Towards a Reference Model for Water Smart Grid

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Abstract- Information and Communication Technology (ICT) provides two-way communication, data storing and analysis, sensing and system monitoring, and intelligence such as historical and predictive analytics. Today’s Energy Smart Grid initiative proposes a highly decentralized and flexible energy supply and distribution by taking advantage of ICT infrastructures. In contrast, many water utilities do not employ technology options beyond basic SCADA systems, though ICT has the potential to provide water management with capabilities such as measuring, sensing, optimising and detecting the status of water and supporting infrastructure. In this paper, we introduce a conceptual reference model for Water Smart Grid, based on Energy Smart Grid reference models. The Water Smart Grid is a transformation of the current water supply system using ICT capabilities. A reference model is key to the design, development, standardization, research, and discuss about water smart grid.

Keywords – smart grid, water management, water supply, reference model, Water Smart Grid.

I. INTRODUCTION

As stated by the Intergovernmental Panel on Climate Change (IPCC): “Water availability and quality will be the main pressures on, and issues for, societies and the environment under climate change.”[1] Other water management challenges include: aging water infrastructure, rainfall variability, high levels of leakage and non-revenue water, climate change and global warming, the need for safe and palatable water, the financial condition of water organizations, water pollution, and water quality problems [2].

In this paper, we focus on water supply, which is the provision of water by public utilities, usually via a system of pipes and pumps. Studies have shown that current approaches to water management are unable to keep up with the expected demands [1]. The study by McKinsey’s “2030 Water Resources Group” projects that conventional source expansion and known water efficiency measures will meet only 40% of demand by 2030 [3]. Reports of leakages typically amount to 35% on average and even up to 65% of total supplied volume of water in some areas [4][5]. The demand for a real-time response to water issues requires new water management intelligence. However, water utilities tend to be fairly low-tech when it comes to information and communication technologies (ICT), considering technology options mostly around basic Supervisory Control And Data Acquisition (SCADA) control systems, which are systems that monitor and control industrial processes [6].

Smarter water systems are critical to dealing with the water challenges of today and in the future, and ICT has the potential to be the basis for these systems because it can [7]:

• Measure, sense and detect the status of water and supporting infrastructure. Sensors could be installed to keep track of water quality, leaks and supply loads in real-time. These capabilities could improve water utilities.
• Interconnect people, systems and data to improve the ability to share information and take action.
• Intelligence (such as historical and predictive analytics) can be applied to water-related data to derive new insights for innovation and process optimization.

On the other hand, today’s Energy Smart Grid initiative proposes highly decentralized and flexible energy supply and distribution. The Energy Smart Grid uses information, two-way communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, distribution and consumption to achieve a system that is clean,
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safe, secure, reliable, resilient, efficient, and sustainable, over the entire spectrum of the energy system from generation to the end points of consumption of the electricity [8].

Our hypothesis is that an ICT-based infrastructure similar to that used in Energy Smart Grids, will provide equivalent benefits if applied to water management. This paper analyzes the similarities between energy management and water management, and proposes a reference model for Water Smart Grid, mostly from the ICT point of view. We deal with information flow in the water network, not water flow or the water grid itself. As in Energy Smart Grid, A reference model is key to the design, development, standardization, research, and discuss about water smart grid.

Section II, describes related work in the water management field. A brief description of the water cycle and water management systems comes in section III. Section IV describes our study of the Energy Smart Grid field, and makes a comparison between the salient characteristics of the Energy Smart Grid and the potential Water Smart Grid. Section V explains the proposed reference model for Water Smart Grid, and describes domains and their relationships and typical applications in each domain. Some benefits and challenges of transforming the current water grid into a Water Smart Grid will be discussed in section VI. Finally we conclude and outline planned future work in section VII.

II. RELATED WORK IN WATER MANAGEMENT

Using ICT to monitor and optimize the water supply system has attracted researchers from both academia and industry. For example, the use of sensor systems for monitoring water distribution network [9–11] and monitoring water quality [12–14] has been investigated. In addition, Iqbal and Lim [15] present a cyber-physical middleware framework for a large-scale water distribution system monitoring effort. They designed a framework to develop an event-driven, specialized and reconfigurable middleware for a time- and resource-constrained cyber-physical system. Makropoulos and Butler [16] present a review of currently available options for distributed water infrastructure and illustrate the potential impact of their deployment through a number of indicative infrastructure strategies. They summarized the main categories of both centralized and decentralized water infrastructure. Barnett et al [17] report their work on the Operation Optimization System project to automate real-time water supply and distribution system automation in the City of Jacksonville, USA. This project used a real-time modeling and reasoning technology platform.

