Economic assessment of converting a pressurised water distribution network into an off-grid system supplied with solar photovoltaic energy

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Abstract
Converting a water pressurised distribution network into an off-grid pumping station supplied by solar photovoltaics represents a challenge for utility managers, user demand assessments evaluate the energy generated in a solar-powered systems to establish energy consumption. This work includes quantifying potential investments and economic savings that could be achieved, as well as the payback period which results as an indicator of the suitability of adapting to a power supply utilising solar panels. A tool (UAsolar) to aid practitioners has been developed, it requires a calibrated hydraulic model to account for the energy requirements in the water delivery process of pressurised networks. The authors encourage students, professionals, and decision-makers to use this tool to identify potential efficiency gains (e.g., delivery schedule, reduction of water use) and to synchronise energy production and consumption. Users can get results with low computational time using the software on six pressurised distribution networks. Practitioners should note that the irrigation networks have sized installations with a few photovoltaic modules, while in urban pressurised networks the results show larger installations are required. In addition, irrigation network managers can match energy demand with energy production by changing consumption over time, this could reduce the quantity of modules required and remove the need for energy storage. The payback period ranges from 6.08 to 13 years for the cases where the investment is recovered—(values that show that this investment yields a high return as the lifetime of the PV modules is 25 years). However, one municipality among those studied shows that in some scenarios it is not viable to convert networks into a standalone system.

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Introduction

Water management is an energy-intensive procedure with 4% of overall global electricity consumption (IEA 2019). Researchers evaluated the energy footprint in the urban water cycle among the 0.21–4.07 kWh/m³ (Wakeel and Chen 2016), amounts which rested on circumstances, such as the topography, water source, climate, treatment technology. Drinking water and wastewater plants account for 30–40 per cent of total energy consumed in some municipalities and this consumption account for 3–4 per cent of total nationwide (U.S.) electricity use (Gude 2015).

Since water distribution is a high energy-consuming process, renewable energy sources gained enormous interest among experts and the public for reducing the reliance on carbon-intensive energy production, minimizing global warming and fossil fuel depletion. Clean energy resources reduce greenhouse gas emissions (Murty and Kumar 2020) and these techniques are used for cities decarbonisation (Sánchez-Zarco et al. 2020), for constructing nearly zero energy buildings (Hossaini et al. 2018) or for scheduling irrigation alternatives to reduce carbon footprint (Pérez-Neira and Grollmus-Venegás 2018) among other initiatives. Photovoltaic (PV) production has expanded around the world for many reasons, such as a rise in the electricity price [0.0885 euros/kWh—2004 to 0.1174 euros/kWh—2018 (Mincotur 2018)], changes in legislation, taxes elimination, etc. The massive use of silicon solar panels has even led to the potential shortage of material in the next decade (Heidari and Anctil 2021).

In the water industry, solar-powered water systems (SPWS) for irrigation (Todde et al. 2019) or supply municipalities (Wong et al. 2014) became one of the hottest topics. This process of switching the electricity supply of a pressurised water network (WPN) from a grid supply to an off-grid photovoltaic supply involves storing energy in header tanks or batteries.

Many studies analysed how to convert direct-drive pumping devices powered by electricity grids into standalone SPWS (Mérida García et al. 2018; Chilundo et al. 2019). Dursun and Özden (2014) developed software to avoid unnecessary water delivery to plots—reducing water and energy consumption by 38%—and other approaches released an algorithm to forecast water demand (Xiangmei et al. 2021) or energy demand (Perea et al. 2021). Moreover, in irrigation networks (or indirect water supply systems) utility managers can accommodate the delivery times to synchronise water use with energy production, not the same situation as in urban water networks. The consumer’s demand (and so its energy expenditure) cannot be changed.
Standalone (off-grid) techniques are the most widely used because of their simplicity, great efficiency, and versatility in all extents and forms of irrigation. This result provides feeding pumps in isolated regions distant from electricity grids (Sebagh et al. 2018), avoiding fuel as a power source. Another improvement is damage control. If a failure takes place, it will influence the standalone process.

