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IOT & SUSTAINABILITY: PRACTICE, POLICY AND PROMISE

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IOT & SUSTAINABILITY: PRACTICE, POLICY AND PROMISE PUBLIC SYMPOSIUM

Co-hosted by CITRIS and Microsoft on May 12, 2016, “IoT & Sustainability: Practice, Policy and Promise,” brought together leaders from academia, industry, and government to discuss the promise of the Internet of Things (IoT) for managing energy, water, and transportation in the urban environment. The symposium highlighted emerging technologies for smarter cities; raised questions regarding privacy and security; and identified issues pertaining to data collection, storage, and interoperability. Tom Siebel, Chairman and CEO of C3IoT and Melanie Nutter, Principal at Nutter Consulting provided keynote remarks.

The event was videotaped and can be viewed at: http://bit.ly/289wkDL

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EXECUTIVE SUMMARY

By 2050 nearly two-thirds of the world's population will live in cities. The global challenges faced in natural resource and infrastructure management are immense. Global temperatures are rising, water shortages are more frequent, food supplies are increasingly scarce, and energy systems are overburdened. The "Internet of Things" (IoT)—physical objects embedded with software, sensors, and network connectivity—are poised to play a key role in enabling resilient and equitable management of urban environments. IoT can provide real-time data collection on the availability and use of energy and water resources, facilitating more informed resource conservation, and can streamline data collection on traffic patterns and parking availability, decreasing gas consumption and CO2 emissions. Yet, the potential benefits of IoT are matched by concerns regarding data security, privacy, and interoperability. IoT devices collect vast amounts of data and are often embedded in public infrastructure, making them prime targets for hackers. Additionally, lack of consistent interoperability standards for data and devices can lead to redundancies, inefficiencies, and data silos.

This white paper provides examples of the application of IoT for sustainability in the energy, water, and transportation sectors and offers recommendations to city-level officials seeking to implement IoT technologies within these domains. The white paper concludes with a recommendation to approach city-level IoT from a holistic perspective whereby collaborative public-private engagement is at the center of all IoT deployment plans and technologies; public-private-academic partnerships are sought for mutually beneficial sustainability outcomes; privacy, security, and interoperability concerns are balanced with trust and reliability; and technologies, data, and insights are shared across sectors and with the public, to the extent advisable for confidentiality reasons. Our findings and recommendations seek to inform public decision-makers, policy officials, technology developers, and consumers who create and implement IoT platforms to improve environmental sustainability and quality of life.

1. INTRODUCTION

Despite undisputed benefits, advances in technology frequently come at a cost to the natural environment. Railroads opened up the American West to migration as well as mining; massive dams powered the development of cities but damaged natural habitats; and industrial expansion provided jobs along with new challenges for managing emissions in the water and air. Today, the proliferation of cloud-based technologies and the "Internet of Things" (IoT)—software and sensors embedded in physical systems and connected to a network—contributes to the growing demand on infrastructure and energy resources. Yet these technologies are also poised to play a key role in transitioning to a more resilient and equitable future.

In this white paper, we discuss the opportunities and challenges of IoT in the context of sustainability within the sectors of energy, water, and transportation, and the relationships among these systems in instrumented buildings and public infrastructure. We provide examples of the application of IoT within these domains, including considerations for security, privacy, and interoperability. Additionally, we offer recommendations for best practices in data stewardship and ownership, enabling access to data, and the opportunities offered by the dynamic exchange of data among public and private actors. Our findings and recommendations will inform public decision-makers, policy officials, technology developers, and consumers seeking to use IoT technologies not only for increasing infrastructure performance and efficiency but also for improving environmental sustainability and quality of life.

2. OPPORTUNITIES & CHALLENGES OF IOT FOR SUSTAINABILITY

In 2016, over half the world's population lives in cities. Each year these cities account for nearly 70% of greenhouse gas emissions, waste 250 to 500 million cubic meters of drinking water, and use 75% of the world's primary energy (UN, 2012a; UN, 2012b). Urbanization will continue to accelerate with an estimated two-thirds of the world's population living in cities by 2050, contributing to a 70% increase in greenhouse gas emissions and energy use (OECD, 2016). Meeting this increased demand on resources and infrastructure will require new strategies. IoT promises to transform urban areas into "smart cities" capable of utilizing information technology to respond to these challenges, improve quality of life, and achieve sustainability goals.

Today connected devices outnumber people on the planet by 2:1. These technologies facilitate better coordination and management of energy, water, and transportation. Cloud-based software and sensor networks help reduce environmental, economic, and social burdens by increasing transparency, accountability, and data-driven management. Sensors in buildings better manage lighting, temperature, and ventilation, increasing energy efficiency and reducing carbon footprints. Sensors in water channels provide information on availability and quality, reducing water overconsumption and waste. Highways embedded with sensors provide insights into changing traffic patterns, enabling more informed management of traffic flow, saving time for commuters, and reducing greenhouse gases.

Yet, these benefits are matched by concerns over how the vast troves of data are managed, stored, analyzed, and used. In a world where everything is connected, dependence on networks, software, and sensors raises questions about security, privacy, and equitable access to the benefits of the infrastructure. These technologies allow not only individual users but also corporations and government agencies to track behavior and decisions in the course of daily activities. How can the private sector, policymakers and other stakeholders best ensure that customers and constituents are protected from faulty or insecure devices or the misuse of their private data and that critical infrastructure is safeguarded from malicious cyberattacks?

IoT devices embedded in public infrastructure collect and transfer vast amounts of data and in many instances are vital to the operation of critical systems, making them prime targets for hackers. The distributed nature of these systems presents unique challenges to ensuring security, in part due to their size and scale, use of wireless communication protocols, and incorporation within critical infrastructure. IoT devices often lack the hardware necessary to enable strong encryption and rely heavily on wireless communications protocols and cloud-based data storage and transfer that may make them and the data they generate vulnerable to third-party interception (Edwards, 2016).

Since many IoT systems contain identical or nearly identical devices, the homogeneity of device structure makes them vulnerable to attacks that can spread rapidly throughout the system (ISOC, 2015). While some IoT devices can be momentarily disabled to halt a cyberattack, devices embedded within critical infrastructure (e.g., traffic control systems, smart energy grids) cannot be easily disabled as doing so may cause damage to the infrastructure and create public safety risks. Thus, system operators and policymakers must consider “the risk that a device will be compromised, the damage such compromise will cause, and the time and resources required to achieve a certain level of protection” (ISOC, 2015, p. 33).

