Smart metering and Internet of Things for efficient water management

Roberta Vadruccio[a]*, Giulio Salvadori[a], Angela Tumino[a]

[a]*Dipartimento di Ingegneria Gestionale (DIG), Politecnico di Milano, Via Lambruschini 4B, Milano 20156, Italy*

Abstract

Global water use has grown steadily in the past decade, and climate change will further worsen the levels of water stress. Another global issue lies in the ageing of water infrastructures, registering conspicuous water losses (40% in the Italian scenario). A great opportunity is represented by the exploitation of new technologies relating to IoT, namely smart meters, which can enable the prediction of water consumption, detect leaks, and customise the service. This paper assesses the economic and environmental impact of smart meters adoption for water consumption, by taking the Italian scenario as a reference context, through the development of an analytical model which considers the benefits and costs associated with their adoption, with the ultimate objective of evaluating the convenience of the investment. Data to feed the model was collected through secondary sources, literature reviews, and interviews with utility companies' employees. Results provide corroborating evidence of the positive impact of smart water meter adoption, both in economic and environmental terms, in particular by increasing the roll-out number, given the higher amount of data available and economies of scale to be exploited. The present study contributes to the academic literature by providing a comprehensive model that considers economic and environmental aspects of smart water adoption, which allows practitioners to have an insightful understanding of the involved variables in such investments.

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1. Introduction

Global water use has increased in the past decade, growing steadily at a rate of 1% per year due to rising population, economic development and shifting consumption patterns. Climate change will further worsen the levels of water stress in areas already affected by water scarcity but also address new areas previously unimpacted, increasing the levels of physical water stress [1]. The progressive reduction of water availability will have implications on water accessibility as a result. Another global issue lies in the ageing of water infrastructures and the increasing damage and disruption risk the latter will have to face due to an increase in flood frequency because of climate change [2]. As for the ageing of water infrastructures, many developed countries currently must deal with related issues and with the problem of water loss. Considering the Italian scenario, 60% of water infrastructures were installed in the late 80s, and the water infrastructure registers an average percentage of water loss of 40% [3]. The mean value for water loss in the EU is 23% [4].

As a result of the aforementioned global issues, there certainly is a need for investments targeted at upgrading existing infrastructures. A great opportunity is represented by the exploitation of new technologies relating to the Internet of Things (IoT), namely smart meters. General features of smart meters for utility include the automatic processing, transfer, management, and utilisation of metering data. From a broad perspective, the main benefits relate to the ability to predict water consumption, the detection of leaks, and service customisation. Furthermore, it can be said that digitalisation, the advancement of current control and

* Corresponding author.
E-mail address: roberta.vadruccio@polimi.it

telecommunications systems as well as lower costs have allowed smart-metering systems to become enablers for a new perspective on the electricity and water businesses changing the client-consumer relationship, generating consistent benefits for both of them [5].

The adoption of smart meters in Europe reached an estimated penetration rate of 30%, driven by the proposal by the Third Energy Package to roll out, for the case of electricity at least, 80% by 2020 [6]. Moreover, the development of smart metering systems is also fostered by the adoption of different legislative measures. For example, EU regulations actively trigger the need for large-scale rollouts of smart meters. In fact, the 2009/72/EC Electricity Directive and the 2009/73/EC Gas Directive promote the adoption of smart electricity meters and smart gas meters, respectively. Despite the current lack of a mandatory legal framework for the deployment of smart water meters in the EU, the level of adoption of the latter is also growing, even if to a smaller extent. The same is happening in Italy, where Decree 93/2017 [7] is currently the most significant piece of regulation on the topic. It pushes the substitution of traditional meters with more than 10 years of operation with smart solutions, by defining the criteria for periodic controls on instruments of measure and their functions in conformity with both Italian and European regulatory frameworks. However, the growing deployment of smart water meters in the EU and Italy also lies in the existence of reward scores in tenders for water meters issued by the municipality for bidding companies that provide connected meters.

