UNIVERSITÀ DEGLI STUDI FIRENZE

FLORE
Repository istituzionale dell'Università degli Studi di Firenze

Irrigation and energy: issues and challenges

Questa è la Versione finale referata (Post print/Accepted manuscript) della seguente pubblicazione:

Original Citation:
Irrigation and energy: issues and challenges / G. Ghinassi. - In: IRRIGATION AND DRAINAGE. - ISSN 1531-0353. - STAMPA. - 69 (S1):(2020), pp. 177-185. [10.1002/ird.2343]

Availability:
This version is available at: 2158/1157006 since: 2024-08-01T17:59:57Z

Published version:
DOI: 10.1002/ird.2343

Terms of use:
Open Access
La pubblicazione è resa disponibile sotto le norme e i termini della licenza di deposito, secondo quanto stabilito dalla Policy per l'accesso aperto dell'Università degli Studi di Firenze (https://www.sba.unifi.it/upload/policy-oa-2016-1.pdf)

Publisher copyright claim:

(Article begins on next page)

28 September 2024

IRRIGATION AND DRAINAGE
Irrig. and Drain. **(2019)**
Published online in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ird.2343

IRRIGATION AND ENERGY: ISSUES AND CHALLENGES†

G. BELAUD[1]*, L. MATEOS[2], R. ALIOD[3], M.-C. BUISSON[4], E. FACI[3], S. GENDRE[5], G. GHINASSI[6], R. GONZALES PEREA[7], C. LEJARS[8], F. MARUEJOLS[9] AND N. ZAPATA[10]

[1]*UMR G-eau, Montpellier Supagro, Irstea, Cirad, IRD, AgroParisTech, University Montpellier, France*
[2]*CSIC, Instituto de Agricultura Sostenible, Cordoba, Spain*
[3]*University of Zagaroza, Huesca, Spain*
[4]*International Water Management Institute, New Delhi, India*
[5]*Arvalis, Institut du Végétal, Baziège, France*
[6]*University of Florence, Florence, Italy*
[7]*University of Cordoba, Cordoba, Spain*
[8]*UMR G-eau, Cirad, Montpellier Supagro, Irstea, IRD, AgroParisTech, Univ. Montpellier, France*
[9]*BRL Exploitation, Nîmes, France*
[10]*CSIC, Estación Experimental de Aula Dei, Zaragoza, Spain*

ABSTRACT

Water-efficient agriculture has implied a large increase in energy consumption for irrigation in recent decades. In many irrigation systems, energy costs are now threatening their sustainability. However, new opportunities have arisen for the use of renewable energies in the irrigation sector. These are some of the aspects of the multifaceted multiple-actor 'water–food–energy' nexus. Technical, economic and environmental issues are linked in many ways, involving farmers, water users' associations, energy suppliers, engineers and other stakeholders. The ICID session 'Irrigation and energy' triggered discussions on these multiple dimensions. This paper presents a synthesis of the presentations, discussions and conclusions.

Four main questions are addressed: How do irrigation productivity and sustainability of water resources exploitation change when farmers have access to energy? What do we know about energy efficiency in irrigation systems, at farm and collective network levels? How can this efficiency be optimized by using advanced technologies, modelling tools, improved management? Is energy production an opportunity for irrigation systems?

These questions have been posed based on multiple case studies from different parts of the world. The BRL network, in southern France, illustrates advanced strategies and opportunities to reduce energy consumption and develop energy production at a network level. General conclusions are drawn from this synthesis, illustrating trade-offs and synergies that can be identified in the irrigation sector at different scales, while opportunities for future research are proposed. © 2019 John Wiley & Sons, Ltd.

KEY WORDS: water–food–energy nexus; irrigation energy efficiency; pumping; energy production

Received 29 November 2018; Revised 7 March 2019; Accepted 7 March 2019

RÉSUMÉ

L'agriculture économe en eau a entraîné une forte augmentation de la consommation d'énergie pour l'irrigation au cours des dernières décennies. Dans de nombreux systèmes d'irrigation, les coûts énergétiques menacent maintenant leur durabilité. Cependant, de nouvelles opportunités sont apparues avec l'utilisation des énergies renouvelables dans le secteur de l'irrigation. Ce sont quelques-uns des aspects du nexus 'eau–alimentation–énergie'. Les problèmes techniques, économiques et environnementaux sont liés à bien des égards, impliquant les agriculteurs, les associations d'usagers de l'eau, les fournisseurs d'énergie, les ingénieurs et d'autres parties prenantes. La session CIID 'Irrigation et énergie' a ouvert le débat sur ces multiples

*Correspondence to: Professor G. Belaud, Montpellier SupAgro - UMR G-eau. 2, place Pierre Viala, Montpellier 34060, France. Tel.: +33 647035119. E-mail: gilles.belaud@supagro.fr
†Irrigation et énergie: enjeux et défis.
*The first authors G. Belaud and L. Mateos coordinated and chaired the Irrigation and Energy Workshop during the ICID Conference in Montpellier, France, 2015.