Public trust and confidence in IoT devices are essential to their successful implementation. The scope and scale of personal data collection may expose people to targeted discrimination and vulnerabilities from data transfer to third parties. Further, the traditional “notice and consent” model for users to express their privacy preferences does not exist within systems-level IoT. These IoT devices are designed to be unobtrusive by seamlessly integrating into existing infrastructure. Many of these devices lack user interfaces and the public is seldom aware of their existence and the data ecosystem being generated (i.e., the types and quantity of data collected, stored, shared, and repurposed). Further, since many IoT devices for sustainability are embedded within public infrastructure (e.g., public transportation, public utility–installed smart water meters), opting out is infeasible. Guidelines for best practices are needed to better ensure privacy within data collection, management, and retention.

The goal of interoperability is a double-edged sword. On the one hand, lack of universal or open data standards and interoperability of IoT devices can lead to redundancies, inefficiencies, and data silos. IoT devices that operate in isolation or only connect with devices from the same manufacturer (i.e., “walled gardens”) limit consumer choice, and hinder availability of insights and efficiencies from data transfer and utilization across IoT systems (ISOC, 2015). Additionally, lack of standards for IoT design has enabled what Huston (2015) calls the “Internet of Stupid Things,” devices that introduce serious security vulnerabilities within IoT systems and potentially the wider internet. Interoperability at many levels (i.e., network compatibility across devices, data formatting) promises to create system-level efficiencies and facilitate data analysis.

Yet full interoperability among devices may be neither feasible nor desirable. Fully interoperable systems may be more vulnerable to failure whether through accidental or malicious acts. Corporate incentives may also be misaligned with interoperability, and imposing standards across devices could curb investment and innovation. These are questions that should be considered by industry leaders and policymakers to encourage system-level innovation and security.

The ability of cities to deal with the immense challenges faced in managing natural resources and infrastructure depends on well-planned IoT initiatives. Smart public policies informed by social, political, and economic factors will be critical to the success of these efforts. Federal initiatives such as the Developing Innovation and Growing the Internet of Things (DIGIT) Act, which will establish a working group of public and private actors to formulate national strategies in IoT development, and the White House’s Smart Cities Initiative, which allocated $160 million to support city-level IoT innovation for environmental sustainability, health, and more, are the first steps in creating an enabling environment for city-level deployment of IoT.

The following sections present case study examples of IoT initiatives for sustainability in the areas of energy, water, and transportation. We conclude with recommendations for city-level officials seeking to implement changes today that will lay the foundation for an IoT-enabled sustainable future.

3. IOT FOR SUSTAINABILITY IN ENERGY

In 2014, electricity usage accounted for 30% of U.S. greenhouse gas emissions.[1] Cities need to prepare for a vast increase in energy demand and consumption from a range of new technologies. In 2012, information communications technologies (ICTs) consumed 4.7% of electricity globally, a figure that grew to 10% just three years later. Demand will also be affected by the increasing number of electric vehicles (EVs). EV sales increased 128% from 2012 to 2014 in the United States, and some estimate that annual sales could grow by 400% by 2024, putting 860,000 new EVs on the road (Institute for Sustainable Communities, 2015).

Both of these trends add urgency to the need to increase utilization of renewable energy resources. While renewable energy supplies increased 66% from 2005 to 2015, renewable energy still only represents about 15% of total installed capacity in the United States, and a much broader transition to wind and solar is necessary to achieve significant reductions in emissions. While the primary virtue of the “smart grid” lies in more effective management of electrical utilities, IoT technologies offer opportunities for increased energy efficiency via both capture and conservation at two points: generation (green energy/renewables at the systems-level) and consumption (consumer-level).

3.1. RENEWABLES AND THE “SMART GRID”

IoT technologies can yield increased capture of renewable energy (solar and wind) because they provide real-time responses to the natural fluctuations in generation associated with renewables. While wind energy sources are usually located outside cities, utilities could integrate IoT technology into local solar energy sources to capture clean energy more effectively. San Francisco, California, has mapped assessments of solar and wind generation potential for each building in the city (see Figure 1). Combined with incentive packages that discount the installation of technology for capturing renewable energy, such mapping technology can help maximize the yield of solar and wind energy from within cities, making them less dependent on fossil fuel-intensive energy sources.

IoT also has a key role to play in the transition to distributed “smart microgrids” that allow cities to utilize local sources of renewable energy instead of coal- or diesel-powered remote generators. In the traditional grid model, power is supplied from centralized power generators, which often—especially at times of high demand—are dependent on less efficient and environmentally polluting fossil fuels. The distributed grid model can use IoT to draw on local sources of renewable energy to power a specific area during times of high demand or during an outage. In Berkeley, California, the municipal building complex switched its backup power source from diesel to solar by remotely connecting solar panels on the roof of a downtown parking lot to nearby facilities and buildings, the first project of its kind in the country. Such distributed microgrids also save energy by transmitting electricity with less loss than traditional power grids (Burroughs, 2015).