As far as literature is concerned, there currently exists a literature gap on the investigation of IoT technologies for smart water management. In fact, pieces of work regarding quantitative analytical models for the understanding of IoT technology benefits in the water sector are very slim and often overlook the financial analysis [8–10]. Additionally, there is also a lack of quantitative models for the measurement of smart water meters benefits independently from a proposed scenario. Indeed, the majority of papers analyse ad-hoc formulas and algorithms applicable exclusively to specific scenarios/systems which are therefore not adaptable to different solutions [11–13].

Therefore, the present paper provides an analysis of the benefits of smart water meters adoption, through the development and application of a quantitative model. The remaining of the article is organised as follows. Section 2 describes the objectives and the adopted methodology. Section 3 provides the model application and the sensitivity analysis. Section 4 summarises the gathered evidence and the conclusions of the paper.

2. Objectives and methodologies

The objective of this paper is to fill the literature gap by assessing the economic and environmental impact of smart meters adoption for water consumption, by taking the Italian scenario as a reference context. To do so, an analytical model was developed, to estimate the costs stemming from the adoption of smart water meters, the related savings, and ultimately evaluating the convenience of the investment. Specifically, the model adopts the utility point of view, therefore the benefits were selected considering their importance for service providers. All benefit figures were identified through literature and market analysis as follows, and computed on a yearly basis.

- **Remote meter reading**, distinguishing between walk-by remote reading and network-based remote reading (e.g., Low-Power-Wide-Area Network, or LPWAN). In the former case, smart meter readings are collected by an operator who moves on foot or by car nearby of the meter, using a tablet or a handheld electric meter reading device that adopts a protocol of short-range communication (tens of meters). The benefits were calculated according to the following formula.

$$Walk-by: \left[N\left(\frac{1}{Rt}-\frac{1}{Rw*Rt}\right)*S*Nvis\right]*(1-FN) \quad (1)$$

N=number of meters; S= salary of the operator (€); R_t = traditional meters reading rate(meters/h); R_w=walk-by meter reading rate (meters/h); N_{vis}=readings (visit) per year (visit/year); FN=Fixed Network mode (%).

In the latter case, the network-based remote reading enables the collection of data through a fixed communication network, according to the following formula.

$$Fixed\ Network: \left[N\left(\frac{1}{Rt}\right)*S*Nvis+C_{km}*D\right]*FN \quad (2)$$

D=distance travelled (km); C_{km} = cost per km (€/km).

- **Efficient Maintenance – Pipe leaks reduction**: intelligent meters adoption enables a more precise detection system of water losses, minimising the time and the number of leakages. Accordingly, the savings in economic and environmental terms (water loss reduction) were computed as follows.

$$l * WL * \beta * WL_{RED} * P_w * 365 + \alpha * C_{REP} * Tot \qquad (Economical) \tag{3}$$

$$l * WL * WL_{RED} * 365 * \beta + (1-\beta) * (T_1 - T_2) * WL \quad (Environmental) \tag{4}$$

l=length of the network (Km); Tot=total number of users (ab); β=leakage post-meter percentage (%); WL=Total water loss (m^3/(km/day)); WL_{RED}=average water loss reduction (%); P_w= unitary water price (€/l); C_{REP}=repair costs (€/ab); α=repair costs reduction (%); T1=network leakage time for identification (ante); T2=network leakage time for identification (post).