In industry, IBM has a number of studies in this field [7][34][19]. The IBM Smarter Water model consists of an information architecture and intelligent infrastructure that enables automated sensing, monitoring and decision support for water management operations [7]. Another study from IBM [19] proposed Integrative Modeling Framework, which is a platform to enable the integration by non-expert users of diverse, sensor-based data, related business data, and complex, cross-disciplinary mathematical modeling, in support of planning, monitoring, management, reporting, and decision support applications for water distribution. Hitachi proposed the “intelligent water system” concept, which performs comprehensive management of the water cycle at a regional or city level [2]. Accenture have also investigated some benefits and challenges of Smart Grid and smart water metering [20].

However, to the best of our knowledge, no work has considered a holistic approach in the use of smart technologies for the full cycle of urban water supply and distribution.

III. URBAN WATER CYCLE

Water is drawn from streams and aquifers (natural ecosystem) and stored in reservoirs to be processed through various processes such as filtration and chlorination (water treatment) before being delivered to residential, commercial and industrial consumers through the system of pipe network (water storage, distribution, and consumption). After use, wastewater is collected by the sewerage system and back to the natural water cycle through wastewater infrastructure (waste/stormwater collection and discharge). Stormwater also finds its way into receiving waters through stormwater collection and treatment systems [7][21]. Fig. 1 shows a simple view of the urban water cycle and its related concerns [7].

![Urban water cycle](image)
After treatment, to preserve water for long-term use, it is stored in various containment systems, such as tanks and reservoirs. As water is needed, it is distributed to consumers by various mechanisms such as pipeline systems. Consumption of water involves personal consumption, energy generation, industrial process utilization, water-related entertainment, agricultural consumption and municipal needs (for example, street cleaning and public parks). Water supply includes the following activities: water treatment, leak detection, pumps and water pressure optimization, ensuring water quality, protecting water from theft and tampering, water metering, detecting meter outage or failure, conducting usage (customer) segmentation, managing demand and encouraging water conservation, wastewater recycling, and performing budget and water price analysis [7].

IV. LESSONS FROM THE ENERGY SMART GRID

Recent research in industry and academia has focused on developing tools and infrastructure for smart electricity management, known as the Smart Grid [22]. The Smart Grid can be regarded as an electric system that uses information, two-way communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption, to achieve a system that is clean, safe, secure, resilient, efficient, and sustainable. This description covers the entire spectrum of the energy system from the generation to the end points of consumption of the electricity [8][23]. A Smart Grid is based on an existing infrastructure. A transition process is envisaged to a new overall system which will provide greater opportunities for active and flexible adaptation of generation, network management, storage and consumption to the constantly changing requirements of the energy markets [24].

A number of Energy Smart Grid reference models have been proposed as follows:

The NIST Framework and Roadmap for Smart Grid Interoperability Standards [22] is coordinated by NIST (National Institute of Standards and Technology, USA) and aims at interoperability between smart grid systems and equipment with special focus on standards in the fields of ICT protocols and data models [25]. It identifies seven different domains for Energy Smart Grid: customers, markets, service providers, operations, bulk generation, transmission, and distribution. The similarities identified for the Energy Smart Grid domains with those required for water management are such that we have considerably based our approach on this framework.

The Microsoft Smart Energy Reference Architecture (SERA) [26] is a comprehensive reference architecture based on NIST’s work and Microsoft products, which addresses technology integration throughout the scope of the smart energy ecosystem and the surrounding systems. While this work is interesting, we require our reference model to be agnostic to particular technologies at this stage.

The IEC SMB SG 3 [27]. The SG 3 (Strategy Group “Smart Grids”) published a draft of a roadmap in 2010 including their standards and eleven high-level recommendations. The main focus of the IEC roadmap is on improved monitoring and control of all components within the network [25]. The general architecture proposed in this work has provided some inspiration for our approach.

The German BMWi E-Energy Program [24] is a public funding program of the Federal Ministry of Economics and Technology (BMWi) and the Federal Ministry of Environment, Nature Conservation and Nuclear Safety (BMU) in Germany. The current objective is to create the so-called "Internet of Energy". The action matrix and the Seamless Integration Reference Architecture in this work are additionally helpful for the Water Smart Grid.