1 https://www3.epa.gov/climatechange/ghgemissions/sources/electricity.html

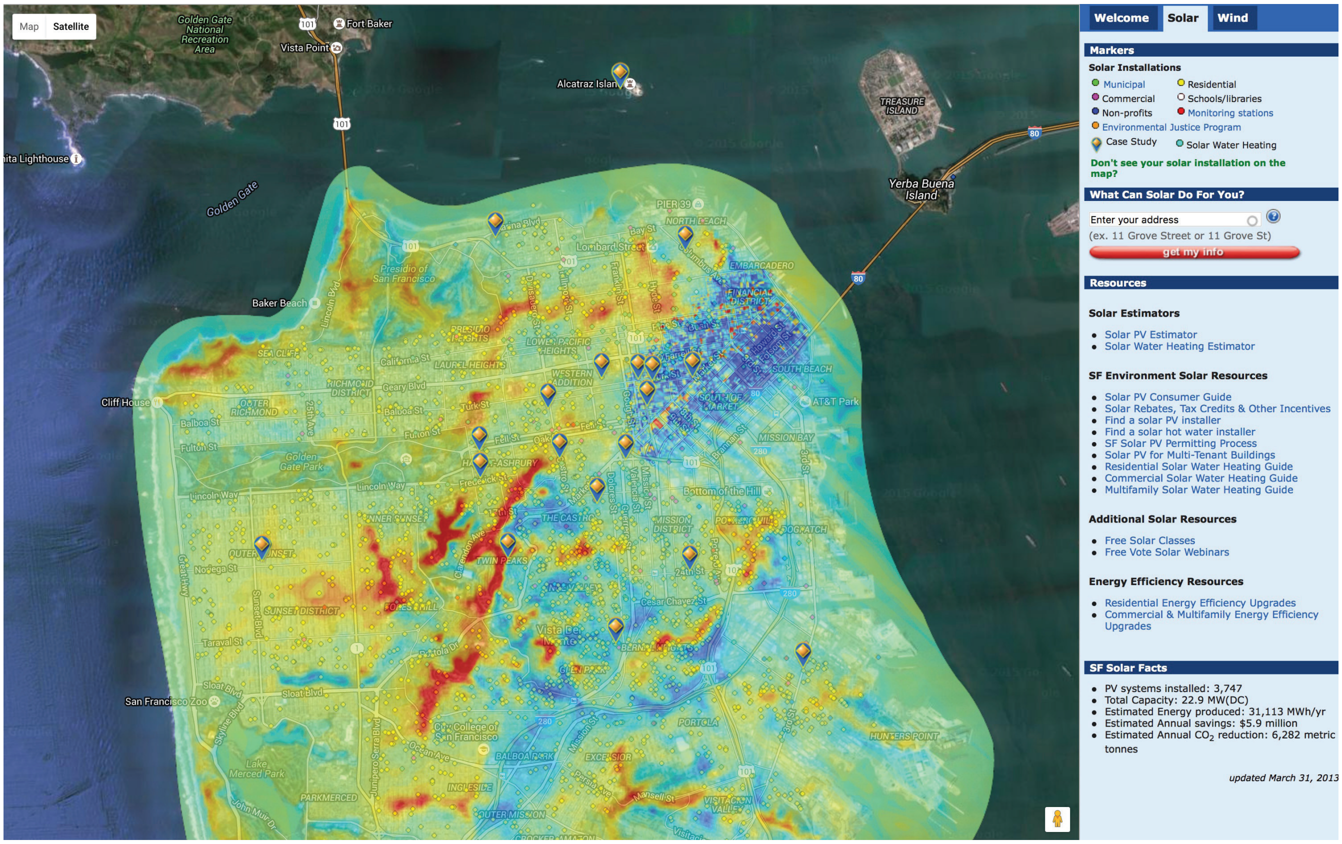

Figure 1. Screenshot of the San Francisco Energy Map, indicating solar energy activity.
Source: sfsolarmap.org

3.2. SMART METERS

As of July 2014, over 50 million residential smart meters had been installed in the United States, covering 43% of American homes—up from about 30% in 2012—and they are fast becoming the norm for many municipal utilities (Institute for Electric Innovation, 2014; St. John, 2014). The potential sustainability benefits of smart meters is realized from the more detailed consumption data provided than automatic meter reading (AMR) systems, allowing for more immediate changes in consumption by occupants and more nimble management by utilities. In AMR metering, meters send daily or monthly consumption totals to a central data collection point using one of several technologies, such as radio signals, power-line communications, or satellite readings (Oracle, 2009). Their purpose is to replace house-to-house meter readers with remote, wireless-enabled centralized data collection.

Smart metering, on the other hand, uses internet communication protocols controlled from a central point and available on demand. Smart metering allows real-time collection—as opposed to just daily or monthly totals—and enables additional services, such as remote disconnects and checks to ensure the availability of service to a particular home or area (Oracle, 2009). For utilities, the more granular data provided by internet-enabled smart meters offers opportunities for increased energy efficiency and conservation. Smart meters allow energy utilities to identify high-usage customers (e.g., buildings that use air conditioning or that may suffer from physical inefficiencies causing energy leakage) who can then receive targeted information and interventions. The Visdom data platform, developed by Stanford in conjunction with Pacific Gas and Electric (PG&E), allows utilities to apply analytics to the detailed data from consumers' smart meters to make tailored recommendations on adjusting and reducing usage, which are generally far more effective in inducing behavioral change than general recommendations (Borgeson, 2016).

The data generated by smart meters can also be made available to consumers through a web portal or an in-home display (IHD) that shows more accurately how much energy residents are using and when (see Figure 2). Preliminary studies suggest that smart metering, combined with in-home displays or portals, could have a modest but statistically significant impact on energy consumption. One study by the Environmental Change Institute at Oxford demonstrated that customers receiving direct feedback from smart meters reduced their electricity usage by 5% to 15% (Darby, 2006). A real-time feedback pilot study by the Ontario utility HydroOne showed a reduction in aggregate usage of 6.5% (HydroOne, 2006). These potential conservation advantages are not limited to private residences. For example, the city of Charlotte, North Carolina uses smart meters combined with public display kiosks to monitor the energy use of 61 public buildings (Institute for Sustainable Communities, 2015).

However, the proliferation of smart meters has not yielded the energy savings expected. This is largely because smart meter technology has not been consistently paired with user interfaces that relay usage information to consumers in real time, and translate that usage into economic savings. However, recent initiatives, such as the “Green Button” industry standard for smart meter information display interfaces, have sparked efforts by vendors, utilities, and advocacy organizations to create user-friendly portals to effectively aggregate and display data from smart meters. These have met with some success. In California, 43% of PG&E’s 6.2 million customers with smart meters signed up for the company’s online portal, and 38% have gone online to look at their data at least once in the past year (Mooney, 2015).[2] However, the availability of web portals may not be sufficient to assure consumer engagement and corresponding energy savings. A 2013 survey by the Smart Grid Consumer Collaborative found that only 8% of people were using online analysis of their energy usage by their utility (Mooney, 2015).

Behavioral studies of energy use suggest that in-home displays combining real-time information about energy consumption and its cost reduce energy usage by 11% to 14% (Jessoe & Rapson, 2014). This evidence points to the need for utilities, vendors, and researchers to work together to develop the most effective behavioral tools for making the data generated by smart meters actionable by consumers. The utility consulting service E Source has developed a framework for smart meter portals that identifies nine elements of successful portals, ranging from the presentation of current, granular data on usage to social gaming functions and options for conversion to renewables (see Hartman & LeBlanc, 2015).

Figure 2. An in-home display from Rainforest Automation, which shows real-time pricing and usage data.
Source: Rainforestautomation.com

2 http://www.greenbuttondata.org

3.3. CONSUMER-LEVEL PRODUCTS AND BUILDINGS

Perhaps the most familiar evidence of IoT is the growing market for consumer-level products. These can potentially save energy and provide substantial sustainability benefits. Cities can offer incentives for the purchase and installation of these devices, require them in their municipal building codes, and install them in city-owned buildings. IoT technology is used in software-based management systems to assess and control energy usage in a building or complex of buildings. Examples of these products include IntelliCommand, which monitors energy, lighting, heating, and cooling to maximize efficiency and notifies building managers regarding issues such as outages and disproportionate usage. Retroficiency allows users to track their energy use and suggest how they might reduce their usage. The program uses data analytics to create models and determine how and where a building is wasting energy. Other IoT building systems, such as Enlightened, Enocean, Lutron, and Philips Hue, focus on lighting, using wireless-enabled sensors to switch lights off when an area is unoccupied.

