Self-Powered Sensor Networks for Water Grids: Challenges and Preliminary Evaluations

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***Abstract*—Water Grids represent a challenge for the scientific community operating in the Sensor Networks (SN) field. Indeed, an increasing water demand and a certain difficulty to access clean water resources can be registered nowadays in several countries, and adequate saving policies have to be applied in order to match the user needs and avoid non-ecological wasting. From this point of view though, the most recent SN technologies can provide viable solutions to perform automatic monitoring to the Water Grid and smart metering of water consumption to support the Public Utilities not only in guaranteeing a transparent service to the citizens but also in optimizing the available resources for a wider sustainable distribution. In this paper, the authors want to focus on the possibility to involve self-powered nodes in Wireless SNs with the aim of maximizing their autonomy, typically bounded by battery lifetime, and thus facilitating their application to a pervasive monitoring scenario, such as that of Automatic Meter Reading (AMR) for water. An overview of the most promising technologies and some preliminary evaluations related to them are thus given. Finally, a realistic case study for the specific smart water metering problem is also discussed and analyzed, by taking the economic feasibility issue into account.**

I. Introduction

SMART grid technologies have gained a big momentum in recent years, especially in the field of electricity distribution and power management. In the field of water grid management and monitoring, however, the situation is less mature: such technologies are only recently gaining popularity and will probably undergo a large market growth if developed countries institutions will recommend or enforce the massive use of smart meters and monitoring systems. Once in place, thousands of sensors could inform municipal water authorities about events such as leaks, or transmit data about user consumption and storm water overflows, to enable real time management of the water plants. From the user's perspective, domestic smart meters will provide households with information for optimization of the water usage, or give alert for possible health threats. A technology similar to the one developed for the power grid will make the transmission and processing of water related data possible. New solutions are being developed to retrofit older water systems, in order to enable smart monitoring without requiring the complete replacement of existing plants. However, a big issue remains somehow troublesome for water grid applications, i.e. how to ensure power supply to the monitoring devices.

Despite the challenges ahead, smart grid technology for water makes plenty of sense and deployments of new technology will be steady. Beyond improved metering, emerging solutions involve new algorithms to optimize water release in urban areas depending on the real needs [1], [2], new sensor capabilities for better leak detection [3], [4], enhanced monitoring of water quality and the ability to better detect security threats to water systems. The drivers for smart grid technology in water are compelling: worldwide demand for water is expected to soar 40% from current levels, according to the 2030 Water Resources Group [5]; and losses from un-metered water total $14 billion in missed revenue opportunities each year, according to the World Bank [6]. These drivers will help fuel a move to smart technology solutions that promise more efficient water systems. Evidence of this trend continues to mount. A few examples include, among the others, Australia's Sydney Water, that began deployment of high-efficiency meters to replace its aging stock; the three-year program will enable Sydney Water (which serves 4.6 million people) to eventually take advantage of automated and advanced metering technology. In England, Thames Water is extending a smart grid trial in the town of Reading to the city of London to better manage consumption and leakage. In Charlotte, N.C., a public-private effort called Smart Water Now is taking place to measure consumption and improve efficiency; the city has partnered with private industries to collect information with the aim of lowering operational costs and improving sustainability.

II. Sensor Networks for the Water Grid

As stated in Section I, water grid technologies are not yet widespread, but a number of pilot and research projects are currently being developed. Some of these projects are investigating the adoption of monitoring sensors inside water pipes, in order to localize or pre-localize possible leakages with a given degree of precision. The problem of leakages in water distribution plants is a quite hot one, either at a local (regional), national, and planetary level [7]. The issue is not to completely avoid leakages (this may be unrealistic), but to reduce problems related to leakage identification and localization: cutting the time requested to localize the leakage and to take suitable countermeasures means cutting the costs,

