q = flow rate (m^3/s); H = hydraulic head expressed in terms of the zero-reference elevation (m)
Provided hydraulic power	$P_{prov}(t) = \gamma \,.\, Q_{prov}(t).\, H(t)$ in which P_{prov} = provided hydraulic power at time *t* (W); $Q_{prov}(t)$ = provided flow rate at time *t* including revenue water, water losses and unbilled authorised consumption (m^3/s); H (t) = head at the storage tank at time *t* expressed in terms of the zero-reference elevation (m)
Minimum hydraulic power	$P_{min}(t) = \sum_{i=1}^{n} P_{min}^{i}(t) = \gamma \sum_{k=1}^{n} [Q^i(t).H_{min}^{i}]$ in which P^i_{min} (t) = minimum hydraulic power at node *i* and at time *t*(w); $Q^i(t)$ = consumption at node *i* and at time *t* (m^3/s); H^i_{min} = minimum required head at node *i* (m); n = number of consumption nodes.
Recovered hydraulic power	$P_{rec}(t) = \sum_{k=1}^{N_T} P_{rec}^{k}(t) = \gamma \sum_{k=1}^{N_T} [Q^k(t).H_{rec}^{k}(t)]$ in which P^k_{rec} (t) = recovered power at node *k* and at time *t*(w); $Q^k(t)$ = turbinated flow at node *k* and at time *t* (m^3/s); H^k_{rec} = recovered head at node *k* (m); N_T = number of nodes with turbines installed.
Hydraulic power in excess	$P_{exc}(t) = [P_{prov}(t) - P_{rec}(t) - P_{min}(t)]$

Table 2. Energy efficiency performance indices

Performance index	Definition
E1 – Energy in excess per unit of input volume (kWh/m^3)	$E1 = \frac{E_{exc}}{V_{prov}} = \frac{\int P_{exc}(t)dt}{\int Q_{prov}(t)dt}$
E2 – Energy in excess per unit of the revenue water (kWh/m^3)	$E2 = \frac{E_{exc}}{V_{rev}} = \frac{\int P_{exc}(t)dt}{\int Q_{rev}(t)dt}$

E3 – Ratio of the energy in excess (dimensionless)	$E1 = \frac{E_{prov}}{E_{min}} = \frac{\int P_{prov}(t)dt}{\int P_{min}(t)dt}$

Other measures were considered in order to evaluate the best alternative in terms of energy efficiency. Pressure management index and non-revenue water performance indicator from International Water Association (IWA) PI system can be an example of these measures.

Table 3 presents the performance indicators used in this study.

Table 3. Performance index and indicators

Performance index/Indicator	Definition
P_{min} – Minimum pressure of supply adequacy (%)	$\frac{\mathit{Number\ of\ nodes\ with\ pressure\ above\ } 20\ m}{\mathit{total\ number\ of\ nodes}}$
P_{max} – Maximum pressure of supply adequacy (%)	$\frac{\mathit{Number\ of\ nodes\ with\ pressure\ below\ } 60\ m}{\mathit{total\ number\ of\ nodes}}$
Fi 46 – NRW – Non-revenue water (%)	$\frac{\mathit{Difference\ between\ the\ system\ input\ volume\ and\ the\ billed\ authorised\ consumption}}{\mathit{System\ input\ volume}} = \frac{A21}{A3} \times 100$

In terms of cost, three metrics were considered as presented in Table 4.

Table 4. Cost measures

Cost measures	Definition
NPV – Net present value	$\sum_{t=0}^{n} \frac{(\text{Benefits}-\text{Costs})t}{(1+r)^{t}}$ where r = discount rate; t = year and n = time horizon (in years)
IRR – Internal rate return	The Internal Rate of Return is the interest rate that makes the Net Present Value equal to zero
PP – payback period	Period of time required to recover an investment

These measures were used to analyse the case study's two main goals: to compare, based on a performance and cost assessment, the existing network with two intervention alternatives; and to analyse the investment payback period (PP) and the net present value (NPV) for different demand scenarios and energy productions.