IoT is also employed in hardware devices. Perhaps the best-known of these is the Nest residential thermostat. Programmable thermostats are not new, but previous models required consumers to input adjustments to their desired temperature. Nest, in contrast, uses IoT and machine learning to recognize patterns in heating and cooling to individualize and automate these adjustments. In the commercial building sector, the Enlightened device is a control system for lighting and HVAC in businesses and industrial spaces. Sensors on fixtures monitor occupancy, lighting, temperature, and energy usage, turning off lights and reducing HVAC energy expenditures in unoccupied areas of a building. Hardware devices are also making it possible for consumers and businesses to select renewable energy sources. A startup incubated in the CITRIS Foundry at UC Berkeley, WattTime has developed an IoT-based technology that allows customers to run appliances that could use electricity on a flexible schedule, such as a washing machine, when renewable sources are available on the grid.[3] The technology can also be applied to electric-vehicle charging, prioritizing times when renewable energy is available. Such devices could be incorporated into civic infrastructure as well as private residences.

3.4. RECOMMENDATIONS FOR IOT IN ENERGY MANAGEMENT

IoT can help cities better manage their energy needs by revealing insights on energy usage and leakage. Energy efficiency gains from public buildings can serve as a critical first step in reducing a city's carbon footprint. We recommend that cities explore development of distributed microgrids to support clean-energy backup for public buildings (e.g., solar panels on nearby rooftops provide clean energy to public buildings). We recommend that cities also deploy smart meters in public buildings with public-facing portals that communicate energy consumption and corresponding environmental and financial impacts. Finally, we recommend that cities develop strategic plans for influencing behavior change for energy use among city inhabitants. Hartig and Kahn (2016) found that the presence of public parks and green spaces in cities significantly contributes to public support of the environment and environmental protection. Development and protection of urban green spaces combined with public communication campaigns on the ecological effects of energy consumption and saving could support development of an eco-conscious public.

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3 http://watttime.org

4. IOT FOR SUSTAINABILITY IN WATER

The recent lead poisoning in Flint, Michigan's water system drew national attention to the crisis facing America's systems for providing clean water. The American Society of Civil Engineers recently gave America's water infrastructure a grade of D+, noting that there are an estimated 240,000 water main breaks in the country every year, and the cost over the coming decades could reach $1 trillion (American Society of Civil Engineers, 2013). Many of these problems result from aging infrastructure and shifts in supply and demand; as Michael Weber, Deputy Director for the Energy Institute at the University of Texas, Austin notes, the American water system "has reached the end of its service life just as climate change and population growth have increased its burdens" (Weber, 2016).

Currently, an estimated 2.1 trillion gallons of clean, treated water is lost each year to leaks in the infrastructure of America's 52,000 water utilities (Adler, 2015; Forer & Staub, 2013). In 2013 alone, the city of Houston lost 15% of its water, some 15 million gallons, to leaking pipes (Adler, 2015). The need for innovation in water capture and conservation is especially critical given the depletion of freshwater resources in numerous areas in the United States and the shifts in water availability due to climate change. Some areas will experience drought and depleted water resources, and will be subject to mandatory conservation measures such as those imposed in California in 2015 during a multi-year drought. Other areas will experience increased rainfall and with it the need to capture and recycle stormwater to manage freshwater resources. IoT technologies offer opportunities to help cities use and conserve water more efficiently and effectively.

4.1. SMART WATER PIPES

New IoT technologies allow cities to make their water pipe systems "smart" by installing remote sensors to monitor flow and prevent leakage. These technologies work in various ways: in Los Angeles, Las Vegas, and Atlanta, a pilot project by AT&T, IBM, and Mueller Water Products used sensors connected to a cellular data network to "listen" for the distinctive sound of leaks in the city's system of underground pipes (Nehls, 2015).

IoT technology also makes it possible to save water by a relatively simple measure: minimizing water pressure in the pipes. Companies such as AquamatiX and i2O have developed embedded sensors that can be installed in water pipes throughout the distribution system and connected to central pumping control systems. The sensors regulate water pumping by monitoring water flow and minimizing the amount of water in the pipes, reducing both the amount of water lost to leakage and the amount of electricity required for pumping.

The distributed nature of the sensor network also allows utilities to detect sudden events such as pipe bursts, facilitating rapid identification and repair (Adler, 2015). Distributed IoT technologies offer the potential for preventing water loss and waste at a vastly lower cost than reconstructing the nation's entire water infrastructure (Tilley, 2015a). IoT can also serve the additional purpose of monitoring water quality and pipe corrosion, which could avert public health disasters such as the recent lead poisoning of the Flint water system (Woo, Piralta & Matthews, 2015).

4.2. SMART WATER METERS

As of 2013, 18% of water meters in America were smart meters, a number that is expected to rise to 29% by 2020 (Tilley, 2015b). Smart water metering offers benefits to utilities and consumers similar to the benefits of smart electric metering. While traditional water meters are usually read manually monthly or yearly, smart water meters record consumer use in real time, and can convey this information to both the utility and the consumer, offering possibilities for improved water management. For utilities, smart meters allow system managers to detect leaks at consumers' homes or businesses. For residences, leak detection is fairly straightforward: if usage never drops to zero, a leak is the likely explanation. For businesses that use water round the clock, utilities can rely on algorithms available from software vendors to identify indications of a leak. The more granular, real-time usage data provided by smart meters also allows utilities to monitor resource-wasting or illegal behavior, such as outdoor watering or non-essential usage during daylight hours (Finley, 2015).

Consumers also benefit from the more granular data provided by smart water meters. They can see how much water they used during various household activities, and can pinpoint and adjust their consumption accordingly to conserve resources and lower their water bill. Companies such as WaterSmart provide consumers with usage data in an accessible and comprehensible format that highlights changes in consumption and opportunities to conserve.[4] Park City, Utah, which has installed 5,200 smart water meters, contracted with WaterSmart to provide detailed information about usage and showed consumers how they compared to similar households. While fine-grained documentation to demonstrate a causal relationship is not yet available, the city is on track to meet the statewide goal of reducing water use per person by 25% from the 2000 level by 2025 (Wang, 2015a). Cities can also implement their own interfaces for information and data visualization programs. San Francisco's smart water meter program features a website where consumers can check their daily usage and compare their consumption with similar households (see Figure 3).