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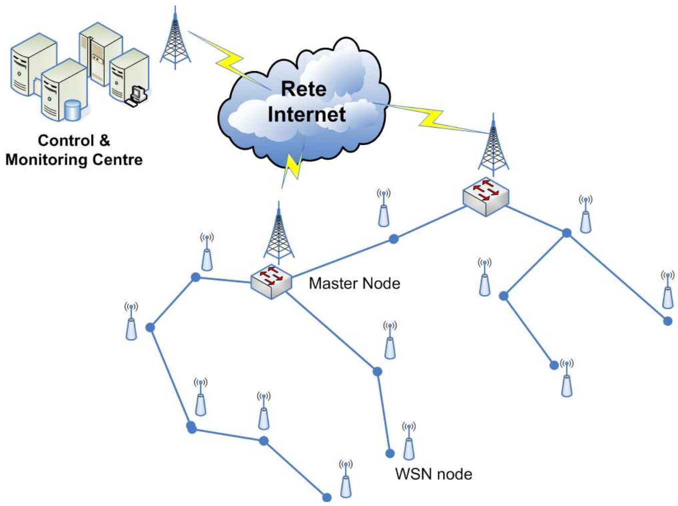

Fig. 1. Hierarchical star network architecture for the water grid.

either financial and environmental, related to water waste. In this context, the availability of an effective monitoring system for the water grid could enable to quickly locate leakages and promptly react to them. Documented pilot projects, often rely on battery power or power grid [8] or solar cells [9]. The power supply strategy can, thus, limit the number or position of the sensor nodes. It is therefore important to adopt a more distributed and independent strategy, to overcome these difficulties and to ensure a continuous, prompt and reliable monitoring of the water plant. Table I highlights the main features of the pilot solutions discussed in [8], [9] for leakage monitoring.

Another relevant scenario for water grid networks is that of the Automatic Meter Infrastructures (AMIs). In this case sensor nodes are usually located at public, domestic or industrial water, gas, or electricity accounting. A traditional communication strategy for AMIs is a hierarchical topology, depicted in Figure 1, where the sensor nodes are connected to gateways, which in turn collect the data and send it to the infrastructure center, where data is stored and processed.

Each node comprises a device for recovering energy through Energy Harvesting (EH) techniques, a flow sensor and an electronic module for data transmission. The latter occurs in a manner depending on the type of node considered: it is envisaged that the leaf nodes in the hierarchical network are able to perform short / medium range radio transmissions at a low power consumption, while master nodes are equipped with long-range transmission capacity, typically enabled by a GSM/3G modem. The master node is responsible for the collection / organization of information from various nodes, and sending the data to the central unit monitoring the subnet, which the master node refers to. At the central unit, the data is processed in order to identify and locate faults in the distribution network. The choice of the individual components, especially those related to a single remote node, must be made with the aim to reduce maintenance to a minimum.

The architecture of the monitoring network will provide master nodes equipped with GSM/GPRS modules: as a matter of fact, master nodes, collecting monitoring data from multiple leaf nodes, must send them to the central unit, over distances typically of the order of a few kilometers. To this aim, master nodes will be powered by the grid or from solar cells rather than by means of EH devices. Short / medium range communication technologies must ensure minimum power consumption. ZigBee, or other solutions based on IEEE 802.15.4 have been widely used for low-power sensor networks, but other protocols, such as the Wireless M-Bus (WM-Bus, EN 13757-4:2005 and EN 13757-4:2011) have been recently proposed by the OMS group [2] for metering scenarios. WM-Bus transceivers require low energy thanks to a low-overhead protocol, Transmission-only modes (which do not require an idle Receive phase) and long-range sub- GHz transmission bands. While the first document EN 13757-4:2005 prescribed the use of the 868MHz ISM and 468MHz bands, the later version EN 13757-4:2011 added new transmission modes at 169MHz with lower data rates. The lower 169MHz frequency band enables longer transmission range due to the inherently lower path losses, while the reduced data rates enable higher sensibility for the receiver, allowing a reduction of the transmission power at the transmitter or a longer transmission range for the same transmission power. The WM-Bus modes of interest are the following:

- T mode: frequent transmission mode (several times per second or per minute), 868MHz, 100kbps data rate from meter to gateway. In mode T2 the transmitter requires an acknowledge (ACK), differently from T1.
- S mode: stationary mode (several transmissions per day), 868MHz, 32.7kbps data rate. In mode S2 the transmitter requires an ACK, differently from S1.
- Nc mode: 169.431MHz, 2.4kbps data rate. N2c requires ACK, N1c does not.
- Na mode: 169.40MHz, 4.8kbps data rate. N2a requires ACK, N1a does not.
- Ng mode: 169.437MHz, 38.4kps data rate. Always require ACK.