The German Bundesverband der deutschen Industrie (BDI) [28] published a study ("Internet of Energy – ICT for Energy Markets of the Future") in 2010, which considers energy shortage, the regulatory environment, technical developments associated with increasing energy prices and the German electricity system including its ICT infrastructure.

European Union: Mandate CEN/CENELEC M/441 [29]. The European Smart Meter Coordination Group (SM-CG) operates in the context of the mandate M/441, which addresses the standardization of smart meter functionalities and communication interfaces for European power, gas, heat and water industries. They develop standards and technical reports, where standards are optional technical specifications and general technical rules for products and systems in the market [25]. The conceptual model for the European Smart Grid and the proposed architecture for the Smart Grid have also provided some inspiration for the Water Smart Grid.

Table I describes the distinguishing characteristics of Energy Smart Grid [10][18] and similar opportunities in water management.

Using digital information and control technologies has the potential to improve the reliability, security, and efficiency of the water grid. Gathering and processing information on the status of delivery allows water agencies to better manage their operations. For example, if a water authority can use meters or sensors to locate problems, such as leaks or sewage overflows,
they can cut their maintenance costs. Moreover, new sensors can be used to track the level of pathogens or chemical contaminants that come from use of pharmaceuticals [6].

Utilizing techniques such as dynamic programming, reinforcement learning, and rules as design constraints proved to be useful in dynamic optimization of grid operations and resources in water distribution systems. Some studies show a more than 12 percent reduction in energy usage over the optimal control design [31][17].

Table I- Distinguishing characteristics of Energy Smart Grid and similar opportunities in water management

<table>
<thead>
<tr>
<th>Energy Smart Grid Characteristics</th>
<th>Similar Opportunities in Water Management</th>
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<tbody>
<tr>
<td>Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid;</td>
<td>The same opportunities in water management.</td>
</tr>
<tr>
<td>Dynamic optimization of grid operations and resources;</td>
<td>The same opportunities in water management.</td>
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<tr>
<td>Deployment and integration of distributed resources and generation, including renewable resources;</td>
<td>The same opportunities in water management. Distributed resources such as different source of water, recycled water, stormwater, rainwater harvesting, etc.</td>
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<tr>
<td>Development and incorporation of demand response</td>
<td>The same opportunities in water management; demand response could be applied in water grid.</td>
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<tr>
<td>Demand-side resources</td>
<td>The same opportunities in water management; including water storage in homes, rainwater harvesting, in-site recycling, point of use treatment, etc.</td>
</tr>
<tr>
<td>Development of smart technologies for metering, communications concerning grid operations and status, and distribution automation</td>
<td>The same opportunities in water management; smart water meters could keep track of consumption, disruptions and possible contamination.</td>
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<tr>
<td>Integration of smart appliances and consumer devices</td>
<td>The same opportunities in water management.</td>
</tr>
<tr>
<td>Deployment and integration of storages and peak-shaving technologies;</td>
<td>The same opportunities in water management.</td>
</tr>
<tr>
<td>Provision to consumers of timely information and control options</td>
<td>The same opportunities in water management.</td>
</tr>
<tr>
<td>Dynamic pricing</td>
<td>The same opportunities in water management.</td>
</tr>
<tr>
<td>Two-way communication and information flow between providers and consumers</td>
<td>The same opportunities in water management.</td>
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<tr>
<td>Two-way energy flow</td>
<td>The returning wastewater might be considered as a source, but two-way drinking water flows could cause some problems.</td>
</tr>
<tr>
<td>Micro grids</td>
<td>The same opportunities (to some extent) in water management.</td>
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</table>

Additionally, customer segmentation and demand response could be applied in water grid. Pressure could be adjusted based on demand. Also, pricing schemes could be applied based on supply-demand balance and customer segmentation.

Demand-side resources are one of the main characteristics of the Energy Smart Grid [22]. This is also could be true for the water system, where water storages in homes, rainwater harvesting and in-site recycling, are some examples of demand-side resources in water management.

Smart water meters could keep track of consumption, disruptions and possible contamination. Broad deployment of smart meters could pave the way for water utilities to do the same [32]. Smart water meters would provide more accurate consumption data and alert customers if there is a problem, such as a leak [6].