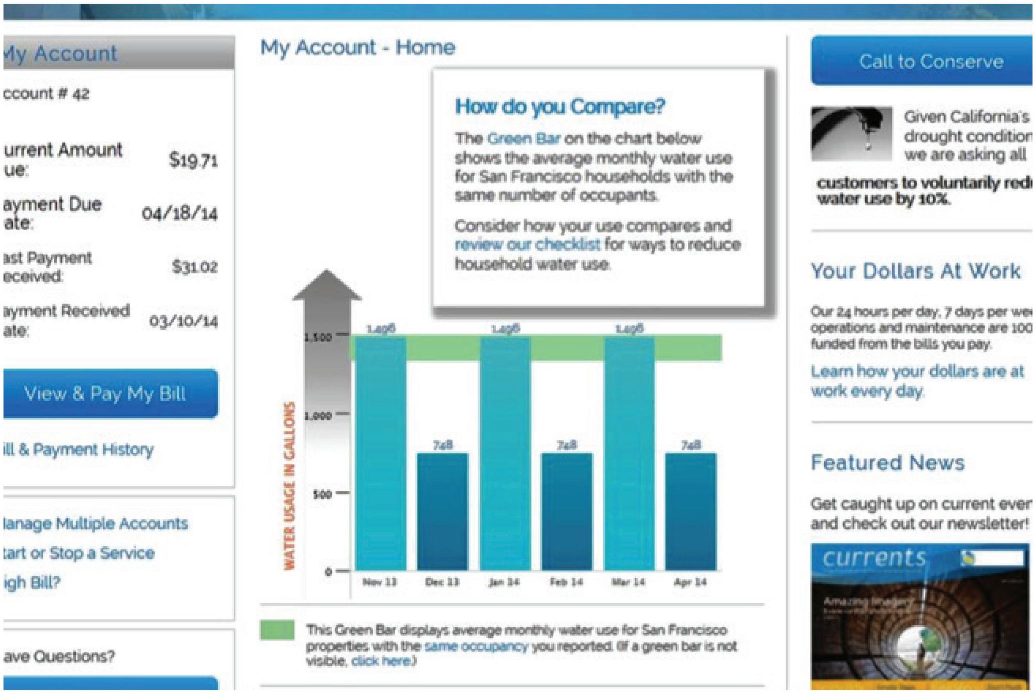

Figure 3. San Francisco's smart water meter data interface Source: San Francisco Water Power Sewer. Source: https://myaccount.sfwater.org/

4 http://www.watersmart.com

In a pilot program in the East Bay Municipal Water District in California, which serves over 1.4 million households, the utility installed 4,000 smart water meters that provide hour-by-hour usage data to residents via a website. Consumers can set a limit to their water usage and receive an alert when their usage exceeds it, and the utility contacts consumers when a smart meter indicates usage for 24 hours a day, usually suggesting a leak. The data collected by the district revealed that about a quarter of all residences had some sort of leak, usually from toilets, irrigation, or water-softener systems (Wang, 2015a).

Although research has not yet documented whether smart meters are more effective in decreasing consumer water usage than other less expensive interventions, preliminary studies suggest that pairing smart meters with direct and immediate feedback can reduce consumption from very modest to significant degrees (Sonderlund et al., 2014). In one study, customers who had a smart-meter-connected visual display installed in their shower with an alarm to indicate when a specified level of water usage was exceeded, decreased water consumption during showers by an average of 27% (Sonderlund et al., 2014). Anecdotal reports are also encouraging. In the Long Beach smart meter pilot program, a corrected irrigation problem reduced water consumption by 70%, and one home reduced consumption by 98% after fixing a leak (Goldenstein, 2015).

4.3. SMART WATER RECLAMATION

As freshwater resources face increasing demand and diminishment from climate change, water reclamation will take on an important role in sustaining cities' water needs. Stormwater reclamation may be an especially useful tool for areas that experience increased rainfall. Currently, during heavy storms, the water-treatment infrastructure in many U.S. cities is overwhelmed by the amount of water. As a result, raw sewage—along with the stormwater—is dumped into waterways, causing pollution and loss of a potential water resource. Opti is using IoT technology to combine information from weather predictions and storage tanks to make sufficient space in the water system to properly process and capture stormwater runoff.[5] Similar IoT technology can also be used to manage and capture stormwater in areas with minimal rainfall. AquamatiX collaborated with the Basingstoke Canal Authority in Hampshire and Surrey Counties in the UK, a region with limited rainfall and a high degree of dependence on a limited water supply, to monitor weather prediction data and canal water levels to control sluice positions that maximize the collection of rainwater (Adler, 2015).[6]

IoT could also improve wastewater reclamation and sewage treatment, which will prove especially critical in areas with threatened freshwater resources. David Jassby, Assistant Professor of Chemical and Environmental Engineering at UC Riverside and an expert in wastewater treatment, notes that since wastewater recycling and reuse can lead to the introduction of pathogens and hazardous chemicals into water distribution systems, online monitoring systems can detect and inform operators about potential exposure in real time. Due to the complex nature of wastewater, which includes both organic and inorganic substances as well as pathogens, the complexities of water treatment require rapid detection, adaptation, and response to the constantly evolving quality of the water stream. IoT devices can use machine learning algorithms to make rapid changes in operating conditions to effectively treat wastewater (Jassby, 2016).

5 https://optirtc.com
6 http://www.aquamatix.net

4.4. RECOMMENDATIONS FOR IOT IN WATER MANAGEMENT

IoT technologies can provide immense insight into sustainable water management. Cities should use IoT technologies to increase efficiency of water infrastructure and to identify critical upgrades. Despite the upfront investment, utilizing IoT technologies is significantly less expensive than a comprehensive overhaul of such systems. Civic leaders should also keep in mind that merely providing citizens with smart meters that gauge their water use on a granular level will likely be insufficient to guarantee conservation and shifts in behavior. Thus, cities should implement programs with an interpretive user interface, whether easily accessible online data or a hardware meter component, designed to communicate environmental and financial impacts of water usage to consumers. Finally, cities should incorporate IoT-enabled measures for water conservation and efficiency in existing public buildings and in new public construction.

5. IOT FOR SUSTAINABILITY IN TRANSPORTATION

Every year Americans cumulatively spend over 6.9 billion hours in traffic congestion causing over 3.1 billion gallons of wasted fuel and contributing to nearly 30% of total greenhouse gas emissions (INRIX, 2014; Barth & Boriboonsomsin, 2009). This congestion is caused not only by overburdened infrastructure but also driver error and inefficiencies. Sudden braking in a smooth flow of heavy traffic causes negative rippling effects, and drivers circling for parking in crowded cities clogs streets, wastes gasoline, and contributes immensely to a city's CO2 levels. IoT systems offer great potential in the management of traffic congestion and driver efficiency (Bayen, Butler, & Patire, 2011).

5.1. VEHICLE TECHNOLOGIES

The Institute of Electrical and Electronics Engineers predicts that autonomous vehicles will make up nearly 75% of all vehicles on the road by 2040 (IEEE, 2014). These vehicles will be fully equipped with cameras, sensors, GPS, and wireless internet. Vehicle-to-vehicle and vehicle-to-infrastructure communication has the potential to enable unprecedented traffic coordination. For example, if one car must forcefully apply its brakes to avoid an obstacle, this information will be instantaneously communicated to vehicles behind it slowing and diverting traffic to avoid accidents and congestion. Another benefit of vehicle-to-vehicle communication will be "platooning" where vehicles follow one another closely to reduce air resistance, thus reducing fuel waste. Vehicles communicating with infrastructure could also enable dynamic speed controls and routes, optimizing vehicle movements through transportation infrastructure bottlenecks (e.g., intersections, bridges, tolls, on-ramps) reducing fuel waste and CO2 emissions from inefficient braking and acceleration (Wang, 2015b).