The WM-Bus is able to achieve longer distance communication with respect to IEEE 802.15.4. Leaf nodes equipped with ZigBee/802.15.4 transceivers can only cover a few tens of meters. Should greater distances be covered in ZigBee/802.15.4 technology, a multi-hop data transfer strategy can be foreseen, according to which each leaf node can also act as a relay to another node, depending on the distance from the master node. Obviously, the ability of relaying depends both on the estimated amount of data each leaf node may generate, and from the overall transmission capacity of the single ZigBee transceiver that must act as a relay: therefore it will be necessary to plan the placement of the nodes, once defined the amount of data to be transferred. Although the WM-Bus enables long ranges it also provides relaying method to cover longer distances with multi-hop techniques described in EN 13757-5.

TABLE I
COMPARISON AMONG PIPENET AND WATERWISE PROPOSALS

	Power Source	Power Consumption	Data Sampling Frequency	Sensor Type	Communication Protocol
Pipenet	12 V battery or power grid	10 mW	100 Hz for 5 s every 5 mins	pressure pH	Bluetooth
WaterWise	photovoltaic cell (50 W)	4.5-6 mW	≈kHz (continuous streaming)	pressure, flow rate hydrophone	3G

III. SELF-POWERED SENSOR NODES: MAIN ISSUES

Undertaking investments on the deployment of large sensor networks over wide areas requires that certain economic criteria are met, i.e. that the network nodes life sufficiently exceeds the expected payback period, that the maintenance costs allow for a few years payback period and they do not increase excessively with the aging of the nodes, that the technology is open or interoperable and is expected to last several decades, in order for the nodes to be usable throughout their whole expected lifetime. In the present work the focus is put on the nodes powering. Nodes powering technology and power management affects the maintenance costs, the transmission technology and range, the nodes uses (low power requirements limit the number of transmissions/receive and data size) and possibly their interoperability (e.g. new power circuitry is needed if the originary battery technology is no longer in production).

One of the open challenges in the deployment of sensor networks over wide rural or urban areas is, thus, posed by the need for energy over extended periods of time, ideally several decades. Current solutions in the emerging application field of water monitoring and metering employ batteries or connection to the power grid (see e.g. [8] or VonRoll Hydro Ortomat [3] and Lacroix Sofrel [4] products), or more rarely, solar cells [9]. For water grid monitoring the power grid and the solar power are seldom at reach (especially in rural areas, or for underground ducts, etc.). On the other side batteries present a number of disadvantages such as high replacement and disposal costs, chemical hazard and eco-compatibility. This section presents, thus, a brief introduction to the power consumptions generally sustained by a monitoring system and alternative EH techniques for the current scenario and preliminary results in their use for monitoring water data.

A. Power Consumptions

In a typical SN for water management the main energy demanding components are:

- the transceiver
- the microcontroller (or custom circuitry)
- the sensing element (if active)

Transmission technology is a critical aspect for minimizing power consumption. Data transmission should be low in length and frequency of transmissions per day. For instance in the WM-Bus protocol, the data is typically transmitted in one chunk, needing a short Active time for the microcontroller and the transceiver, which are otherwise in Sleep state. The sleep current for the node components is, henceforth, not negligible although a few orders of magnitude lower than the Active/Transmission current. Further cause for energy consumption is the presence of active sensing elements, which may be needed for chemical water analysis, accurate flow measure, etc.