© 2019 John Wiley & Sons, Ltd.

dimensions. Ce document présente une synthèse des présentations, discussions et conclusions.

Quatre questions principales sont abordées: Comment la productivité de l'irrigation et la durabilité de l'exploitation des ressources en eau changent-elles lorsque les agriculteurs ont accès à l'énergie? Que savons-nous de l'efficience énergétique dans les systèmes d'irrigation, au niveau de l'exploitation et des réseaux collectifs? Comment optimiser cette efficience en utilisant des technologies avancées, des outils de modélisation, une gestion améliorée? La production d'énergie est-elle une opportunité pour les systèmes d'irrigation?

Ces questions ont été posées à partir de multiples études de cas provenant de différentes régions du monde. Le réseau BRL, situé dans le sud de la France, illustre les stratégies avancées et les possibilités de réduction de la consommation d'énergie et de développement de la production d'énergie au niveau du réseau. Des conclusions générales sont tirées de cette synthèse, illustrant des compromis et des synergies pouvant être identifiés dans le secteur de l'irrigation à différentes échelles, tandis que des opportunités de recherche future sont proposées. © 2019 John Wiley & Sons, Ltd.

MOTS CLÉS: nexus eau–alimentation–énergie; efficience énergétique; irrigation; pompage; production d'énergie

INTRODUCTION

All irrigation systems require energy, which is dissipated along the system. This is the base for uniform water application. The difference between systems lies in the amount of energy needed and the way it is dissipated. While traditional systems used only gravity to convey water to the fields, modern systems generally require external sources of energy. The designing of modern pipe irrigation systems, either collective networks or application systems, is based on energy criteria by setting head loss limits. The same applies, for instance, to the selection and dimensioning of filters and emitters. Moreover, irrigation energy use depends not only on the design of the system but also on how it is operated and maintained. Thus, the carrying out of audits is becoming increasingly common for assessing energy use efficiency and identifying ways to reduce energy consumption and costs. Such an analysis cannot be separated from agricultural water use efficiency.

However, the water–energy–food (WEF) nexus, linking these three priorities for human well-being, goes beyond these technical aspects (Vlotman and Ballard, 2014; Pradeleix *et al.,* 2015); in fact, it is a multifaceted multiple-actor issue. Socio-economic and environmental aspects are linked to technical aspects in many different ways, involving farmers, water users' associations, energy suppliers, engineers and other stakeholders. The irrigation sector, therefore, provides distinct illustrations of the WEF nexus complexity and stresses the need for better understanding of the interdependencies (trade-offs and synergies) for designing effective natural resources policies (Bazilian *et al.,* 2011).

The objective of this paper is to highlight recent research outcomes regarding irrigation and energy issues, documenting the interrelations at different scales. The paper first discusses the effects of the access and use of energy for irrigation; then it reviews measures and tools for improving energy efficiency; and, finally, it outlines opportunities for generating energy using irrigation infrastructure. The paper ends by presenting an example of a successful integration of energy and water management. The last section synthetizes the examples presented in the paper from the WEF nexus perspective.

WHAT DOES ENERGY ACCESS CHANGE?

Modern irrigation is closely tied to the use of energy. The advent of diesel and electric motors in the mid-twentieth century led to the development of pressurized irrigation systems and allowed the intensive use of groundwater (Bouarfa and Kuper, 2012). Access to energy boosts irrigation wherever water resources are available and the rainfall is not sufficient to meet crop water needs. One paradigmatic example is in the US Great Plains, one of the most intensively farmed lands in the world. Corn, wheat, soybean and forages are cultivated over 55 million ha, producing 22% of the total crop value in the USA. About 8 million ha of this area is irrigated, the result of a rapid expansion which started in the 1950s with the invention of centre pivot irrigation systems, rural electrification, and improved well drilling and pump technologies (Evett *et al.,* 2014). Initially, farmers thought that the Ogallala aquifer, the main water source, was unlimited; however, they soon found that, especially in the southern and western parts of the aquifer, their pumping exceeded the recharge so that the water table began to decline (Scanlon *et al.,* 2012).

One more recent example with further consequences is in Syria. Syria's government implemented policies to increase agricultural production, including irrigation projects and subsidies for diesel fuel. Food production goals were achieved successfully, although at the cost of endangering Syria's water security by over-abstracting water resources (Aw-Hassan *et al.,* 2014). Some authors argue that this unsustainable policy may have contributed to the current political unrest in the country (Kelley *et al.,* 2015).

In India and Pakistan, the number of wells and energized pump sets has also grown exponentially since the early

© 2019 John Wiley & Sons, Ltd.