Yet, even before autonomous vehicles become ubiquitous, use of sensors, GPS, and software can provide significant efficiency gains in transportation. The city of Paris partnered with 63 surrounding suburbs and Microsoft to establish Autolib', an electric vehicle–sharing program that connects 2,300 electric vehicles with 4,300 charging stations and 850 registration kiosks. Autolib' analyzes multiple data streams to optimize vehicle availability, predict commuter behavior, and streamline parking for Autolib' electric vehicles (Microsoft, 2014). The program has taken thousands of cars off the road and reduced CO2 emissions by providing real-time data on the location of Autolib' electric vehicles, charging stations, and parking. IBM has partnered with NXP semiconductors in Eindhoven, Netherlands to equip 200 vehicles with telematics chips that gather data from a vehicle's central control system on braking, acceleration, location, and car maintenance (i.e., tire pressure, use of anti-lock brakes) (IBM, 2013). Using IBM's SmartCloud Enterprise service, the system was able to identify 48,000 road incidents (e.g., potholes, bottlenecks, icy conditions) and could communicate these insights with drivers (e.g., recommending a reduced driving speed due to upcoming road conditions) and central transportation operators who could make nearly real-time decisions on traffic management. The Smithsonian Institute installed sensors and GPS tracking across its fleet of 1,500 vehicles to collect data on vehicle location, driving characteristics, engine diagnostics, and maintenance needs (Shaw, 2014). Cloud-based software allowed drivers and central operations staff to optimize routes and number of vehicles in the fleet, resulting in a reduction of fuel consumption by 52% (Shaw, 2014).

5.2. SHARED MOBILITY AND TRAVELER INFORMATION TECHNOLOGIES

Shared mobility technologies including car-sharing services like Zipcar and ride-sourcing services like Uber and Lyft have the potential to significantly contribute to transportation efficiency and sustainability through a “reduction of vehicle use, ownership, and vehicle miles traveled” (Shaheen et al., 2015, p. 19).[7] A UC Berkeley study of the effects of City CarShare, a car-sharing service in San Francisco, found use of the service reduced automobile ownership and increased participants’ use of alternatives, including walking, biking, and public transit (Cervero, Golub, & Nee, 2006).

In addition, traveler information technologies that provide real-time data can empower commuters to “overcome barriers that might previously have deterred them from taking public transportation, sharing a ride with a friend (or a trusted stranger), or biking or walking to their destination” (Dutzik, Madsen, & Baxandall, 2013, p. 15). For example, Waze and Google Maps provide real-time data on traffic congestion, commute times, and availability of different modes of travel (i.e., vehicle, walking, bike, public transit). Moovit and Swiftly provide real-time data on public transit availability by combining GPS location data on public transit systems with crowdsourced information from commuters. To enable multi-modal travel, Uber and Lyft recently partnered with TransLoc, an app that provides real-time public transit tracking and route planning, to provide first- and last-mile shared mobility services for public transit commuters (Somerville, 2016).

Not only do these technologies empower commuters with information that can inform decision-making on transportation choices, but they also collect vast amounts of data that can be used by city officials to better inform transportation management decisions. Sidewalk Labs, a unit of Google’s Alphabet, is projected to launch Flow, a system that will integrate and analyze data from GPS mapping and sensors to identify the causes and potential solutions to traffic congestion.[8] The platform will also enable experimental tests of the effects of city-level transportation decisions (e.g., adding a bus line or a bike-share lane to a street) (Dougherty, 2016).

5.3. TRANSPORTATION INFRASTRUCTURE AND SYSTEMS OPERATIONS

Connected IoT devices and sensors placed within transportation infrastructure enable real-time data collection on the presence and movement of vehicles through fixed points. Combining data from fixed IoT (e.g., sensors embedded in infrastructure) with data from mobile IoT (e.g., commuters’ smartphones, sensors embedded in vehicles) enables collection of rapid, ubiquitous, and reliable data on real-time traffic throughout a transportation system. Two examples of using data from fixed and mobile IoT are SFpark, to enable smart parking, and the Mobile Millennium and Connected Corridors projects to test innovative systems-level traffic management.

In a 15-block area of Los Angeles, drivers spend an additional 100,000 hours looking for parking, causing them to use an additional 47,000 gallons of fuel and emit 730 tons of CO_2 within the span of a year (Shoup, 2005). All cities face this problem and city management of parking is a critical component to its resolution. “Smart parking” initiatives have demonstrated impacts on reducing parking search time, traffic congestion, and CO_2 emissions.

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7 Shaheen, Chan, Bansal, & Cohen (2015, p. 4) define “shared mobility” as the “shared use of a vehicle, bicycle, or other low-speed mode that enables users to have short-term access to transportation modes on an ‘as needed’ basis…[and] includes carsharing, personal vehicle sharing…, bikesharing, scooter sharing, shuttle services, carpooling and vanpooling, ridesourcing/transportation network companies…”

8 While the exact business model has not been established, cities will likely be charged according to a subscription-based model for access to different tiers of data and analytics (Dougherty, 2016).

Launched in 2011 by the San Francisco Municipal Transportation Agency, SFpark seeks to reduce the time it takes commuters to find parking by providing real-time data on parking availability, demand-response pricing, and smart meters (SFMTA, 2014).[9] SFpark gathers parking availability information from sensors in the pavement, alerts drivers of available parking, and sets the price of parking relative to the level of demand (see Figure 4). For example, parking spaces are priced higher if in close proximity to an event or during peak commute hours. This encourages drivers to find lower priced parking outside of congested areas of the city. Smart meters communicate with the SFpark database to set pricing based on demand and enables payment from cash, credit/debit cards, and SFMTA parking cards. To promote equitable adoption, SFpark is available as an iOS and Android app, online, or by phone.

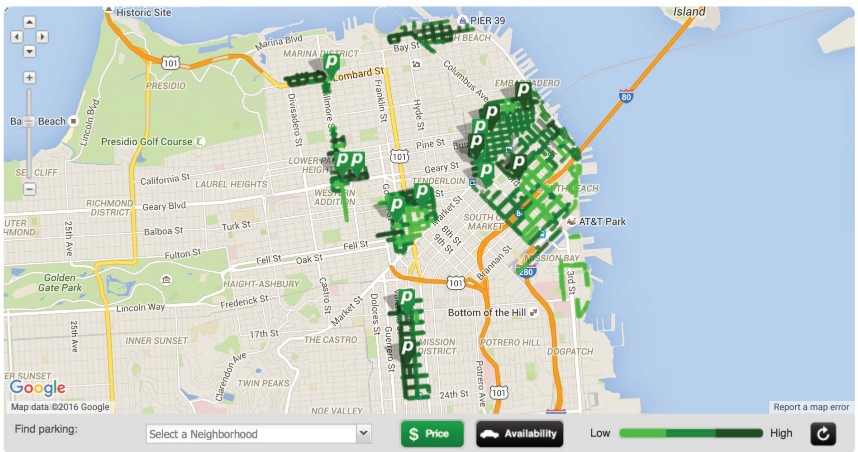

Figure 4. Screenshot of SFpark user interface.
Source: http://sfpark.org.