In our early experiments we estimated the diverse energy needs for the different components and operation modes. Figure II reports average figures for a sensor node equipped with a Texas Instruments MSP430 microcontroller, Texas Instruments CC1120 transceiver and additional sensing elements. Please note that task energy estimates are based on measured value for the MSP430 operating at 3V, 1MHz, the CC1120 transceiver operating in WM-Bus Ng mode at maximum transfer power, while are based on average consumption figures taken from several datasheets for sensor reading. Transceiver and MCU task duration are based on measured data while are based on technical white papers for sensor reading. In the MSP430 MCU there are several Sleep states, among which the Low Power Mode 3 is the deepest one. The 1 hour Sleep figure, depicted for comparison is based on measured data on the MSP430. The microcontroller has been chosen for the good technical support provided by the manufacturer for the WMBus protocol and metering scenarios in general [5]. It is apparent from Figure II how different sensors require different current consumption for powering and reading. Passive techniques, not shown in the Figure, may greatly enhance power consumption. Another notable information, is the high energy cost of the Sleep phase, relative to the other tasks. One hour of Sleep requires almost as much energy as that needed for the most energy-expensive sensor readings. If the frequency of the wakeups and sensing tasks is low the Sleep state is the main energy drain. Lower current drains are possible if a custom circuitry is designed in order to maintain only a very low-power RTC (Real Time Clock) to wake up the MCU periodically.

Figure 2 depicts the current required during the active and Sleep states, including wakeup, sensing, transmission (Tx), idle receive (Rx) and suspend. The faded areas indicate uncertainty in the current consumption due to several factors,

[2] http://www.oms-group.org/en_index.html
[3] http://www.wagamet.ch/en/Products/Water/Leakmonitoringsystems/ortomatlc/tabid/3391/language/en-US/Default.aspx
[4] http://www.sofrel.com/products/data_acquisition_devices/gsm_data_loggers_for_destrict_metering_and_leakage_control.html
[5] http://www.ti.com/solution/docs/appsolution.tsp?appId=407

TABLE II
ENERGY REQUIREMENTS FOR SEVERAL SN TASKS

Task	Energy
MCU Wakeup, Sense, Tx	120 uJ
Transceiver Tx	3.3 mJ
Transceiver Rx	5.9 mJ
1h Sleep	29.1 mJ
Flow Sensing (Hall)	0.7 mJ
Flow Sensing (Rotor)	49 uJ
Flow Sensing (Magnetic)	0.75 mJ
Flow Sensing (Ultrasonic)	50 mJ
pH Sensing	33 mJ

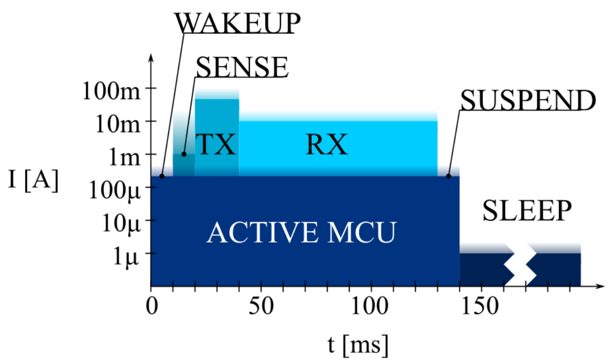

Fig. 2. Current draw for the periodic active and Sleep states. Please note: to improve readibility current draw is logarithmic.

including the sensor type in the sensing phase, the transmission power in the transmission phase, the number of active peripherals in active and Sleep modes. Task energy estimates are based on measured value for the MSP430 operating at 3V, 1MHz, the CC1120 transceiver operating in WM-Bus Ng mode at maximum transfer power, while are based on average consumption figures taken from several datasheets for sensor reading. Transceiver and MCU task duration are based on measured data while are based on technical white papers for sensor reading. Tasks timing are based on a WM-Bus Ng mode transmission at 38.4kbps and 1MHz MCU clock.

Depending on the specific application, the data length, the frequency of transmissions, and the active peripherals or sensors may differ. Figure 3 reports hourly energy requirements for sensor nodes implementing different WM-Bus transmission modes for different daily wakeup frequencies. Figures are calculated from measured data using the aforementioned MCU settings and maximum transmission power. Power demand of the WM-Bus is very low compared to other transmission systems, such as GPRS and allows for km-range distances.