- **Efficient Maintenance – Faulty meters reduction**: economic savings related to simplified maintenance and faster failure identification. The quantification of this benefit was done by considering the difference between the time required for detecting and repairing traditional meter failures, and the time required for spotting and resolving a failure in a smart water meter, focusing on the water loss (unbilled water) that would occur in these time intervals.

$$\left(\frac{N}{l}\right) * Fs * Ql * 30 * 24 * \left(MTFt - MTF_{(w\ or\ f)}\right) * Pw \quad (Economic) \tag{5}$$

$$\left(\frac{N}{l}\right) * Fs * Ql * 30 * 24 * \left(MTFt - MTF_{(w\ or\ f)}\right) \quad (Environmental) \tag{6}$$

*MTFt=mean time for faulty meter ident. (traditional) (months); $MTF_{(w\ or\ f)}$=mean time for faulty meter identification (walk-by or fixed) (months); F_s=faulty rate (%); Q_l=average water loss (m^3/(h*km)).*

- **Demand management**: benefits were computed by developing two specific formulas. The first one is the efficient solution, referring to demand management strategies where the smart meters cooperate with water-efficient applications or fixtures at the household level. The main advantage is the reduction of consumption indoors and outdoors, computed as follows.

$$(Q * K_{dm}) * Tot * 365 \quad (Environmental) \tag{7}$$

Q=Average quantity used (m3/ab); K_{dm}=water consumption reduction (%).

The second is the operational solution, which concerns demand management strategies that have an impact on the network management (e.g., reduction of the size of new mains due to the joint effect of peak shifting and demand reduction, reduction of chemicals quantity needed), calculated as follows.

$$(C_{chem} * K_{chem} + E_{pump} * C_{el} * K_{dm} * 365) * Tot * Q \quad (Economic) \tag{8}$$

C_{chem}= average cost for chemical treatment (€/m^3); K_{chem}=chemical cost reduction (%); C_{pump}=average cost for pumping (€/m^3); E_{pump}=electricity for pumping (kWh/m^3); C_{el}=cost of electricity (€/kWh).

- **Arrear consumers control**, i.e., reduction in delayed payment of the bill. The formulation of the benefit was divided into two steps. The first one computes the amount of cash flow (CF) that the utility will receive on delay.

$$CF = (D_1 - D_2) * Tot * P_w * Q * \left(\frac{365}{Nbills}\right) \tag{9}$$

The reduction of payments in delay means better management of the financial flows and circulating capital for the utility, which depends on the cost of capital (i). The second step considered this impact.

$$NCF = \frac{CF}{(1+i)^{1/Nbills}} \tag{10}$$

Finally, the positive financial effect arising from better-circulating capital management was computed as the difference between the value of the cash flow (CF) and the value of the discounted cash flow (NCF) that they would have if the payment would be in delay.

$$D1 * (1 - red) * Tot * Q * \frac{365}{N_{Bill}} * P_u * \left(1 - \frac{1}{(1+i)^{1/N_{Bill}}}\right) \tag{11}$$

D1=Payment in delay (%); red=Payment in delay target reduction (%); i=cost of the capital (%); N_{bills}=number of bills per year; CF= Cash Flow (€); NCF=Net Cash Flow (€).

- **Fraud reduction**, i.e., reduction of water theft, metering inaccuracies and unbilled authorised consumption detection through real-time detection of any anomalous use of the system. The model quantifies this benefit by considering a reduction coefficient for the fraud rate, as follows.

$$365 * (NRW_1 - NRW_2) * F * Tot * Q * (1 - K_{WL}) * P_w \quad (Economic) \tag{12}$$

$$365 * (NRW_1 - NRW_2) * F * Tot * Q * (1 - K_{WL}) * P_w \quad (Environmental) \tag{13}$$

NRW_1=Non-Revenue Water (ante)(m3/day); NRW_2=Non-Revenue Water (post) (m3/day); F=Average Fraud rate (%); K_{WL}=Water loss (%).

- **Accurate billing**: smart meters allow billing of the exact quantity of service consumed by the client, reducing the number of complaints and juridical procedures to solve the contention that could arise from inappropriate values for water consumption in the bill, saving the following cost for the company.

$$CC * Compl * Kcompl * N \tag{14}$$

CC=cost of complaint (€/compl); Compl=verage cost of complaints and inaccurate billing (€/compl); K_{compl}=reduction of complaints and inaccurate billing (%).