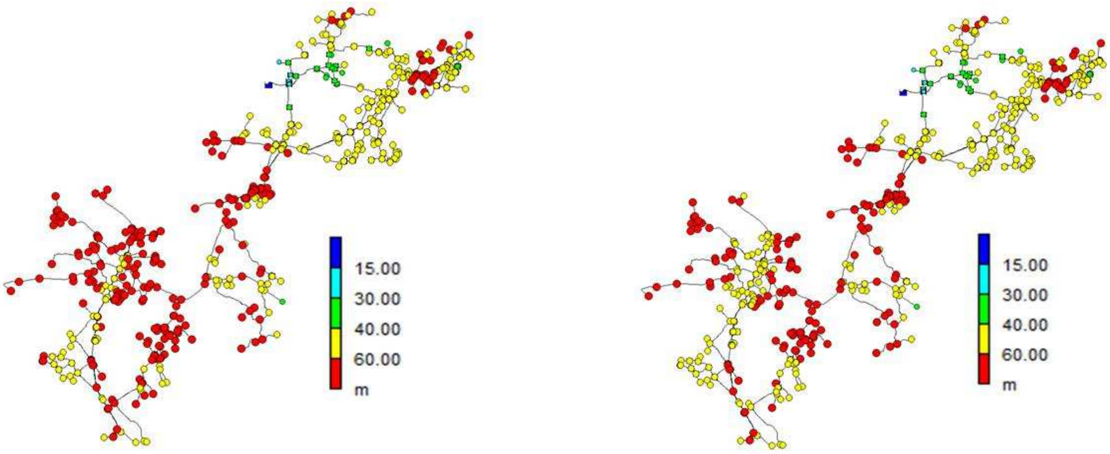
CASE STUDY

Description

The case study is focused on one of Águas de Barcelos' DMA. Águas de Barcelos is a municipal concession responsible for public water supply and wastewater treatment, in a Portuguese municipality located in the north of Portugal.

The case study, *DMA Fornelos*, is a water distribution network with 92 km pipe length that supplies 1,878 users. The network is in PVC with pipe diameters ranging between 50 and 250 mm and pipes' age from 1 to 15 years. The network average consumption demand is 22.85 m^3/h and non-revenue water represents 22% of the input volume. DMA is supplied gravitationally by Fornelos' tank with 1,000 m^3 capacity and a 90 m elevation.

The difference between tank's elevation and the lower network node is 78 m, which causes network pressures above the national requirements of 60 m and contributes to a higher leakage flow and bursts frequency. EPANET software was used to build the network hydraulic model. Figure 3 shows the network pressures at the lowest and highest consumption hours.



Network pressure at 4:00 AM

Network pressure at 20:00 PM

Figure 3. Fornelos' DMA network pressures.

In order to improve network performance three intervention alternatives were established:

- alternative *status quo* – maintain the existing network;
- alternative 1- install a water pressure reducing valve;
- alternative 2 – install a pump working as a turbine (PAT) combined with a pressure reducing valve (PRV).

For both alternatives 1 and 2 the same location for the equipment installation was considered, according to Figure 4, which covers 57% of total network demand and the same reduction pressure in the network.