B. *Energy Harvesting Solutions for the Water Grid*

Sensor networks for water management allow for long stand-by periods between each transmission or data acquisition. If some energy storage mechanism is provided to the node, the EH needs, thus, not be continuous. As reported in Figure 3, depending on the use case different consumption

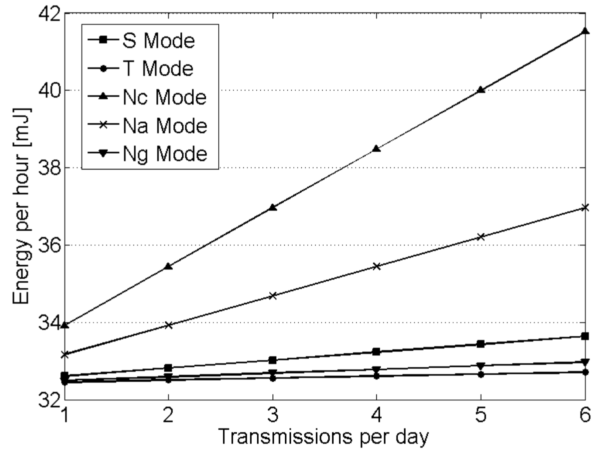

Fig. 3. Energy per hour required for a sensor node depending on the number of transmission per day, for the different WM-Bus transmission modes.

profiles are possible for water management networks. We propose/illustrate here the use of EH techniques based on the exploitation of water kinetic energy by means of piezoelectric materials and water turbine, which are then compared to the use of commercial Li-ion batteries.

Waterworks water conveys high kinetic energy which is converted from gravitational potential energy or inducted by pumping (which in turn requires some sort of energy). A negligible amount of this kinetic energy can be converted into electric energy to power the sensor nodes. This enable for pervasive water monitoring as long as the water flows in the ducts.

A first mean to convert water kinetic energy to other forms of energy is the century-old principle of the mill. More specifically, a small dynamo turbine can be placed in contact with the flowing water (e.g. in a duct) to generate electric energy. This device allows for the harvesting of a moderate quantity of energy and proves very cheap in production. We conducted some preliminary tests with a commercial turbine from Seed Studio Works for micro hydro power generation. A few other turbines can be found on the market with slightly different values and characteristics. We found however that the chosen one fitted best the use in the current scenario.

Figure 4 shows the setup used for measuring the output power of the turbine. The turbine is 80x81.4x43.8mm in size, with a nominal output of 3.6V and 300mA for water flow ranging 1.5 to 20 l/min. It must be noted that a buffer battery is provided inside the turbine to achieve a continuous supply of energy and regulated voltage output. The energy storage issue will be discussed in Subsection III-C.

The maximum output power of the turbine is 1W, enough for powering a sensor node with the power requirements discussed in the previous section when continuous water flows at sufficient speed in the duct. Even with intermittent water flows (of the entity of those in a domestic, industrial or public building) the EH still satisfies the SN needs.

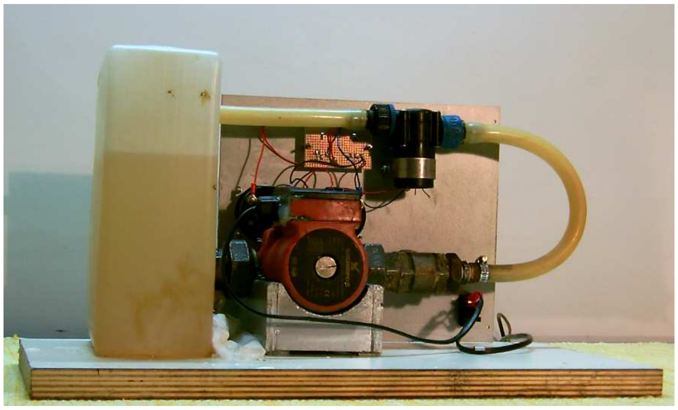

Fig. 4. Setup for evaluation of the micro-turbine energy harvesting. The water is pumped and recycled through the tank on the left. The micro-turbine is placed on the top-right. On the opposite side of the setup current and voltage readings are displayed, which vary depending on the water flow.

To recharge a typical Water Closet, for instance, 7l of water are required to flow in 30s on average. This is enough to supply approximately 1W for 30s, equivalent to 30J of energy that can be stored in the battery and ideally cover e.g. 120 days of transmission with WM-Bus Nc mode (the most energy-expensive) at a rate of 1 transmission every 10 minutes [6]. Although in practice the figure may drop significantly due to current leakage, especially with harsh environmental conditions or with the aging of the components, it gives motivation for further investigation on this energy harvesting approach.