Some approaches presented the energy production in solar power plants (Fan et al. 2018) and estimated the effect of many factors (such as the azimuth or the tilt angle) in energy production (Božíková et al. 2021) and also much commercial software estimate these numbers as PVPCase (PV Design Software focused on households) or Grundfoss size page tool, which is focused on sizing an SPWS for irrigation. But these tools do not calculate energy consumption in a water pressurized network. Some other software as UAenergy (Pardo et al. 2019b) calculates the overall energy audit for water distribution systems but this does not consider the photovoltaic production. So, this tool considers both approaches (energy production and consumption) and depicts, as a result, the energy savings, and the economic solution for the utility manager. Results of photovoltaic production have been checked with those obtained on “global solar Atlas” website getting the same results (note that UA solar software considers motor and inverter efficiency).

This study aims to release software (UA Solar) that allows professionals to quantify energy expenditure in a PIN (or a WPN) and the energy produced by photovoltaic modules. This program considers the investment to be performed and the future revenues got (got by future management of the network off-grids—without being connected to the general electricity supply network—). The payback period (the time required for investments to return) is calculated by the software, a value that considers costs variation over time because of inflation and the real interest rate. The authors release this program for professionals and students, as an engine for calculating and sizing the PV systems. UAsolar calculates the PV modules required to supply the WPN. This software does not include the synchronisation problem and a battery (or a head tank) to store energy is required to make sure this transformation into an off-grid system.

The major limitations of UAsolar are that it requires the WPN modelled in Epanet (which may be an obstacle in small municipalities) and the user must know how to run MATLAB® in their computer. Moreover, the software considers that the utility manager selects a PV cleaning maintenance program (to ward off dirt and dust energy losses and shading losses) and it assumes that the irradiance remained steady over the coming years of study—a non-conservative assumption as much research has shown that the annual average daily solar increases with time (Zhou et al. 2019).

Finally, the pressurized irrigation network (PIN) operates as an off-grid SPWS without taking power from the electricity grids. Irrigation scheduling must adhere to a rigid rotation predetermined schedule (Replogle and Kruse 2007).

Authors encourage the reader to download the program and source codes available at https://bit.ly/3eQCTEU. To ease the management, an interactive MATLAB® application handles all the processes guiding the users and a video outlining how to run the software has been available on YouTube (in English, https://bit.ly/3Cuk5Ge, French https://bit.ly/2RvY46Z, and Spanish https://bit.ly/3ttn9Na). Synthetic and real cases have been published with this open-source software so that users can reproduce the results. Some cases presented here are included when downloading the software and user’s can replicate results.

The manuscript is organised as follows. “Software requirements” section presents the software requirements, “Energy production calculation” and “The energy supplied by pumping stations” sections describe energy production and consumption in WPN, respectively. “Economic analysis” section introduces the economic analysis performed and a block diagram of the whole process can be observed in “Workflow of the system” section. The results achieved are presented in “Results achieved by the software” section. “Case study” section presents the cases analysed and “Results” section shows results. “Discussion and future improvements” section discusses the results, with key conclusions identified in “Conclusions” section.

**Steps to calculate energy production and consumption in water pressurized networks**

There are few steps to execute the case studies. Those are as follows:

a. *Step 1* Energy production calculation.

b. *Step 2* Energy supplied by pumping stations.

c. *Step 3* Economic analysis.

Each step is described briefly in below sections. The graphical user interface has been released to help the user through all the processes and can be found in Online Appendix A. Finally, the process is described with a workflow and the results achieved are shown.

**Software requirements**

The requisites to run the software are:

- The computer must include Matlab® 2016a or later programming software working (equal performance is achieved on Windows®, Mac OS®, X, and Linux®) as the program used MATLAB APP designer.
The hydraulic approach. This research group distributed this tool under the MATLAB (Eliades et al. 2016) has been used in this computing environment that allows connection to network and using the Eq. (1). The hydraulic solver must calculate the steady-state conditions for every \( t_k \) time (reporting time step), from the initial time to the total simulation duration \( (t_f = 1 \text{ day}, 1 \text{ week}, \text{etc.}) \). For example, if \( t_f = 1 \text{ h} \) and the total duration is \( t_f = 1 \text{ day} \), the sum will account for 24 values for \( n_p \) pumping stations. This term is the incoming energy into the system needed to satisfy water demand at the consumption nodes. The water utility must pay for this electricity (the energy operating costs in the WPN). And, so, the higher the consumption, the more useful (and important) will be the change from grid-connected to off-grid solar PV supplied system (because of the direct cost involved).