1950s. One consequence has been the increase in irrigation efficiency and flexibility (the capacity to irrigate at the desired time), contributing significantly to agricultural and economic development (Plusquellec, 2002). However, because of groundwater over-abstraction, water tables have declined beyond the depth at which salinization can be expected. This policy and its consequences have continued. West Bengal is currently implementing a programme that facilitates farmers' access to electrified irrigation, hoping to trigger a second Green Revolution. The potential impact of this electrification programme has been assessed recently (Buisson, 2015). Access to electric pumps and electrification has increased income by favouring intensification of the cropping pattern and shifting it towards *boro* rice, a high-value crop but also a large water consumer. Therefore, from the groundwater management point of view, once again the sustainability of electrification policies has been questioned.

New irrigation developments facilitated by subsidized energy access are also taking place in other regions, leading to agricultural intensification but also to high energy costs. An assessment of the direct and indirect economic effects of policies subsidizing agricultural and irrigation water has been conducted in Morocco using a social accounting matrix at a regional level (Doukkali *et al.,* 2015). The results have shown that individual (private) and mixed (individual–collective) irrigation schemes have the lowest multipliers' effect on added value, while investments in rainfed, large-scale and small- and medium-scale collective irrigation schemes are more profitable for the economy of the country. The water policy targeting 'water-saving' techniques has also led to an increase in the use of subsidized butane for private irrigation (Doukkali *et al.,* 2015). Investments in irrigation led to the rapid growth of agriculture and improved the sector's contribution to the national economy but resulted in high energy costs. The conclusion was that agricultural development should be more balanced in favour of rainfed agriculture.

In summary, the irrigation and water-saving policies behind the above examples show that access to energy increases the capacity to irrigate and produce food as well as water use efficiency and productivity. However, it may have a rebound effect: water consumptive use may increase leading to unsustainable exploitation of water resources, while water saving (if any) is at the cost of the consumption of non-renewable energy.

In a more advanced developmental phase, and in response to the increase in water use due to new agricultural, environmental, urban and industrial demands, one water users' association has partnered with the Société du Canal de Provence, a company with greater financial capacities and expertise in canal control (Prevost and Guichard, 2015). The possibility of generating electricity using existing assets has provided the opportunity for well-regulated, service-oriented, integrated water resource management. That is to say, that irrigation and energy development can also result in positive synergies.

KNOWING ABOUT THE SYSTEM TO IMPROVE ITS ENERGY EFFICIENCY

Modern irrigation systems consume energy at the pumping stations (to lift water from the source and to pressurize it in the distribution network), to filter the water, along the pipes, when the water flows across ancillary network components, and to apply the water uniformly. Design constraints and improper design or operation and management lead to extra energy needs that could be potentially saveable (Cabrera *et al.,* 2014) or recoverable (Pérez-Sánchez *et al.,* 2016).

Water users are interested not only in saving energy, but also in reducing energy costs. Irrigation energy auditing identifies potential energy savings and proposes measures to improve energy efficiency and reduce energy costs (Rocamora *et al.,* 2013). One example of extensive auditing of collective irrigation systems is the 'Strategy for Energy Saving and Efficiency in Spain 2004–2012' promoted by the Spanish Institute for Diversification and Energy Savings.

In France, a study conducted at the Carpentras Irrigation Scheme (Department of Vaucluse, France) evaluated, on the one hand, energy inefficiency due to water losses between the pumping stations and the hydrants serving the farmers, and, on the other hand, the most economical electricity tariff for the particular complexity of the irrigation demand in the scheme (Marzougui *et al.,* 2015). The study found that up to 60% of the water was lost in the network or not recorded in the hydrants (thus not billed), while an alternative electricity tariff appeared to be more economical than the current one in 82% of the cases analysed.

Another French study with similar objectives but at an irrigation block level was conducted in the Garonne catchment (Gendre *et al.,* 2015). The evaluation involved nine traveller irrigation systems (gun and hose mounted on a moving reel). One of the systems was evaluated in more detail, describing pressure losses in its different components; 82% of the energy was used to transport the water to the gun, and the rest was used to apply the water onto the field. Unexpectedly high energy losses were found at the check valve installed at the pump outlet. Recommendations emphasized measures to save part of that energy.

A similar study has been reported for a very different environment: smallholdings in a public irrigation district in north-east Brazil (Mateos *et al.,* 2015). The assessment showed that pumping energy efficiency greatly varied from farm to farm. It was less than 50% in 17 out of the 37 farms in which it could be determined. When compared to the

© 2019 John Wiley & Sons, Ltd.

efficiency claimed by the pump manufacturer, only two pumps showed their efficiency in the catalogue. The assessment was extended to the entire system. Figure 1 illustrates, for a representative farm, the system's components where energy could be saved or where more energy should be used for proper functioning. This particular system could operate with 23% less energy than that actually being used. Most of the saving would derive from improving pumping efficiency (Figure 1(above)). An excess of energy dissipation was detected at the head of the sector in operation (valves and regulators) as well as in the sector itself (emitters and laterals) (Figure 1(a)). The latter was likely to be related to the lack of filtration, so that one recommendation for this farm was to install an appropriate filtering system, which, as well as a small additional energy requirement from the motor, would imply a 3% increase in energy needs (Figure 1(below)). Therefore, the balance after improvement according to the diagnosis would be a 20% energy saving. Moreover, application uniformity in the sector under operation could increase from 57 to 95%, with the consequent increase in irrigation efficiency and crop yield. The existence of on-farm irrigation systems with good performance in the district opens up opportunities for using benchmarking methods to provide individual and collective recommendations to improve energy efficiency.