A second more advanced device, may exploit the piezoelectric effect of a membrane to transduce vibrational energy into electric energy. Several devices can be devised to allow for the maximal power output given some physical constraints (e.g. duct dimension, water pressure, turbulence etc.). Some patents are registered for the use of piezoelectric devices for energy harvesting into fluids, e.g. [10]–[12]. Up to the author's knowledge no commercial products exist for harvesting energy from fluids using piezoelectric devices. A simple setup employing a cantilever beam and a piezoelectric module from Smart Materials [7] (M 8528P2) has been created for evaluation of the technology. The piezoelectric material has maximum output power at the resonant frequency which is usually at Hz frequency range or at 50-200Hz frequency range. Provided that the resonant frequency is obtained by cantilever oscillation, the output power obtained by matching the load is 2.9mW, as shown in 5. The maximum power obtained by the MFC module is, hence, lower than the one obtained by the turbine. The piezoelectric technology is meant for harvesting energy in different mechanic conditions and it clearly cannot match a micro-turbine generator in that the alternator can better exploit the mechanical energy. However the piezoelectric technology is in fast development and proves to be much less invasive. It can also be used for measures of flow in certain ducts types.

[6]interpolated from Figure 3

[7]http://www.smart-material.com/

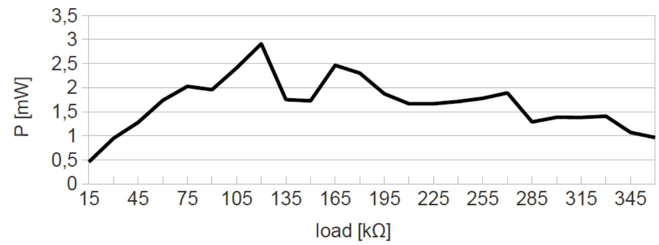

Fig. 5. Output power of the discussed piezoelectric transducer at resonant frequency and different load conditions.

C. Energy Management and Storage for the Sensor Nodes

Up to now the discussion focused on the harvesting of the kinetic energy and its conversion to electric energy. The voltage and power provided by the energy harvesting source have time-varying characteristics and may be intermittent, depending on ambient conditions, and therefore they cannot be directly used to supply the subsequent circuits and a suitable Power Management (PM) interface is required on purpose [13]. The harvested energy should be converted to chemical energy (batteries) or potential electric energy (capacitors) for storage and later use. All the elements impedance (input, storage and load) must be adapted. A few commercial solutions emerged recently that provide storage and management on a single board, such as Cymbet CBC-EVAL-08 [8]. The objective of this unit consists in allowing the extraction of the energy from sources of different electrical impedance when available and store it on the energy buffer (a solid-state battery) which then powers the system load. In this way the system can work even under intermittent harvesting operating conditions. The typical elements characterizing a PM circuit are the following (as in the CBC-EVAL-08):

- *AC/DC rectifiers*, to deal with those harvesters (like Vibration and RF based ones) producing AC output Voltages
- *DC-DC converters*, to provide stable voltages and smooth currents for the application of interest; the primary requirements to satisfy are efficiency, conversion factor flexibility and ability to work in presence of very-low power levels. Boost converters and charge pumps are generally used in dependence on the harvesters in usage.
- *Energy Processors*: with this name we refer to the set of circuits typically devoted to maximize the energy transfer from the source (by means of suitable Maximum Power Peak Tracking solutions) and to disconnect the transducers from the energy buffer when there is no generation in order to avoid discharge occurrence due to leakage currents.
- *Cold-Start unit*, to guarantee the system boot-strap when the storage elements do not contain enough energy. This unit is application dependent and optional.
- *Regulator*, to provide a regulated voltage from the energy buffer.