**Energy production calculation**

The first stage when sizing a PV system is to find the hourly irradiance (W/m²) at the site to be installed. The hourly irradiance can be calculated from the Duffie and Beckman equations (Duffie and Beckman 2013) and these equations are presented in Online Appendix B. Many circumstances affect energy production in PV modules (azimuth, temperature, latitude, tilt angle, etc.) and these values are numbered in “Economic data” section to calculate the energy output. By performing the calculations, the hourly energy production of the solar PV installation is achieved.

**The energy supplied by pumping stations**

To calculate the energy consumed in pumping devices, a hydraulic solver is needed. EPAnet (Rossman 2000) has been selected as the software to solve hydraulic equations (conservation of mass and energy for incompressible fluids as water). This software uses a fast and precise global gradient algorithm (GGA) (Todini and Pilati 1988) to make the system converge. The hydraulic input data is a calibrated model (in EPAnet input format) which simulates the hydraulic behaviour of the water pressurised system. Every error appearing in the hydraulic model will keep when running UAsolar software.

Open-source software for connecting EPAnet-toolkit with MATLAB (Eliades et al. 2016) has been used in this approach. This research group distributed this tool under the European Union Public License. MATLAB® is an adopted computing environment that allows connection to network knowledge through a data system, to do direct requests to the EPAnet library, to change water pressurised systems. UAsolar calculates the energy consumption in pumps from the energy equation, and the software integrates over time in a user-selected period. Users could also confirm results by solving the hydraulic problem in a pressurised irrigation network and using the Eq. (1).

Shaft work supplied by the pumps is calculated as follows (Cabrera et al. 2010):

\[
E_p(t_p) = \gamma \cdot \sum_{t_k=0}^{t_f} \left( \sum_{i=1}^{n_p} q_{pi}(t_k) \cdot h_{pi}(t_k) \right) \cdot \Delta t_k
\]

where \( \gamma \) is the specific weight of the fluid (N/m³) \( q_{pi}(t_k) \) and \( h_{pi}(t_k) \) are the flow rate pumped by the station (m³ s⁻¹) and the pump head (m.w.c.) at the time \( t_k \). This equation must be solved for the \( n_p \) pumping stations supplying shaft work to the network at each discrete time \( t_k \). The hydraulic solver must calculate the steady-state conditions for every \( t_k \) time (reporting time step), from the initial time to the total simulation duration \( (t_f = 1 \text{ day}, 1 \text{ week}, \text{etc.}) \). For example, if \( t_f = 1 \text{ h} \) and the total duration is \( t_f = 1 \text{ day} \), the sum will account for 24 values for \( n_p \) pumping stations. This term is the incoming energy into the system needed to satisfy water demand at the consumption nodes. The water utility must pay for this electricity (the energy operating costs in the WPN). And, so, the higher the consumption, the more useful (and important) will be the change from grid-connected to off-grid solar PV supplied system (because of the direct cost involved).

**Economic analysis**

The payback period is the indicator that defines how interesting to adopt one policy or another. The lower the value, the earlier the return on investment and the more interesting the alternative. Being \( I_0 \) the investment performed in year 0 (a value that considers purchasing “\( n \)” PV panels, control valves and automation, electrical devices, etc.) (\( C_{PV} \)), the cost of batteries \( C_{bat} \) and their average life expectancy (\( t_{bat} \) and \( t_{bat} \)). Given the fact that battery lifetime is shorter than photovoltaic panels, we define the number of batteries required for the life expectancy of the PV panels as \( k = \text{ceil} \left( \frac{20}{h_{bat}} \right) \). The investment is calculated as follows:

\[
I_0 = n \cdot C_{PV} + \sum_{i=0}^{k} (C_{bat} \cdot e^{-r t_{bat}} dt)
\]