Initial results of SFpark indicate reductions in daily driving times by 43%, miles driven by 30%, and greenhouse gas emissions by 30% (SFMTA, 2014). By providing information on parking availability and differential pricing based on congestion, the city has been able to reduce traffic congestion and enable distributed parking across its public parking infrastructure.

Technologies such as fixed loop detectors in pavement, radio-frequency identification (RFID) transponders, radars, and cameras have enabled systems-level monitoring and response to traffic flow. However, these technologies only show “snapshots” of traffic patterns at fixed locations and lack the ability to show real-time traffic flow throughout the entire transportation network (Bayen, Butler, & Patire, 2011). Integrating data from fixed and mobile IoT technologies offers the potential to gather rapid, ubiquitous, and reliable data on real-time traffic patterns, enabling more informed decision-making on behalf of traffic control operators and commuters.

The Mobile Millennium project was launched in 2008 to tap into a readily available network of sensors, accelerometers, and GPS-enabled devices connected to the internet throughout a transportation network: commuters’ smartphones.[10] Launched by researchers at the UC Berkeley California Center for Innovative Transportation in collaboration with the California Department of Transportation; the US Department of Transportation; Nokia; and NAVTEQ, a leading US map manufacturing company, the Mobile Millennium project was one of the first pilot tests to show the value of combining traditional traffic flow data from fixed location IoT technologies with crowdsourced traffic data from commuters’ smartphones (Bayen, Butler, & Patire, 2011). Over 5,000 smartphone users opted into the program in the San Francisco Bay Area, providing real-time GPS location and vehicle speed data from their smartphones. This data was then combined with traffic flow data from traditional fixed technologies (e.g., loop detectors and RFIDs) and analyzed through traffic models to provide real-time traffic insights (see Figure 5).

9 http://sfpark.org
10 http://traffic.berkeley.edu

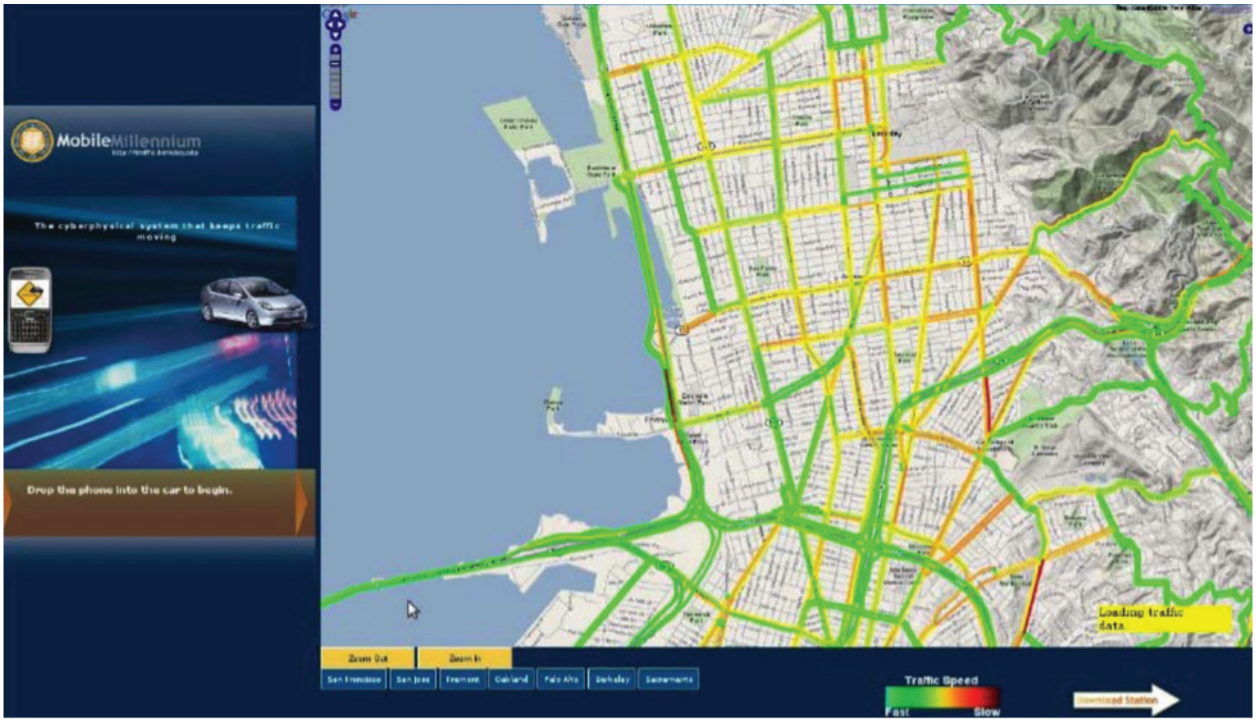

Figure 5. The Mobile Millennium Project User Interface.
Source: Bayen, Butler, & Patire, 2011.

The Mobile Millennium project marked a shift in traffic management from top-down to inclusion of bottom-up, real-time data collection from and presentation to commuters, enabling more informed decision-making on commute routes and timing. Work in this area has continued through the Connected Corridors project launched in 2013 by the California Department of Transportation and Partners for Advanced Transportation Technology (PATH) at the University of California, Berkeley.[11] The Connected Corridors project builds on the work of Mobile Millennium to manage transportation corridors in California. Connected Corridors uses an integrated traffic management approach whereby real-time data is collected and integrated across mobile telecommunications, sensors, GPS, and social networking technologies to support holistic management of an entire transportation network (PATH, 2016).

5.4. RECOMMENDATIONS FOR IOT IN TRANSPORTATION MANAGEMENT

While transportation systems of the future will be marked by sensor networks, automation and real-time data analytics, careful consideration should be taken to ensure these systems, including data ownership, management, and distribution, are equitable, accessible, and secure. Cities must plan for the incorporation of automated transportation networks by creating smart city plans that incorporate rights-of-way for shared mobility services; develop physical and cyber-physical infrastructure to collect, analyze, and communicate real-time data on available transportation modes and traffic patterns; and establish data sharing platforms across public and private entities. Furthermore, municipal transit agencies should be sensitive to providing equitable access to these systems. Wherever possible, traffic management systems and insights should be communicated across multiple platforms, including as iOS and Android apps, online, or by phone, and include information on public transit options.