Integration of smart appliances and consumer devices could also be considered for water. Devices such as washing machines or dishwashers could work during night-time when the demand for water is lower (as it is for energy). Deployment and integration of storages and peak-shaving technologies could also be considered for water management. Water storage in homes and rainwater harvesting systems are some examples.

Provision to consumers of timely information and control options for of water usage proved to be helpful in water management [33]. Consumers could be alerted about potential anomalies and leaks and could have a better understanding of their consumption patterns and compare it with others.

Two-way communication and information flow between providers and consumers also have the potential to be beneficial in water management. Gathered data could be analysed to trigger notification of potential leaks and anomalies, and help consumers understand their consumption in detail. Citizens would be able to view their own consumption habits while
providers can see the aggregate data [33]. Furthermore, Autonomous Housing (houses that are almost completely self-sufficient, including their use of water [16]) could be compared to Micro Grids.

There are, of course, many important differences between the nature of energy and water:

- The nature of water and electricity are different and there is a immense difference between the transmission of electricity and water.
- Water quality is an important issue in water management and has different aspects and vital consequences.
- There is a notion of two-way energy flow between consumer and provider in Energy Smart Grid. It is not impossible to have two-way water flow in water grid in theory, but in practice it could have some consequences considering the risk of spreading contamination and finding the sources of it and the responsible parties.
- There are rapid fluctuations in energy supply, considering some sources of energy such as solar energy or wind farms. Supply fluctuation is normally smoother for water.
- The water infrastructure is generally older and more costly and more time-consuming to change and upgrade, compared to energy network infrastructure.

While these difference are important, our hypothesis is that we can learn from experiences with the Energy Smart Grid by considering its reference models and information flow.

V. WATER SMART GRID REFERENCE MODEL

A reference model is an abstract framework for understanding significant relationships among the entities of an environment, and for the development of consistent standards or specifications supporting that environment. It is based on a small number of unifying concepts and may be used as a basis for education and explaining standards to a non-specialist. A reference model is not directly tied to any standards, technologies, or other concrete implementation details, but it does seek to provide common semantics that can be used unambiguously across and between different implementations [34][35].

Building on both the Energy Smart Grid field and water-related work, we propose a reference model for a Water Smart Grid. We assume a balanced short-to-medium term portfolio of technological options for water management [16]. A distinction is made between potable and non-potable water, so we consider a dual water supply system, with potable water sources (rivers, wells, dams, sanitation, etc.) and non-potable water sources (local groundwater, recycled water, or rainwater, etc.).

In this model we considered the entire cycle of urban water management as a whole system (an ultra large system or a system of systems [36]), with a double water supply system: drinking and non-drinking water (potable and non-potable) which can have multiple water providers, different pricing schemes, different qualities, and different consumers. Given these characteristics, we need a water market [37]. We have considered renewable water sources such as rainwater harvesting, and wastewater recycling (in-site, community, and municipal) in this model.

The existing infrastructure, geographical conditions, and other situations and limitations should be considered in each implementation of the reference model. For example, in many places, there is no infrastructure for a double water supply system, or there is no recycling in some other places.

A. Domains and their relationships in Water Smart Grid

We identified 8 domains in the Water Smart Grid of the future:

- **Customers:** The end users of water, who may also generate, store, and manage the use of water. Traditionally, three customer types are discussed, each with its own domain: residential, commercial, and industrial. Customers use water for a variety of purposes including drinking, washing, chemical uses, heat exchange, fire extinction, gardening, recreation, industrial applications, and food processing. Typical application categories in this domain include Smart Meters, In-Site Recycling, Point of Use Treatment, Building Automation System, Rainwater Harvesting System, and Water Service Interface.

- **Drinking Water Plants:** The suppliers of drinking water in bulk quantities, which extract raw water from different sources such as water wells, sanitation, dams, rivers, and treat it to make water which is suitable for drinking. A plant may also store water for later distribution. Typical application categories in this domain include Plant Controller, High Service Pumps Controller, Sensor Data Management, Asset Management, Water Quality Monitor, and Market Interface.

- **Wastewater / Drainage Recycling system:** The recycling systems which receive wastewater, stormwater, and drainage and recycle them for a variety of purposes, from agriculture to even drinking. Typical application categories in this domain include Recycling Controller, High Service Pumps Controller, Sensor Data Management, Asset Management, Water Quality Monitor, and Market Interface.
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**Drinking Water Distribution System:** The distributors of drinking water to customers. May also store and supply water. Typical application categories in this domain include Distribution Controller, Sensor Data Management, Local Analytics, Measurement & Control, and Market Interface.