The economic savings \( S_i \) (achieved by eliminating electricity bills) will be obtained (an accumulated cost to be paid monthly—gathered by the integral).

\[
S_i = \int_{t_p}^{t} \left( C_{EN} \cdot E_p \right) \cdot e^{-r t} dt
\]

Being the cost of energy \( C_{EN} \) (EUR/kWh) and \( r \) the equivalent continuous discount rate used to express future savings in monetary units at the present. The payback period is the time necessary to recover the cost of an investment. This indicator shows a more favourable scenario the lower since, for a specific investment, higher water and energy savings are desired. It can be calculated with (Eq. (4)).

\[
T_i = \frac{-1}{r} \cdot \ln \left( 1 - \frac{r \cdot I_0}{S_i} \right)
\]
Workflow of the system

The general flow-chart of UASolar which visualizes the process of the software is shown in Fig. 1.

The process is described here:

Step 1: UASolar provides an application that allows users to introduce this information. The software placed common values as default values in the program to give information to the user. The input data are shown here:

- Tilt Angle ($\beta$) is the angle of inclination (radians) of the photovoltaic panels.
- The latitude angle ($\varphi$) (radians).
- The albedo ($\rho$) (–).

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**STEP 1** ENERGY PRODUCTION

**INPUT DATA**

- $\beta$ Tilt angle (°)
- $\varphi$ is the latitude angle (radians)
- $\rho$ the albedo

**Solar photovoltaic panel values:**

- Peak power (W)
- $T_{\text{sc}}$ the Nominal operating cell temperature under standard test conditions (°C)
- $d$ performance decay (°C⁻¹)

**Location and seasonal values:**

- $n$ is the month (1-12)
- $H$ global irradiance on horizontal surface (kWh/m²)
- $T_{\text{avg}}$ Monthly average Temperature (°C)
- $\eta_{\text{am}}$ Asynchronous efficiency
- $\eta_{\text{c}}$ Converter efficiency

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**STEP 2** ENERGY CONSUMPTION

**INPUT DATA**

- Network model in inp format

**Are the efficiency curves added in the network EPAnet model?**

- YES
- NO

User can insert a value manually (0-100 %)

---

**STEP 3** ECONOMIC INPUT DATA

- Cost of PV panels (EUR)
- Expected PV panels lifetime (EUR)
- Cost of batteries (EUR)
- Expected batteries lifetime (EUR)
- Cost of energy (EUR/kWh)
- $r$ discount rate (%)

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**STEP 4** CALCULATE RESULTS

- Numerical results
- Graphical results
- Numerical results

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Fig. 1 Workflow for the calculation process
Parameters of the solar panels:

- The peak power of a PV module (PP) (W).
- Nominal operating cell temperature (NOCT) (°C).
- The performance decay \((d)\) coefficient. This term considers the increase in cell temperature \((°C^{-1})\).

Parameters vary with month and location:

- Month, the software incorporates the representative day of the month (being 1 January and 12 December). In these latitudes, December is the worst value for energy production.
- Global irradiance on horizontal surface \((H)\) \((\text{kWh} \text{ m}^{-2})\)
- Average temperature month \((T_{\text{avg}})\) (°C)

Other limits:

- Motor efficiency \((\eta_{\text{am}})\) (–).
- Inverter efficiency \((\eta_{\text{fc}})\) (–).

**Step 2** The users may introduce the input data model using a button shown in the general screenshot of UASolar. The better the model represents the current operation (the model must be calibrated), the more accurate the results will achieve. This network model incorporates hydraulic data such as:

1. Consumption nodes (elevation, base demands, consumption patterns).
2. Pipelines (diameters, lengths, settings, roughness, loss coefficient, status (open-closed)).
3. Pumps (representative H-Q, P-Q, efficiency-Q curves).
4. Reservoirs (total head).
5. Tanks (elevation, diameter, initial, minimum, and maximum values of water level).
6. Valves (diameter, type, setting, loss coefficients, status (open-closed)).

Users can get these values by exporting the model using the EPAnet interface to achieve the input file (.inp extension).