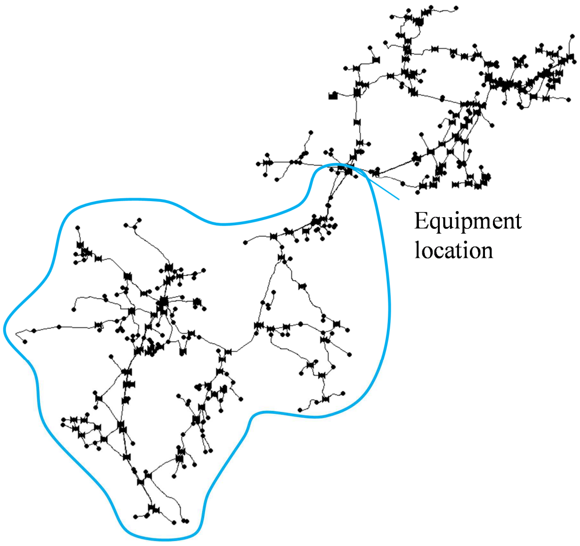
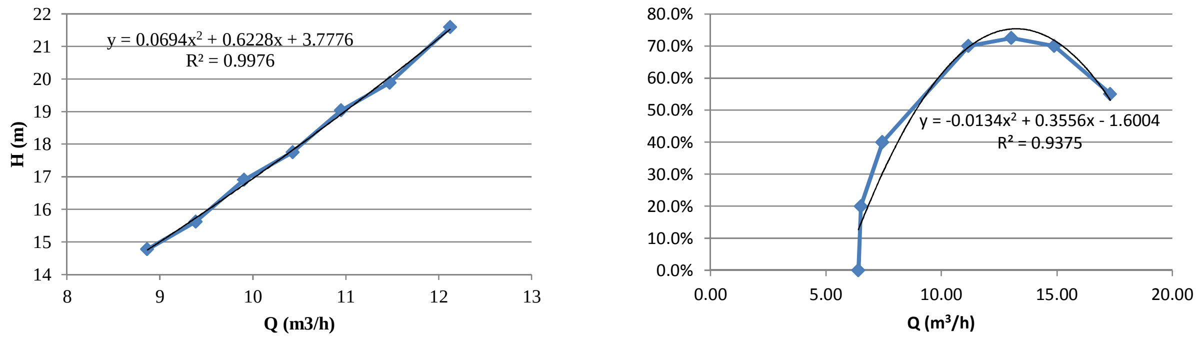


Figure 4. Equipment location and network covered on alternatives 1 and 2.

The hydraulic model developed to support the analyses was based on audited GIS' data, SCADA and billing information systems. For each modelling simulation it was considered:

- the average network demand - weekly daily pattern with a 15 minutes time step;
- a 25 m reduction in the pressure reduction valve;
- the non-revenue water corresponds mainly to real losses and decreases with pressure reduction.

For alternative 2 analysis regarding energy production of a pump working as a turbine, measured real data from a similar installation was used (Livramento 2013). Based on this study two adapted curves were established for the case study enabling the calculation of energy production with this type of equipment, Figure 5.



Flow *vs* head

Flow *vs* turbine efficiency

Figure 5. Flow *vs* head curve and flow *vs* turbine efficiency curve.

The investments needed and assumptions established for the financial analysis in each alternative are presented in Table 5. Investments needed, water acquisition cost (decreasing in alternative's 1 and 2 due to water losses reduction), equipment maintenance cost and energy sales income were considered in each alternative for financial analysis.

Table 5. Investment and financial analysis assumptions.

Assumptions	Alternative *status quo*	Alternative 1	Alternative 2
Investment	0.00 €	3,000.00€	15,000.00€
Equipment service life	-	15 years	
Equipment maintenance cost	-	3% of investment value (annual)	
Discount rate	8%		
Water acquisition	0.53 €/m^3		
Energy price (revenue)	0.65 €/m^3		

Alternative's performance and cost analysis

Results from performance and cost analysis of each alternative are presented in Table 6 and Table 7.

Both alternatives 1 and 2 present better results regarding pressure management and non-revenue water due to water losses reduction with pressure (Table 6).

Regarding energy efficiency performance indicators (E1, E2 and E3) alternative 1 is better than *status quo* due to water losses reduction. Alternative 2 presents the best results in these three measures due to the combination of water losses reduction and turbine energy production.

Cost measures' results indicate that alternatives 1 and 2 are financially acceptable (
Table 7). In both alternatives NPV is positive, IRR is higher than discount rate (8%) and PP is lower than equipment service lifetime (15 years).

Considering performance and cost evaluation alternative 2 represents the best solution.

Table 6. Performance indicators and index results.

Alternatives	Performance					
	Pmin (%)	Pmax (%)	NRW (%)	E1 kWh/m^3	E2 kWh/m^3	E3 (-)
Alternative *status quo*	100	60	22%	0.14	0.18	2.44
Alternative 1	100	91	20%	0.13	0.16	2.32
Alternative 2	100	91	20%	0.11	0.14	2.10

Table 7. Cost results.