**Non-Drinking Water Distribution System:** The distributors of recycled (non-)drinking water to customers.

**Markets:** The operators and participants in water markets. Typical application categories in this domain include Market Management, Adaptive Pricing, Retailing/Wholesaling, and Aggregator.

**Service Providers:** The organizations providing services to water customers and water utilities. Typical application categories in this domain include Building Manager, CIS (Customer Information System), Billing System, Service Management, Installation & Management, and AMI Infrastructure.


Fig. 2 illustrates the different domains and their relationships in the Water Smart Grid, which is inspired by the NIST conceptual reference model [22].

Treated drinking water flows from Drinking Water Plants to Customers through Drinking Water Distribution System. Waste water flows from Customers (and other source like drainage on stormwater) to Wastewater/Drainage Recycling system and after recycling, flows towards Customers through Non-Drinking Water Distribution System. Information flows two-way from and to Operations to all other domains. Control flow is from Operations to Other domains. There is an information flow between Customers and Markets (about real-time pricing schemes), and between Customers and Service Providers (about the needed services and emergencies).

This reference model is the result of the ICT driven transition process of current water grid into a new overall system, which will provide greater opportunities for active and flexible adaptation of supply, distribution, and consumption of water.

Fig. 2 - Domains and their relationship in the Water Smart Grid. Narrow lines show the flow of information and control, the thicker dashed lines show the flow of drinking water (blue), the flow of wastewater (black), and the flow of recycled wastewater (grey).

**VI. DISCUSSION**

The benefits of using ICT capabilities in water supply and distribution and transforming the current water grid into a Water Smart Grid include but not limited to the following [7],[20]:

**Benefits for customers:**

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ISSN: 2319-1120 /V2N3: 310-317 © IJAEST
Lower water cost thorough smarter consumption (for example in periods which the price is lower, or using some renewable sources in-home),

Demand management by providing real-time information about water usage,

Considering new and sustainable technologies like rainwater harvesting, in-site recycling, etc.,

Identification of leakages and/or anomalies in meters based on water consumption trends and patterns, and

Improve service to customers using service providers’ Building Manager system, CIS, and Portal,

**Benefits for utility providers and managers:**

- Holistic view of the whole water distribution cycle,
- Energy efficiency in water distribution resulting in lower electricity costs,
- Supply and demand balance,
- Better identification of leaks and breaks in water (local and regional) network using sensors and analytics,
- Fewer meter readers by using Advanced metering Infrastructure (AMI), and better meter reading accuracy,
- Faster theft or other loss detection,
- Remote and automatic management of pumps and meters,
- Faster contamination detection and sourcing,
- Forecasting of future demand and balancing supply with demand,
- Increased work crew productivity by optimizing schedules,
- Identification of potential anomalies in meters based on water consumption trends and patterns,
- Asset management, monitoring, costing and tracking and enterprise asset management capabilities for long and short-term planning, and
- Optimized distribution network planning.

**VII. Conclusion**

In this paper we proposed a conceptual reference model for Water Smart Grid using the idea of Energy Smart Grid and its reference models. We described 8 domains in Water Smart Grid of the future: operations, drinking water plants, drinking water distribution system, customer, service provider, markets, wastewater recycling system, and non-drinking water distribution system. We mentioned typical application categories in each domain and finally explained the benefits and challenges of using information and communication technologies in water management. The proposed reference model is technology-independent and enables selection of suitable technologies for different parts and domains.

However, there are some challenges too, including consideration of the business case (customer propositions / pricing / availability, and value for water utility), and cooperation between water utilities and/or between other utilities, policy / regulation (privacy / security / encryption), standards (technology and protocols, both national and international), technology architecture (components / systems integration / communication / event handling), and water quality measurements [20]. Furthermore, upgrading the water grid may be difficult. Water utilities are generally slow-moving and reactionary. Improvements would be invasive, and therefore expensive.

We conclude that there is much to be learned from the Energy Smart Grid that can be applied to water management, and we plan to further verify and develop the details of this reference model to urban-scale water management systems.

**Acknowledgements**

The authors cordially thank Ashley Sterritt for his helpful comments on the draft of the paper. This work was supported, in part, by Science Foundation Ireland grant 10/CE/I1855 to Lero - the Irish Software Engineering Research Centre (www.lero.ie).

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