Afterwards, the user can choose between “YES” if the pump efficiency curve is incorporated in the model selected, or “NO” to add a constant value for the pump efficiency.

**Step 3** The economic input data are the investment costs.

- \(C_{\text{PV}}\), the cost of PV Panels (EUR).
- \(C_{\text{bat}}\), the cost of batteries (EUR).
- \(t_{\text{PV}}\), the expected lifetime of PV Panels (years).
- \(t_{\text{bat}}\) the expected lifetime of batteries (years).

To compute annual energy savings, the software demands the saving costs:

- \(C_{\text{EN}}\) cost of energy (EUR/kWh).
- \(r\) the equivalent continuous discount rate used to express future savings in monetary units at the present.

All this information is entered into the software which provides common values as default values to users.

With these data inserted into the tool, the calculate button is activated and the software is ready to compute results.

**Results achieved by the software**

Once the calculate button has been pressed, the software facilitates the following output data presented in Table 1. These are separated into energy consumption, energy production and economic results.

Moreover, the software also presents graphical results as a plot showing energy produced and consumed (Online Appendix A). Users may store this graph in many image formats (jpeg, tiff, pdf, etc.). The raw data achieved is exported by UASolar software using a report file called “Name. inp—report.txt”. This text file is stored on the network path and it contains the simulation data, the path where to find the model, and all the numbers calculated for the energy produced and consumed. The user can export these in a spreadsheet for future analysis.

| Table 1 | Numerical results achieved by the software |
|---------|------------------------------------------|
| **Energy production results** | The energy produced per PV (kWh) | Number of Panels required (–) | Total energy production (kWh) |
| Energy consumption results | Daily energy consumption (kWh) | Total energy consumption (kWh) |
| Economic results | Investments (EUR) | Savings (EUR) | Payback period (years) |
Case study

The following case shows the effectiveness of the proposed software in well-known WPNs. Real cases are located in the southern east region of Spain.

Energy production data

Table 2 depicts the average temperature for 30 years and these data has been provided by AEMET (Meteorology Spanish agency) at climate station 8025 at 81 m height (Latitude 38°22′21″ N–Longitude: 0°29′39″ W).

To compare the cases, the same solar data has been used. The values selected are:

- Tilt Angle ($\beta = 15^\circ$ for synthetic cases A, B and $\beta = 35^\circ$ for other cases).
- Albedo ($\rho = 0.2$).
- The peak power of a PV module (PP = 250 W).
- The performance decay ($d = 0.004 \, ^\circ C^{-1}$).
- The inverter efficiency ($\eta_{ic} = 100\%$).
- The motor efficiency ($\eta_{am} = 100\%$).

Information data varies with the location and the month. In our cases, December has been selected as the month study as the worst month in terms of solar energy production in this latitude. The data used for December are:

- Average temperature month ($T_{avg} = 12.4 \, ^\circ C$).
- Global irradiance on a horizontal surface ($H_{avg} = 2.2 \, kWh \, m^{-2}$)

Energy consumption data

The hydraulic input data required are incorporated in the WPN model. Six different networks are analysed here. Cases A and B are artificial networks that allow a quick simulation because they are not composed of many elements. These can ease knowledge acquisition by students/users as their results can be replicated. In contrast, cases C and D are real irrigation networks and Cases E and F are real WPN supplying municipalities in the Alicante province. Figure 2 shows the layout of these networks.

Case A (Anytown) incorporates one reservoir and three pumps (no pump efficiency curve here). Much information about this water pressurised network was published in the literature (Farmani et al. 2005). It includes three pumps running in parallel to deliver water to customers.

Case B (Short) is an urban WPN network with one reservoir, one pump (pump efficiency curve incorporated this network) and one compensation tank to store water and energy. This tank delivers water to the municipality when the pump is switched off and the tank is filled with water when the pump is operating. This network is described in (Cabrera et al. 2010).

Case C (Albamix) is a branched network with one reservoir and one pump (no pump efficiency curve in this network) (Pardo et al. 2019a). This is a well-known pressurised irrigation network.

Case D (the University of Alicante irrigation network) has one reservoir and four pumps (no pump efficiency curve here). This network was described in earlier research (Pardo et al. 2020c).