Alternatives	Costs		
	NPV (€)	IRR (%)	PP (years)
Alternative *status quo*	-	-	-
Alternative 1	18,529.26	84%	2
Alternative 2	26,458.90	32%	4

Energy production analysis
Assuming alternative 2 has the best solution to further analysis payback period and NPV were calculated for different consumption demand scenarios. For all these scenarios an average daily flow (Qmed) with a constant daily pattern was considered.

Reference values for payback period and NPV were established classifying the results as Good, Fair or Poor. Results are presented in Figure 6. Results from Figure 6 demonstrate that with an average flow reduction of 30% alternative 2 has a positive NPV with a poor payback, but equal to equipment lifetime.

Cost indicators		
Scenarios	Payback years	NPV €
45% Qmed	- 🔴	-8 745 € 🔴
50% Qmed	- 🔴	-7 171 € 🔴
60% Qmed	- 🔴	-3 613 € 🔴
70% Qmed	15 🔴	509 € 🟢
80% Qmed	10 🟡	5 158 € 🟢
90% Qmed	7 🟢	10 201 € 🟢
100% Qmed	6 🟢	16 054 € 🟢
110% Qmed	5 🟢	19 277 € 🟢
120% Qmed	5 🟢	21 542 € 🟢
130% Qmed	5 🟢	22 623 € 🟢
140% Qmed	5 🟢	22 291 € 🟢
150% Qmed	5 🟢	20 320 € 🟢

Reference values	Payback period	NPV
Good	[0; 8] 🟢	< 0 🟢
Medium	]8; 12] 🟡	= 0 🟡
Bad	]12; +∞[🔴	> 0 🔴

Figure 6. Cost's measures results.

Figure 7 presents the NPV variation in different demand scenarios. The NPV increases up to 130% Qmed with a reduction to higher flows due to the turbine efficiency's decrease.

Considering operational conditions and reference values assumptions analysis shows that the best solution requires an average daily flow increase of 130%.

In spite of these promising results, it should be noted that efficiency of the turbines applicable to the range of heads and flows of WDS have a high sensitivity to flow fluctuations, as illustrated in Figure 5. This may still be a limiting factor to the practical adoption of this type of solution. Variable speed turbines may partially overcome this aspect.

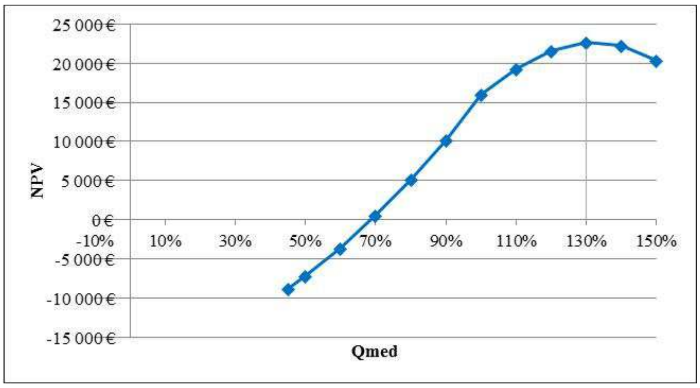


Figure 7. NPV and average daily flow variation.

CONCLUSIONS

The aim of this work was to apply IAM approach focusing the analysis on energy efficiency in a real network. In order to support reliable analyses, hydraulic models are an essential tool to establish new assessments. The case study represents a real network and it was studied with two main goals: the first one was to compare, based on a performance and cost assessment the existing network with two intervention alternatives; the second goal was to analyse investment payback period and net present value for different demand scenarios and energy productions, for the best alternative. It is important to note that the metrics adopted are also valid to compare alternative solutions with different layouts, ou to compare the potential for energy efficiency improvement between different WDS or different DMAs.

Classical approaches are based on the level of investment and in some cases in basic operational analysis. The use of new metrics to support decision making processes is very important, especially when efficiency is a major concern. The case study allowed the application of energy efficiency performance indicators and contributed to a more sustainable solution in terms of performance and cost, giving a step forward to an ideal network achievement.

Results show that implementation of energy production solutions in gravitational water distribution networks with high energy excess can contribute to performance improvement as well as financial savings.

Knowing that gravitational water networks represent an important part of WDS this analysis can be a good start to evaluate different solutions and obtain energy gains.

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