The costs related to the investment in smart water meters were of two main typologies. **Capital Expenditures** (CAPEX), i.e., the initial investment, which includes the purchasing costs and installation costs of the devices as well as IT integration and communication systems costs, and staff training expenditures, calculated as follows.

$$(C_{smart} + C_{inst} + C_{IT}) * N + C_{train} \tag{15}$$

C_{smart}=smart meter cost (€/meter); C_{inst} = installation cost (€/meter); C_{IT} = System Integration cost (€/meter); C_{train}=Training and process redesign (€).

Operating Expenses (OPEX) refers to periodic (annual) costs, namely operating costs related to network management, marketing and sensibilisation campaigns, and extraordinary meters substitution due to damages, reported in the following formula.

$$(C_{op} * N) + CPC * \left(\frac{Tot}{Ma*1000}\right) + (C_{smart} + C_{inst}) * N * \%bat \tag{16}$$

Ma= abitant per meter (ab/meter); C_{op}= Operating cost for network management (€/meter); CPC=Cost for campaign (€/(1000 ab)); %bat=Batteries damaged yearly (%/year).

More in detail, the cost components regarding the meter purchase (C_{smart}) and the operating cost for network management (C_{op}) were considered as a differential cost, considering the case where smart meters are installed in the place of traditional ones to replace obsolete meters.

The economic evaluation of the investment was then conducted by calculating the Net Present Value (NPV) and Payback Time (PBT). The NPV assesses the value of cash outflows over a period of time. The reference period considered is 10 years, corresponding to the lifespan of a meter according to current regulatory frameworks and working smart water meter systems. The PBT is the time, expressed in years, needed to repay the investment.

The environmental impact, on the other hand, was assessed through the following KPIs: (i) **water savings** computed through the above-illustrated formulas, which consist of annual water savings and relative water savings, obtained by dividing annual water savings by the total annual water consumption expressed as water injected into the network, and (ii) **energy efficiency savings**, obtained through an optimised peak demand reduction enabled by lower consumption of pumps and auxiliaries and a consequent reduction in electricity consumption and computed as follows.

$$EE = Epump * Kdm * 365 * Tot * Q \tag{17}$$

The model was first applied to a base case scenario defined through interviews and market analysis. Then, a sensitivity analysis on relevant input parameters was conducted, to evaluate the convenience of the investment under different circumstances. Data to feed the model was collected through secondary sources, literature reviews, and interviews with utility companies' employees.

3. Model application

3.1. Base case scenario

The model applies to a base case scenario of 200.000 traditional counters and considers a reference case of 50.000 smart meter implementations at the household level in Italy, considering an average number of 2,3 inhabitants per device [14]. The average length of the network infrastructure per inhabitant was calculated as follows [15].

$$l = avgAbkm * Tot = 0{,}073 * 115000 = 836{,}54\ km \quad (18)$$

The "aqueduct water tariff" (P_w) represents the cost sustained by customers only for the water resource, excluding the other fixed figures (e.g., purification treatment, maintenance of network), and was calculated as follows.

$$P_w = P_u * C_v = 1{,}94 * 60\% = 1{,}16\ ^{€}/_{m^3} \quad (19)$$

where P_u is the total price seen by customers for a cubic meter of source and C_v is the quota related to the aqueduct [16].
Table 1 reports the input values used for the variables described in the methodology section and their source reference.