[8]http://www.cymbet.com/pdfs/DS-72-08.pdf

In recent literature the term power management is also used to denote a knowledgeable usage of the available energy in the buffer to optimize the execution of certain predefined tasks in the sensor node or drive the storage unit and the sinks (microcontroller, transceiver, etc) in order to minimize the risk of momentary shortage of energy [14]–[17]. From this perspective, suitable algorithm are expected to run in the SN micro-controller to yield a suitable adaptive strategy of task scheduling taking into account the amount of available energy and the power consumption related to each task.

The energy storage element can be of different nature. Requirements for energy storage devices are small size, high energy density, high durability, low discharge current, low cost. A trade-off is required between these. Common storage devices are Li-ion batteries, NiMH batteries, alkaline batteries, electric double-layer capacitors (in short supercap) and Lithium polymer solid-state batteries which are of more recent introduction in the market.

Table III reports some of the advantages and disadvantages of these solutions.

From Table III supercaps evidently have the longest lifecycle in terms of charge cycles but at the expenses of a high cost and have a low energy density (although they have a high power density). Supercaps are electrolytic, meaning that their lifetime, irrespective of the charge-discharge cycles, is of the order of the 5-10 years, not unlike many chemical batteries. However supercaps provide the maximum power density and peak power. The solid-state batteries have a high energy density and low leakage. While the supercap and solid-state batteries are expected to improve steadily in the future years, research is also proposing hybrid supercap and solid-state devices to provide improved performances [18].

IV. A Smart Water Metering Case Study

In this Section a sample case study is reported, referred to the possible adoption of smart water meters at the users' premises, in order to provide the water utility with a near real time monitoring of consumptions, down to a single-user level. In the proposed scenario, a total amount of 20,000 user premises (i.e. meters) are considered, in a urban environment, spread over an area of almost 10 km^2; this scenario may realistically apply to a district of a medium Italian town.

In order to evaluate the economic advantage provided by a smart water metering infrastructure, in which the monitoring nodes are powered by means of EH technologies, with respect to traditional solutions based on batteries, two configurations, namely CONF1 and CONF2, are considered. In CONF1 it is assumed to have a battery-powered node for each single user meter; in CONF2, it is assumed to apply a single node, in which the battery life is sustained by the presence of a turbine-based EH solution, for a given number k of user meters, where k = 2, 4, 6. Parameter k may be interpreted as the average number of premises in a block, i.e. the average number of meters the measurements of which may be collected and transmitted by means of a single node, fed by the joint contribution of a battery and a turbine-based EH device. In order to provide a realistic evaluation, meters and turbines are supposed to have an estimated lifespan of 30 years. It is assumed that the batteries used in CONF1 have a lifespan of 5 years (according to a number of studies and reports available in the technical literature), whereas it is increased up to 10 years for the batteries in CONF2, where the EH device helps in prolonging the power availability. Finally, in order to compare the two configurations in the same conditions, it is assumed that at time T0 all the smart meters have been already deployed over the district.

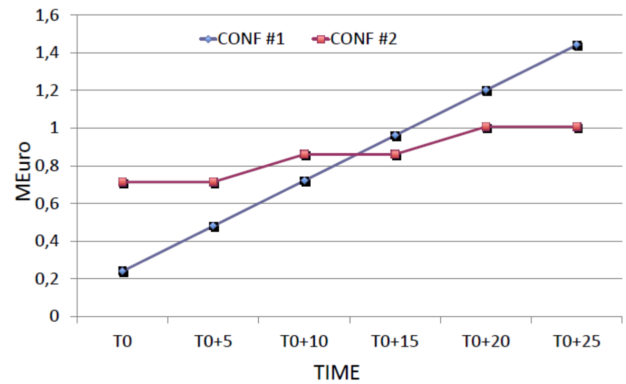

Fig. 6. Time evolution (years) of maintenance costs for CONF1 and CONF2, k = 2.

Figure 6 shows the estimated time evolution (in years) of maintenance costs for the configurations CONF1 and CONF2. In CONF2 it is assumed that each EH-powered node is able to transmit data generated by 2 different meters. It must be noticed that, at time T0, the costs related to the placement of batteries at each meter have been accounted for in CONF1, whereas the costs related to batteries and turbines placement have been assumed for CONF2. Costs due to moving work teams in charge of maintenance activities have been accounted for at time T0, for both the configurations under evaluation, together with the hypothesis of complete deployment. Figures 7 and 8 show the time evolution of maintenance costs, again referred to CONF1 and CONF2, in the case k = 4 and k = 6, respectively.