A more global approach to assessing irrigation systems from an energy perspective is computing the carbon footprint throughout their life cycles. Guiso *et al.* (2015) did so while comparing annually replaced dripline systems with hose reel machines equipped either with a travelling rain gun or spray boom. Interestingly, the results showed that dripline systems have a greater global warming potential than hose reel machines, due mainly to their shorter lifetime.

IMPROVING ENERGY EFFICIENCY IN IRRIGATION SYSTEMS

Collective systems that deliver pressurized water are particularly sensitive to the cost of energy and are usually better organized to identify energy-saving opportunities. However, reducing energy can lead to inefficient water application at field level (e.g. by reducing the pressure in spray irrigation systems) and constraints in water access (not enough pressure or discharge in pressurized irrigation systems, diminution of irrigation periods, etc.). Therefore, it is essential to identify the key factors in prioritizing energy reduction so that the expected gains are not cancelled out by dissatisfied end-users, who would be affected by losses in crop production, or would demand greater volume to compensate for heterogeneous application.

Energy reduction at farm level

Energy is needed to convey water from the delivery point to the crops. While the energy necessary to overcome gravity is unavoidable (e.g. the energy required to lift groundwater and bring it to the highest plots on the farm), possible gains can be obtained by reducing head loss during transport and application, and by reducing the amount of water used for irrigation. This last point (water use efficiency) is the subject of many studies and will not be developed here.

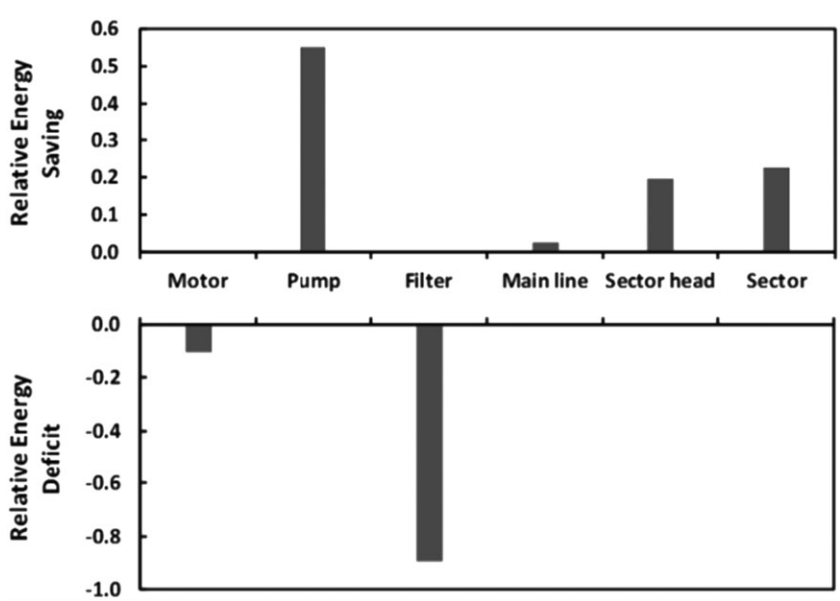

Figure 1. Relative energy saving and deficit at farm C06.3 in the Baixo Acarau Irrigation District, Ceará, Brazil. The system could operate with 23% less power (2 kW) than what it is actually using: (above) Relative saving in the different system components. The system would require additional power (0.5 kW) for proper operation: (below) Relative deficit in the different system components

© 2019 John Wiley & Sons, Ltd.

Pressurized irrigation covers a large variety of systems, from low-pressure drip emitters needing a pressure of around 100 kPa, to guns needing a pressure 6–8 times higher. A high pressure is associated with a long application distance, so that limited investments are necessary to cover large areas. Using less energy-demanding emitters requires more expensive equipment, such as centre pivots, low-discharge sprinklers and, in the extreme case, drippers. Furthermore, Robles *et al*. (2017) have shown that, for standard solid-set irrigation systems, it is possible to reduce pressure at the sprinkler nozzle from 300 to 200 kPa without affecting corn yield and gross income. The simulation analysis of a collective irrigation network performed by Zapata *et al*. (2015) indicated that operating at a reduced pressure at the sprinkler nozzle (200 kPa) is economically profitable because of the decrease in network investment and exploitation costs that largely compensate for the slight reduction in corn yield.