Table 1. Input variables for benefits computation

Variable	Measure unit	Value	Source	Variable	Measure unit	Value	Source
Pu	€/m^3	1,94	[16]	*Kcompl*	%	70%	Interview, [17]
Pw	€/m^3	1,164	[16]	*Kwl*	%	43,70%	[15,16]
S	€/h	16	Interview, [18]	*Q*	m^3/ab	0,419	[15]
Rt	meter/h	12	Interview, [19]	*Kdm*	%	1,5%	[20], Interview
Rw	meter/h	16	Interview, [19]	*Cchem*	€/ab	0,67	[21]
Nvis	visit/year	4	[22]	*Kchem*	%	10%	[23]
FN	%	80%	Interviews	*Epump*	kWh/m^3	0,184	[24]
D	km	150.000	Independent variable	*Cel*	€/kWh	0,1984	[16]
Ckm	€/km	0,45	[25]	*NBills*	bill/year	4	Indipendent variable
NRW1	%	3%	[15]	*D1*	%	6%	[16]
NRW2	%	1,25%	[26]	*red*	%	16%	Interview
F	%	23%	[15]	*i*	%	4,8%	[27]
Tot	ab	115.000	Indipendent variable	*T1*	day	90	Interview
MTFt	months	3	Interview	*T2*	day	7	Interview
MTFf	months	0,25	Interview	*WL*	m^3/(km/day)	22	[16]
MTFw	months	1,5	Interview	*β*	%	95%	Interview
QL	m^3/(h*km)	0,916666667	Interview, [15]	*Wlred*	%	5%	Interview, [28]
Fs	%	2%	Interview	*α*	%	5%	[23]
Cc	%	0,3%	Interview, [15]	*%Rep*	%	16%	[23]
Compl	€/compl	50	Interview	*CREP*	€/ab	15,6	Indipendent variable

The resulting benefits obtained through the application of the formulas illustrated above are displayed in Table 2.

Table 2. Economic value of the benefits.

Benefit type	Value
Remote meter reading	317.333,33 €/year
Walk-by	50.000,00 €/year
Fixed Network	267.333,33 €/year
Pipe leaks reduction	461.088,93 €/year

Reduction of faulty meters	2.295,88 €/year
Walk-by	275,51 €/year
Fixed Network	2.020,37 €/year
Demand management	12.859,04 €/year
Arrear consumers control	5.784,79 €/year
Fraud detection	46.390,81 €/year
Accurate billing	5.250,00 €/year
Total	**€ 851.002,78 €/year**

As far as the computation of the costs is concerned, Table 3 reports all the CAPEX and OPEX.

Table 3. Cost figures.

CAPEX			**3.840.000 €**	
Cost item		***Measure unit***	***Value***	***Source***
Smart device cost	*Csmart*	€/meter	40	[29], Interview
Installation cost	*Cinst*	€/meter	30	[29], Interview
IT System Integration cost	*Cit*	€/meter	6,70	[29]
Training and process redesign	*Ctrain*	€	5000	[29]
OPEX			**42.823 €/year**	
Cost item		***Measure unit***	***Value***	***Source***
Network management	*Cop*	€/meter	0,50	[26]
Cost for campaign	*CPC*	€/ (1000 ab)	6.46	[30]
Number of adv campaigns	*NADV*	camp/year	1	n.a.
Batteries damaged yearly	*%bat*	%/year	0,5%	[16], Interview

Finally, Table 4 displays the financial indicators' values resulting from the installation of 50.000 smart meters considering the above-illustrated costs and benefits figures.

Table 4. Financial indicators of the 50.000 meters scenario.

NPV	**PBT**
2.461.608,74 €	6,09 years

Focusing on the environmental side of the investment, Table 5 shows the water savings in absolute and relative terms, and the energy saving.

Table 5. Environmental indicators of the 50.000 meters scenario.

Benefit	**Value**
Efficient Maintenance - Pipe Leakage	319.169,76 m^3/year
Efficient Maintenance - Faulty meters	1.972,40 m^3/year
Demand management	263.812,88 m^3/year
Fraud Detection	39.854,65 m^3/year
Total water saving	**624.809,69 m^3/year**
Total demand of water	17.587.525,00 m^3/year
% water saving	**3,55%**
Energy saving	**48.541,57 kWh**

3.2. Sensitivity analysis

A sensitivity analysis was then performed, with the objective to assess the convenience of the investment by varying the conditions. Table 6 displays the input parameters varied.

Table 6. Input parameters used in the sensitivity analysis.