Case E (municipality 1) is an urban WPN network supplying water to 1000 inhabitants (900 connections) in Alicante province. This network incorporates one reservoir, one tank, and one pump (with head-flow curve $H = 66.67 - 5.976Q^2$ and the pump efficiency curve $\eta = -0.2798Q^2 + 8.2262Q + 13.286$; being $Q$ (l/s), $H$ (m.w.c) and $\eta$ (%)). This municipality contains 14.61 km of pipes (10% of the total length are diameters below 60 mm and 90% are diameters between 60 and 150 mm). The materials that make up the network are 38.19% fibre cement, 13% polyvinyl chloride (PVC) and the remaining 48.79% low-density polyethylene.

Case F (municipality 2) is an urban WPN network supplying water to 3400 inhabitants (342 connections) in Alicante province. This network incorporates two reservoirs, one tank, and one pump (head-flow curve $H = 53.33 - 0.01411Q^2$ being $Q$ (l/s), $H$ (m.w.c). This municipality contains 12.21 km of pipes (18% of the total length are diameters below 60 mm, 74% are diameters between 60 and 150 mm and 8% are diameters above 150 mm). Most of the network is made of high-density polyethylene (HDPE) 90% and 9% of fibre cement.

Economic data

For every network analysed, the same economic data has been considered. The cost of PV panels is (300 €), batteries are 8500 €, the energy entails 0.201 € kWh$^{-1}$ in Spain and $r = 2\%$.

| Month   | January | February | March | April | May | June | July | August | September | October | November | December |
|---------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| $T_{avg}$ (°C) | 11.7 | 12.3 | 14.2 | 16.1 | 19.1 | 22.9 | 25.5 | 26.0 | 23.5 | 19.7 | 15.4 | 12.6 |

Table 2  Average temperature in degrees Celsius in Spain
Results

Computational time got was lower than one minute for each case. Solving the (Duffie and Beckman 2013) equations should take 1 or 2 h and solving the energy audit in WPNs should take 4–5 h for every case. The results found when using the data are described herein divided into two separate blocks energy production and consumption and economic analysis.

The energy produced in an SPWS, and energy consumed in WPN

Case A (Anytown network) is an energy-hungry WPN. The energy demand is much larger than the other cases. The software shows a high number of PV panels to be fed by solar energy (Table 3), the cost of total investment (purchase of panels and batteries) and the annual energy savings (the current energy consumption; Table 3).
Table 3  The energy produced and consumed for the cases

| Simulation period (h) | A    | B    | C    | D    | E    | F    |
|----------------------|------|------|------|------|------|------|
| E consumption per day (kWh) | 24   | 24   | 15   | 72   | 240  | 480  |
| E production (kWh)     | 8917.53 | 1274.6 | 627.18 | 63.83 | 1928.28 | 4.969 |
| Number of panels       | 15.728 | 2248 | 718   | 72   | 2202 | 6    |
| Total energy produced (kWh) | 8917.83 | 1274.62 | 627.65 | 64.31 | 1928.88 | 5.33 |

Table 4 shows specific data about energy demanded by pumps in the Anytown network (Case A; (Farmani et al. 2005)). These values are gathered from the text file exported when running UASolar (Fig. 3). The user can change the value “reporting time step” and simulation duration in Epanet. UAsolar returns as many values of energy per pump operating. When summing each pump energy consumption, the energy consumed is equal to \(2972.51 + 2972.51 + 2972.51 = 8917.53\) kWh, Table 3.

Case B consumes 1274.60 kWh/day. The short network needs 2248 PV panels and UAsolar retrieves the pump efficiency from the Epanet model and calculates the pump efficiency for every time step of the simulation. This value shows that supplying water to a city involves a high number of modules as the pumps must fill the tanks in a few hours (6–7 in these latitudes). Professionals who performed this installation selected pumps in this WPN to run for many hours (as required). Here, the compensation tank must be filled during the day and this tank must have a higher capacity to allow water delivery at night-time.