At farm level such adaptations are effective, providing that networks are able to adapt and reduce their pressure as well. In individual networks, this may be reduced to changes in the pumps. In collective networks, efforts towards pressure reduction made by individual farmers may be useless unless pressure is also reduced at the common pumping stations. Therefore, collective networks need collective efforts through participatory learning processes leading to the collective adoption of low-energy on-farm systems (for instance, low-pressure emitters, low head-loss filters).

Energy reduction at network level

The efforts made in Spain have provided benchmarks to illustrate the opportunities of energy saving. Based on 10 typical irrigation districts in Andalusia (covering a total of 66 000 ha), González Perea *et al*. (2015) presented a regional analysis of irrigation districts, focusing on energy consumption and pumping efficiency. They identified expected gains of about 20–30% on energy consumption, through three types of action:

- network sectoring, consisting of grouping hydrants with similar energy requirements and organizing irrigation in turns;
- critical point detection and correction: measures are taken at hydrants with special energy requirements, usually due to their distance from the pumping station and/or their elevation; and
- optimization of pumping station design and operation.

Decision support tools

The above examples and actions to save energy have shown the importance of using sophisticated strategies for design and management, when considering the varying demand for water and pressure at seasonal and daily timescales. Decision support tools are essential for designing infrastructure and for evaluating its performance in water distribution and energy costs, for identifying its critical points and for improving it accordingly.

Aliod *et al*. (2015) have developed a tool specifically conceived for pressurized irrigation networks. Recent developments have included simulation modules for pumping stations, indicators related to energy consumption, and demand management methods to minimize energy costs while respecting required volumes and pressures. Applications to real-time scheduling showed the clear advantages of optimized strategies compared to trial-and-error methods. In contrast to on-demand distribution, optimized distribution schedules have reduced by 16–32% the energy costs in four study cases in northern Spain.

At a farm level, Cintegral simulation software integrates energy losses into the distribution network with the effect of reducing the pressure in irrigation uniformity and yield (Zapata *et al.,* 2015). This enables an evaluation of the expected gain or cost when reducing the pressure at the pumping stations.

Energy-saving studies are less common in gravity-fed systems. However, the optimization of pumping stations also has impacts on canal control. The software SIC (Simulation of Irrigation Canal Control) was used to simulate hydraulic heads for such systems (Lozano *et al.,* 2012), and currently includes a module for energy consumption at pumping stations.

USING THE IRRIGATION INFRASTRUCTURE FOR ENERGY PRODUCTION

Many water schemes have the double purpose of irrigation and energy production; these sometimes are complementary uses and sometimes conflicting ones. This largely depends on the potential energy of water, namely the elevation at which water is available. When water schemes have the double purpose of irrigation and generating energy, water planning and management should be based on water allocation optimization (Anwar and Kusumawati, 2015).

However, some new avenues are opening up for the use of the irrigation infrastructure itself for producing energy. Irrigated systems naturally receive a large amount of solar energy as well as hydraulic energy when water is abstracted from water sources above the elevation of irrigated fields. Despite a potential of 2.8 Wh m^{-3} for 1 m of difference in elevation, hydraulic energy is seldom used in irrigation canals, and it is therefore lost during transport and field application. Similarly, only a small fraction of the solar radiation incident on the land under irrigation schemes is used for

© 2019 John Wiley & Sons, Ltd.

photosynthesis. Some solutions are now being developed to take advantage of these sources of energy, driven by expected new financial resources. In some countries, these developments are (or have been) encouraged by public policies to reduce dependence on fossil energy.

The increasing role of solar energy in irrigation systems

The use of solar energy for pumping is increasing with the need to decrease greenhouse gas emissions by increasing the share of renewable energy. Any available areas are likely to be equipped with solar panels. With the increasing electricity bill, irrigation schemes (including those with canal networks) and farmers have started to install solar panels on unproductive areas. Optimizing those installations, such as employing the electricity produced for their own use, taking advantage of the shading effect or using water to increase panel efficiency, are innovations under evaluation. In Mediterranean environments, solar radiation and evapotranspiration have parallel time trends (monthly and daily), so that peak solar power coincides in time with maximum irrigation water requirements. Consequently, solar systems have the potential to be the most suitable renewable source for irrigation, even more so when considering that the price of solar panels has dropped dramatically in recent years. A good example of solar irrigation is the Sun Water Project system in southern Spain (González Perea *et al.,* 2015). Another interesting strategy is the use of the solar panels on crops, with the beneficial effect of shading in water-scarce regions (Dupraz *et al.,* 2011).