Variable	**Measure unit**	**Value**
N	meter	160.000
D	km	480.000
Csmart	€/meter	30

Wlred	%	6%
NRW2	%	1%

More in detail, the increase in the number of meters installed enables the activation of economies of scale which reduce the acquisition cost of the meters. Furthermore, according to interviews and experts' opinions, there are some benefits which become more relevant and consistent when the rollout involves a wider network of meters [31]. Indeed, by increasing the number of meters, it is possible to conduct district-specific analysis that considers multiple data contributions, allowing more efficient detections of breaks and leakages. For this reason, the value associated with the water loss reduction (*Wlred*) was increased by 1%. Similarly, taking advantage of the increased resolution of data coming from multiple meters in the same area, which allows to spot water thefts and irregularities faster and more efficiently, the non-revenue water after the installation of smart meters (*NRW2*) was reduced from 1,25% to 1%.

The resulting financial and environmental indicators are reported in Table 7.

Table 7. Financial and environmental indicators of the 160.000 meters scenario.

NPV	PBT	Absolute water savings	% water saving	Energy saving
11.529.921,74 €	4,81 years	2.217.280,34 m^3/year	3,94%	155.333,02 kWh

4. Discussion and conclusion

The present study aimed at identifying the benefits stemming from the introduction of smart meters for water consumption and the associated costs, with the ultimate objective to assess the convenience of the investment. The figures resulting from the analysis provide corroborating evidence of the positive impact of smart water meter adoption, both in economic and environmental terms. Indeed, considering the base case scenario (50.000 meters roll-out) the NPV is highly positive, being equal to 2.461.608,74 €, and the investment can be repaid in a short-medium term (6,09 years). On top of that, considering that replacing obsolete meters with new ones is mandatory by law for utility companies, the savings provided by the adoption of smart meters represent additional benefits. Moreover, connectivity also enables the customisation of the service, allowing utility companies to improve their offer and creating a competitive advantage. Focusing on the environmental side, smart water meters can also be associated with a positive impact as the quantities of energy and water saved are quite substantial, both for water resources (624.809,69 m3/year, -3,55%) and energy component (48.541,57 kWh/year). This is particularly relevant, especially considering the ever-increasing global water use levels and the negative impact of climate change on water. So, the exploitation of smart water meters represents an excellent opportunity for more efficient management of water loss, especially in the light of current water loss levels to which the persistence of old infrastructures contributes. This ultimately also benefits the company's image from a sustainability point of view.

By increasing the number of meters installed (160.000), also the benefits raise, given the higher amount of data available to be exploited to optimise the management of pressure and water losses. At the same time, the associated costs decrease due to economies of scale, which allow to reduce the unitary purchasing cost and to further spread the fixed costs. Consequently, both financial (PBT equal to 4,81 years) and environmental (3,94% water savings) indicators improve.

However, despite the high economic and environmental benefits that can arise from the installation of smart meters, today what drives utilities the most towards this new market still remains regulatory compliance. In fact, according to some regulations currently in force [7], the installation of smart water meters by a utility allows in many cases to obtain a lengthening of the period available for the replacement of the meters, with direct effects on the economic return of the investment of the actors in play.

Considering the contribution of this research, from the academic perspective, it fills the literature gap by providing a comprehensive quantitative model that considers many aspects (i.e., economic and environmental) of smart water adoption, including the financial analysis, which is typically overlooked. For what concerns the managerial contribution, it enables the understanding of the variable involved which must be considered when evaluating such investments.

Future developments of this research could potentially include new benefit categories, such as the “pressure management” benefit, and further benefits which do not affect service providers directly. They relate for instance to sociological factors: better-informed, more environmentally conscious, and more responsible customers can reduce their water demand and avoid water waste, thus having a positive impact on the environment and society at large. Another research avenue could investigate the difference between mono-utility and multi-utility smart water meters installations, and the synergies that can arise both in relation to CAPEX reduction (in terms of system integration costs and data management competencies), and benefits increase resulting from total service management, when smart water meters are coupled with smart electricity meters and smart gas meters as well.

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