Case C is the first irrigation network. It operates for 15 h (when the users irrigate) and the energy consumed is 627.18 kWh. This network requires 718 photovoltaic modules for the most unfavourable month. Case D shows that the energy consumed is 63.83 kWh per day. This irrigation network demand 72 PV panels to work as a standalone irrigation system supplied with photovoltaics. Case E and F represent real cases in urban water distribution networks, the first represents high energy consumption and Case F is the opposite. Results found here prove that in cases with low energy consumption conversion is not convenient.

Figure 3 presents the energy absorbed and provided for the simulation time for the smallest number of modules. The PV system works out the energy needed by the water networks, but this number highlight that the SPWS requires a battery to accumulate power generated at midday. UAsolar users can adjust energy expenditure in pressurized irrigation systems (Case A and B) to meet energy production.

**Investments and savings produced by converting a water pressurised distribution network into an off-grid SPWS**

Table 5 shows the cost of all investments, the annual energy savings and the payback period for all cases got by UASolar. The payback period ranges from 6.08 years (Case E), a very affordable scenario that shows that from 6.08 to 25 (the lifetime of PV panels) the installation will deliver higher revenues. Cases C and E represent cases where conversion to SPWS is a very affordable scenario. Cases A, B and D represent cases with payback periods over the range of
Fig. 3 The graphical results of cases. a Anytown; b short network; c Albamix, d UA irrigation network; e municipality 1; f municipality 2

Table 5 Economic results for the cases analysed

| Cases | A       | B       | C       | D       | E       | F       |
|-------|---------|---------|---------|---------|---------|---------|
| Total investment (EUR) | 5,532,502 | 814,502 | 627,659 | 52,902  | 798,402 | 29,802  |
| Savings (EUR/year)     | 645,272.5 | 92,230.1 | 45,383.02 | 4618.93 | 139,530.32 | 359.59 |
| Payback period (years) | 9.41    | 9.72    | 6.56    | 13.01   | 6.08    | Inf     |
9–11 years (common values) which presents viable projects where maybe the high investments to be performed are the only obstacle to performing these changes. Finally, Case F show a case with very low energy savings in which investment is never recovered.

**Discussion and future improvements**

The indicator that practitioners use for identifying which PIN is more convenient to transform into a standalone supply system is the payback period. The results achieved here when analysing the WPNs are included among (6.08 and 13.0 years), values lower than those achieved in another works as 7–8.82 (Pardo et al. 2020a), like 9 years (Formica and Pecht 2017) and profitability around 15% (Guaita-Pradas and Blasco-Ruiz 2020) or 10.6% (Sugihara et al. 2012). Other authors identify 7 as the usual value for the payback period (Tsalkis and Martinopoulos 2015) in PV installations in residential buildings. With this tool, utility managers could find Sizing the SPWS choosing the worst month means that, in warm months, the installation is an oversized PV system. This is a typical issue for the correct sizing of off-grid photovoltaic residential generation systems (Quiles et al. 2020). The utility manager must size the system knowing that as irradiance depends on the latitude, extra power is produced in the warm season.

Results write down that energy-hungry WPNs involve higher savings and lower payback periods. The key tendency is obvious, although other parameters influence this relationship (Fig. 4). It is also interesting to mention that low energy consumption cases, such as those found in case F, imply that the investment is never recovered, and the software returns infinite as the payback period. This underlines that using solar photovoltaic panels is not a universal cost-saving technique, and its suitability depends on the characteristics of the energy-consuming system.

The procedure described here may help practitioners to choose the energy storage choice that is better. This is of paramount importance in Case A, where the great pumping operation hours need a great number of modules (reducing profitability). Some authors highlighted that the life-cycle cost of an optimised photovoltaic water pumping scheme with batteries is cheaper than embracing a tank as energy storage (Soenen et al. 2021). But these authors highlight monetary conditions might decline if service managers do not keep maintenance and recycling. Storing water in head tanks as potential storage involves increasing tank capacity, a challenge that reduces profitability (Pardo et al. 2020b).