Hydraulic energy

A major limitation on the development of micro-hydropower units has been their low return-on-investment ratio, considering the small production that can be expected from each potential site. The constant increase in electricity costs is changing this situation. The Société du Canal de Provence (SCP), which manages water conveyance and distribution through a large network of canals and pressurized networks from mountainous regions to farmers, municipalities and industries, has installed hydropower units on its own infrastructure. The power production reaches about a quarter of the energy used for pumping. However, many canal networks are managed by water users' associations that have limited financial capacities. The unique partnership set up between SCP and ASCO Canal de Craponne, one of the largest water users' associations in southern France, overcomes this difficulty (Prevost and Guichard, 2015). The agreement is based on the joint holding of the power unit. While the financial risks are borne by the SCP, as well as contributing with its expertise in similar power units, ASCO Canal de Craponne supplies the water rights and the infrastructure where the turbine is installed. The expected production is about 5 GWh, corresponding to the electricity consumption of more than 600 households. Its profits reinforce the sustainability of the traditional infrastructure, without changing the priority given to the supply of irrigation water.

Storage is a major concern for renewable energy. Some irrigation canals have the possibility of storing water and releasing it on demand. Advanced strategies of reservoir/pumping station operation include economic optimization, considering variable electricity tariffs throughout the day. Canal irrigation networks could also contribute to renewable energy storage by developing advanced control strategies defined as 'intelligent storage' (Maruejols and Deffontaines, 2015).

THE LANGUEDOC-ROUSSILLON REGIONAL HYDRAULIC NETWORK: AN EXAMPLE OF IRRIGATION ENERGY OPTIMIZATION

The Languedoc-Roussillon Regional Hydraulic Network (LRHN) in southern France, operated by the French company BRL, is a good example of the integration of water and energy use monitoring, performance assessment, optimization, and integration with energy production. The network consists of 3 dams, 100 km of canals, 6 water treatment plants, 90 pumping stations and about 4000 km of pressurized pipes. About two-thirds of the water supply is pumped from the River Rhone (water elevation close to sea level), and delivered to various users among whom farmers are the main ones. Water is delivered to the farm hydrants, ensuring sufficient pressure for any type of irrigation system. Pumping represents 95% of the 80 GWh annual energy consumption, with a cost that has increased by more than 60% in the last 10 years to reach €5 million in 2016. This has pushed BRL to develop an ambitious energy-saving programme (Maruejols *et al.,* 2015), leading to an ISO50001 certification on the whole system. The basic performance indicator used by BRL is energy consumption per unit of volume of water. This indicator is applied to each network subsystem and pumping station. When applied to the networks, it provides a global assessment that not only considers energy consumption but also water losses. Computation of this indicator requires not merely recording energy consumption but also installing flowmeters. Continuous recording allows a detailed diagnosis and correction of pump malfunction. BRL estimates that proper performance assessment-based maintenance has reduced energy consumption per cubic metre of pumped water by up to 10% in some areas. The installation of variable speed drivers in about 100 pumps on the network is estimated to

© 2019 John Wiley & Sons, Ltd.

have reduced the energy needed to pump a cubic metre of water at between 10 and 20%, depending on the configuration of the pumping station, and up to 50% in pumping stations dimensioned for the irrigation water peak demand in the summer.

Additional savings in energy costs have been achieved by developing and applying software that allows optimization of the LRHN energy bill. The optimization is based on the conditions of the utility companies, but also on the continuous recordings and calculation of performance indicators in real time. Furthermore, the software analyses sensor readings, alerts when there are anomalies, and prevents reactive energy penalties and surpassing the power contracted.

Analysis of the operation of each subsystem permitted further energy saving through specific optimal pump control strategies. Based on this, large investments were made with the support of the basin water agency, contributing to both water and energy saving. An example is described below, illustrating the co-benefits of energy- and water-saving strategies, and possible technical and management solutions supporting them.

Mas Soulet subsystem

The Mas Soulet sector supplies irrigation hydrants and a drinking-water plant with an annual volume of between 8 and 10 million m^3. It is regulated by a reservoir downstream of the pumping station, offtaking from a branch of the Canal du Bas-Rhône. Its six pumps used to be operated based on level thresholds in the reservoir. The maximum height in the reservoir is 54 m, while the maximum discharge is 1200 $l\ s^{-1}$. In 2016, the reduction in energy consumption led to reconsidering the operation of pumps, with a reduction in the target level during the winter, and an operational mode depending on actual demand. This led to replacing some pumps to allow small discharges, and to install flowmeters, pressure sensors and variable-frequency drives with a real-time controller (Figure 2). In 'winter mode', the level in the reservoir was lowered to a height of 31 m, while the pumps were operated according to the measured flow. This resulted in a drastic reduction in water loss and energy due to the diminished pressure and volume. The volume pumped in February 2016 was found to be 30% lower than previous years, corresponding to an energy saving of around 25 MWh during 1 month.

New perspectives for energy optimization

The pilot tests have shown the potential for energy and water saving by reducing the pressure, without affecting service provision, thanks to an appropriate supervision of the network. Another expected advantage is the diminution of pipe breakages, which will be observed over time.