By comparing Figures 6, 7, and 8 it is clear that the possibility of connecting more meters to the same node, fed by a battery and an EH device, reduces the maintenance costs significantly in time, and may provide a pay-back period of approximately 10, 5, and almost 0 years, for k = 2, k = 4, and k = 6. After 20 years from T0, according to the evaluation performed, CONF2 provides a significant cost saving with respect to CONF1, for k = 4 and k = 6. It is possible to state that the adoption of a smart node equipped with an EH device, to sustain the battery lifetime, may allow to collect data generated by several meters, thus optimizing the deployment of the smart water grid infrastructure and reducing the

TABLE III
COMPARISON OF DIFFERENT ENERGY STORAGE TECHNOLOGIES

	Alkaline	*Li-ion*	*Ni-MH*	*SuperCap*	*Solid-State*
Charge lifecycle	N/A	1000	<1000	100000 – 1mln	10000 - 50000
Leakage	negligible	low (<1%/day)	Highest (4%/day)	low (µA-range)	negligible
Output Voltage Stability	stable	stable	stable	unstable	stable
Energy Density	300 Wh/l	400 Wh/l	200 Wh/l	5-20 Wh/l	800 Wh/l
Packaging/Assembly	no SMD, big	no SMD	no SMD	SMD only for small package	SMD, smallest
Chemical Safety	bad	bad	bad	decent	good

maintenance costs in the AMR context, at the same time.

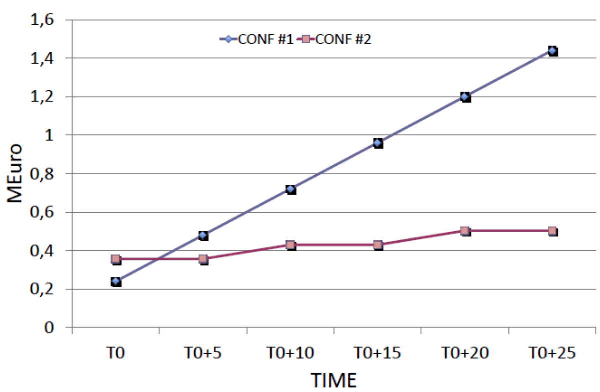

Fig. 7. Time evolution (years) of maintenance costs for CONF1 and CONF2, $k = 4$.

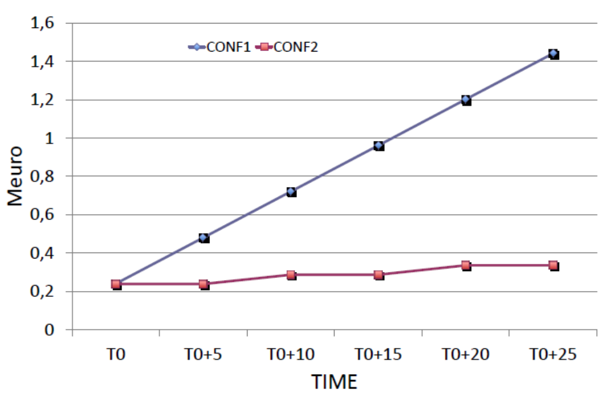

Fig. 8. Time evolution (years) of maintenance costs for CONF1 and CONF2, $k = 6$.

V. CONCLUSION

This work deals with the employment of self-powered sensor nodes for the water grid monitoring. A description of the main related issues has been given, together with some preliminary evaluations made on real case studies and considering HW/SW equipment available on the market. In particular, the Automatic Meter Reading problem has been taken as reference for the experiments, carried out to show the main technical aspect to take into account and how they can be effectively faced. Moreover, an insightful analysis about the main economic issues related to the application of a self powered sensor network in a realistic scenario is also provided. This work intends to represent a useful starting point for the future development and deployment of suitable networked solutions for smart water metering. At the same time, it yields reasonable reference results for application of self-powered sensor network paradigm for water grid monitoring, at even wider scales rather than the metering one.

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