In pressurised irrigation networks (Case C and D), the scenario is distinct as the water utility manager can adjust the irrigation schedule to satisfy the energy production times (Pardo et al. 2019a) and to cut down energy expenditure by delivering a stable flow rate (Alonso Campos et al. 2020). Efficient solar energy panels on a larger scale would help the community and climate, being UASolar the first software which links energy production and consumption in WPNs. This program can assimilate all the aspects discussed here and enable a device to promote the scheduling of water demands in irrigation networks while addressing the emissions released into the environment. UAsolar responds quickly to utility managers when planning to calculate energy needs.

Future improvements of this program should let the users simulate other configurations as a smaller PV system storing the surplus of energy in batteries or compensation tanks (Pardo et al. 2020b) or consider the possibility of taking power from the grid. Another choice would be to find an algorithm that matches the energy consumption with energy production in a PIN with a programmed irrigation schedule. This issue bears an applied practice in pressurised irrigation systems, as service managers can adjust water and energy needs. Similar results have been found in (Navarro-Gonzalez et al. 2021) but they reduced this approach, as this algorithm considers fixed segments in programmed irrigation schedule. This hypothetical algorithm would be incorporated in UASolar for the future and the user would get an irrigation schedule to decrease PV modules. We must find a deterministic method with limited computing time which does not assure have the ultimate smallest size for the system and with large computational times.

**Conclusions**

This approach presents six cases study using a tool that incorporates energy production in photovoltaic arrays (information that can be gathered on websites and
commercial software) with energy consumption in water pressurized networks. The latest can be achieved by solving the energy equation in its most general form to the control volume—being the control volume of the water pressurized networks with known amounts of water and energy flowing through its boundaries. Finally, because of being water incompressible, the mechanical and thermal equations are not coupled—so the energy problem can be solved after the hydraulic one.

UASolar enables users to design an off-grid SPWS for urban (or agricultural) water supply. This program has been distributed to the water industry and the hydraulic data is embedded in the Epanet model of the WPN. This software provides results with less computational time (the software requires 30 s to gather the results) and professionals can reproduce the results using a spreadsheet and Epanet's hydraulic simulation model (with longer calculation times, 2–3 h corresponding to experience).

Six cases (two synthetic WPNs, two real PINs and two real urban WPNs) were examined, and results highlight sizing a standalone SPWS depending on the network features (layout, pipe sizing, etc.). This tool permits a quick response and provides water utility managers to consider this fresh renewable technology. Users could identify the WPN or PIN as more convenient to transform into an Off-grid system by calculating the total investments required to buy and install PV modules and batteries and calculating the annual energy savings and the payback periods. Some scenarios have been identified (e.g., Case F), where it is not profitable to make the necessary investment to supply the distribution grid with solar PV panels. In this case, the investment is not recouped. The payback period achieved in a southern Mediterranean climate was found to be between (4.82 and 17.06 years), values that suggest high revenues as the PV panels lifespan is 25 years. Cases with low water and energy expenditure (Case F) reached the worst results because of low energy savings. This case shows that it is not always appropriate to switch the supply of an on-grid supply to a solar PV supply. The energy production and economic data are a set of limits influencing the payback period calculation that can be listed, but not the energy consumption input data. These latest are incorporated into the WPN model and can be considered using the open-source UAsolar tool.

This work outlines that PIN allows for energy demand management, a distinctive position. This circumstance is significant in WPNs whose energy is fed by the pumping station (all cases presented here). The added factors as water scarcity, leakage in WPNs, climate change reinforce these procedures. The greater the energy footprint of water, the more attractive these investigations become.

**Author contributions** HEC and AR performed modelling and analysis in software. MAP designed the research, concept, and method. MAP and AR cooperated in the research task, supervision, and data curation. MAP and AR read and approved the final manuscript. All authors have read and agreed to the published version of the manuscript.

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**Availability of data and materials** The videos describing how to run the software are available online at https://www.youtube.com/watch?v= gzbU8jROjzMr&t=1s (English), https://youtu.be/t2AYHFGCanc (Spanish), https://www.youtube.com/watch?v=JNav8_Z4kYA&t=3s (French).

**Code availability** The code can be downloadable at: http://rua.ua.es/dspace/handle/10045/114524.

**Declarations**

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Economic assessment of converting a pressurised water distribution network into an off-grid...