In an attempt to further integrate water and energy use, BRL is evaluating:

- The installation of solar panels on LRHN land on around 4000 m^2 for its own needs (pumping stations and auxiliary installations), for an estimated power of 600 kW in summer.
- A 'smart energy storage' strategy: pumping water into the canals during off-peak hours and turbines during peak hours.
- Hydroelectric power generation at diversion weirs.

DISCUSSION AND CONCLUSIONS

The global scale perspective

While energy needs for irrigation represent a small fraction of the total energy consumption by human activities, energy has become an important issue for the irrigation sector and a critical factor for food security. Energy access enables the use of modern techniques. However, in many contexts, energy costs can be a factor limiting its use, while subsidies for energy access can lead to massive use of water resources and unsustainable development of irrigated agriculture. The examples presented in this paper provide illustrations of the

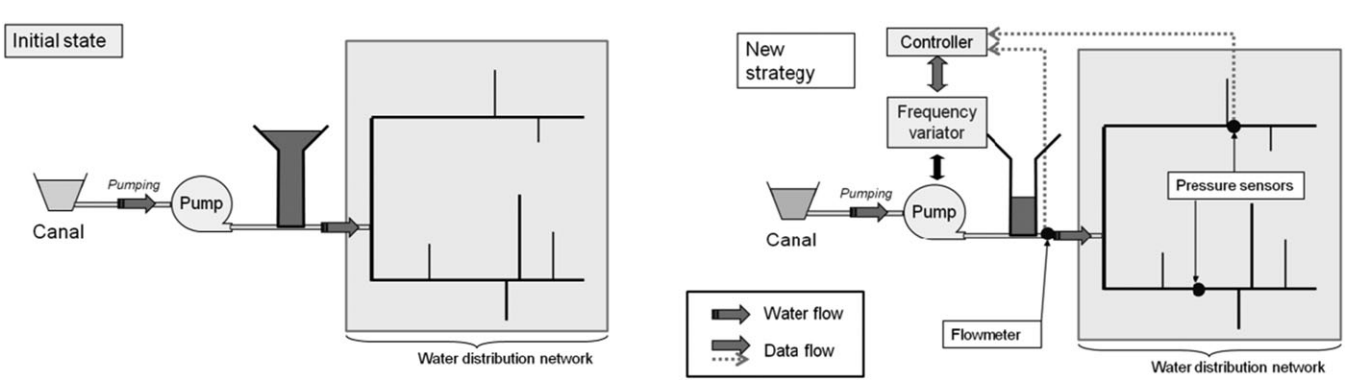

Figure 2. Mas Soulet network: original design (left), and after water- and energy-saving programme (right)

© 2019 John Wiley & Sons, Ltd.

water–food–energy nexus that should help to identify risks of irrigation policies, but also opportunities to develop synergistic strategies.

In the long term, and at large scale, while energy access has been beneficial for food production through an easier and more efficient access to water, it has also led to over-abstraction of water. This rebound effect shows that trade-offs are necessary to make the systems sustainable. Another common example of the necessary trade-off is the competition between hydropower and irrigation priorities for water release from dams, as experienced in many countries (World Commission on Dams (WCD), 2000). It is therefore essential to develop a thorough understanding of the interconnections, with quantitative assessments.

Moving to local scales

The increasing pressure from the energy, water and food production sectors is forcing to the optimization of the irrigation systems to reach acceptable trade-offs. These trade-offs are essential at a global scale, but also are claimed by actors at farm and irrigation scheme levels. Some solutions have been reviewed here, including technical and organizational ones. The examples gathered in this paper illustrate appropriate tools and solutions regarding energy efficiency, water productivity and irrigation efficiency.

The examples also point out the necessity of energy and water accounting to support decisions. In particular, diagnosing actual energy consumption, and not only design consumption, from which the former can largely deviate, is crucial to identify energy-saving opportunities.

Innovations for synergistic solutions

The examples also revealed multiple possible synergies, such as the dual use of irrigation networks delivering water and producing renewable energy beyond biofuel production. Another important message is that efforts to save irrigation water will contribute to saving energy as well.

The driver of these initiatives is the economic gains that can be expected from both energy saving and energy production. The BRL example is a good illustration of initiatives that can be explored in this regard, the benefits of which could reduce the energy footprint in the irrigation sector significantly.

Research and innovation should contribute to designing such 'win–win' solutions, like valorizing hydraulic energy loss during transport, or producing electricity with solar panels installed over the crops resulting in an increased land and water use efficiency.

REFERENCES

Aliod R, Faci E, García S, Paño J, Seral P, Gracia A. 2015. Algorithms and tools for optimum scheduling of on-demand irrigation for an effective energy cost reduction. ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

Anwar N, Kusumawati S. 2015. Water allocation optimization for combined users of energy generation and irrigation demand at the upstream Brantas river reach using mixed integer linear programming method. ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

Aw-Hassan A, Rida F, Telleria R, Bruggeman A. 2014. The impact of food and agricultural policies on groundwater use in Syria. *Journal of Hydrology* **513**: 204–215.

Bazilian M, Rogner H, Howells M, Hermann S, Arent D, Gielen D, Steduto P, Mueller A, Komor P, Tol RS, Yumkella KK. 2011. Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* **39**(12): 7896–7906.

Bouarfa S, Kuper M. 2012. Groundwater in irrigation systems: from menace to mainstay. *Irrigation and Drainage* **61**(S1): 1–13.

Buisson M-C. 2015. What does pump sets electrification change? Impacts on cropping patterns, productivity and incomes in West Bengal. ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

Cabrera E, Gómez E, Cabrera E Jr, Soriano J, Espert V. 2014. Energy assessment of pressurized water systems. *Journal of Water Resources Planning and Management* **141**(8): 04014095.

Doukkali M, Lejars C, Mengoub F, El Ghandour A. 2015. What are the indirect and direct effects of irrigation policy on energy costs? A social accounting matrix assessment in Tadla (Morocco). ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

Dupraz C, Marrou H, Talbot G, Dufour L, Nogier A, Ferard Y. 2011. Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes. *Renewable Energy* **36**(10): 2725–2732.

Evett SR, Colaizzi PD, O'Shaughnessy SA, Lamm FR, Trout TJ, Kranz WL. 2014. The future of irrigation on the US Great Plains. In *Proceedings of the 26th Annual Central Plains Irrigation Conference*; 2–25. 25 February 2015. Burlington, Colorado, US.

Gendre S, Dejean C, Georges J, Deumier J-M. 2015. Hydraulic irrigation installation diagnosis: knowing of the system to improve it. ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

González Perea R, Camacho E, Montesinos P, Fernández García I, Rodríguez Díaz JA. 2015. Reducing the energy demand in irrigation water supply systems. Experiences from southern Europe. ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

Guiso A, Ghinassi G, Spugnoli P. 2015. Carbon footrpint of three different irrigation systems. ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

Kelley CP, Mohtadi S, Cane MA, Seager R, Kushnir Y. 2015. Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proceedings of the National Academy of Sciences* **112**(11): 3241–3246.

Lozano D, Dorchies D, Belaud G, Litrico X, Mateos L. 2012. Simulation study on the influence of roughness on the downstream automatic control of an irrigation canal. *Journal of Irrigation and Drainage Engineering* **138**(4): 285–293.

Maruejols F, Deffontaines G. 2015. Optimisation energetique du systeme BRL. ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

© 2019 John Wiley & Sons, Ltd.

Marzougui T, Ben Elghali S, Doumenc F, Outlib R. 2015. An analysis of energetic cost for an irrigation network in France. ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

Mateos L, dos Santos Almeida AC, Frizzone JA, Ribeiro Vieira Lima SC. 2015. Irrigation pumping efficiency at smallholdings in North East Brazil. ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

Pérez-Sánchez M, Sánchez-Romero FJ, Ramos HM, López-Jiménez PA. 2016. Modeling irrigation networks for the quantification of potential energy recovering: a case study. *Water* **8**(6): 234.

Plusquellec H. 2002. Is the daunting challenge of irrigation achievable? *Irrigation and Drainage* **51**(3): 185–198.

Pradeleix L, Roux P, Bouarfa S, Jaouani B, Lili-Chabaane L, Bellon-Maurel V. 2015. Environmental impacts of contrasted groundwater pumping systems assessed by life cycle assessment methodology: contribution to the water–energy nexus study. *Irrigation and Drainage* **64**: 124–138.

Prevost F, Guichard G. 2015. Réalisation et exploitation d'une microcentrale: modalités d'un partenariat durable entre l'ASCO des irrigants de la Crau et la Société du canal de Provence. ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

Robles O, Playán E, Cavero J, Zapata N. 2017. Assessing low-pressure solid-set sprinkler irrigation in maize. *Agricultural Water Management* **191**: 37–49.

Rocamora C, Vera J, Abadía R. 2013. Strategy for efficient energy management to solve energy problems in modernized irrigation: analysis of the Spanish case. *Irrigation Science* **31**(5): 1139–1158.

Scanlon BR, Faunt CC, Longuevergne L, Reedy RC, Alley WM, McGuire VL, McMahon PB. 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences* **109**(24): 9320–9325.

Vlotman WF, Ballard C. 2014. Water, food and energy supply chains for a green economy. *Irrigation and Drainage* **63**: 232–240.

World Commission on Dams. 2000. Dams and development. A new framework for decision-making. The Report of the World Commission on Dams, Earthscan, London.

Zapata N, Latorre B, Citoler FJ, Gallinat J, Bescós M, Castillo R, Mantero N, Burguete J, Playán E. 2015. Collective irrigation network design and management for energy optimization: the 'Cintegral' tool. ICID Conference, Special Session 'Irrigation and Energy', Montpellier, France.

© 2019 John Wiley & Sons, Ltd.