11 http://connected-corridors.berkeley.edu

6. RECOMMENDATIONS FOR IOT IN SUSTAINABILITY

While widespread deployments of IoT initiatives may take years to achieve, city-level officials have an opportunity to implement changes today that will lay the foundation for a sustainable future. This section provides recommendations for foundational components that will assist in the development of smart, sustainable cities. We focus our recommendations with civic engagement and collaboration across stakeholders (e.g., citizens, industry, public sector) at the core of all IoT deployment efforts in energy, water, and transportation (see Figure 6). The success of smart city initiatives depends not only on technology but on tapping the ingenuity of people who have firsthand experience, enabling connections between systems- and consumer-level IoT deployments, fostering collaboration and data sharing across sectors, ensuring trust and reliability, and supporting efforts that turn data insights into sustainable action (see Figure 6).

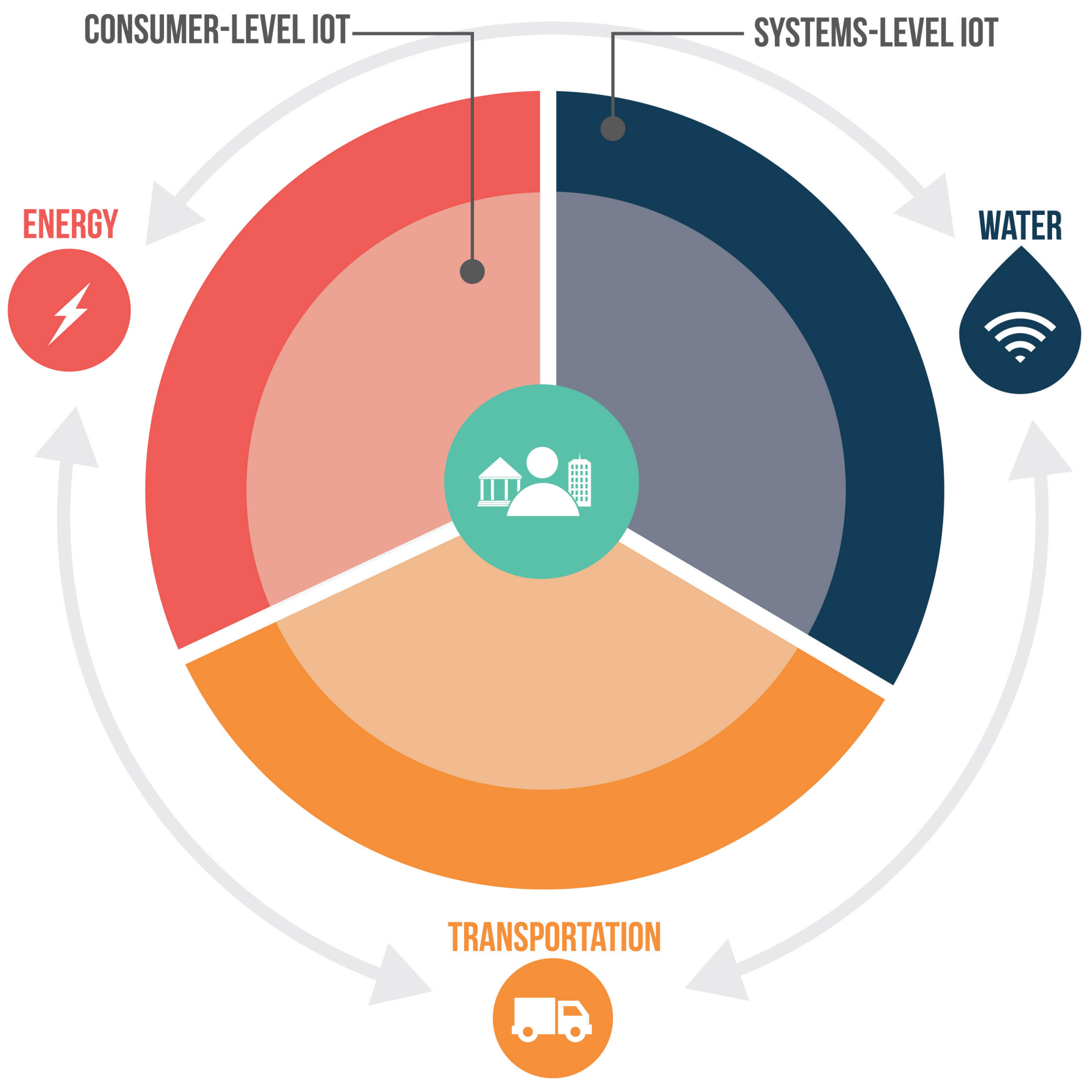

Figure 6. Holistic Approach to City-Level IoT for Sustainability.

6.1. INCLUSIVE PLANS

Cities are in the midst of an exciting transition. New IoT technologies offer unprecedented potential to gather vast amounts of real-time data, revealing previously unknown patterns and insights into how a city functions. While IoT platforms can lead to widespread benefits, these investments can be costly, time-consuming, and difficult to influence long-term behavior change. Thus, it is imperative that city-level officials develop inclusive plans before committing resources and infrastructure to IoT deployments.

We recommend strong collaborative engagement with constituents when drafting plans to incorporate IoT technology and encourage plans that achieve sustainability objectives across relevant sectors (see Figure 6). These plans should identify sustainability goals and targeted interventions that can be used to support coordinated efforts and deployment of appropriate technologies. For example, a core objective to reduce CO2 emissions could involve both the transportation and energy sectors, along with community engagement to foster trust and behavior change. By deploying sensors on public transportation infrastructure, the sensor network can simultaneously monitor traffic patterns and synchronize traffic lights to reduce idling and CO2 emissions, while also collecting motion data from traffic and pedestrians to trigger responsive street lighting. Such a connected system would cut energy costs and improve public safety.

6.2. THE PROMISE OF PARTNERSHIPS

The value of IoT deployments will be enhanced not only through collaboration across city-level sectors but also through engagement with public, academic and private sector stakeholders. Cities should tap the collective intelligence of their constituents to identify priority sustainability issues and appropriate applications of IoT. Including the public as co-creators in IoT initiatives will better ensure development of appropriate solutions and buy-in at all levels. The United Kingdom recently launched IoTUK, a public outreach platform that seeks to raise public awareness and feedback on the perceived benefits and risks of IoT deployments within the areas of security and trust, data interoperability, and co-designed IoT initiatives.[12] Cities should offer feedback mechanisms, whether in-person, online, or both, where they can crowdsource priority issues and bottom-up solutions from their constituents.

Cities are growing at an unprecedented rate, increasing urgency for the public sector to identify efficient and equitable solutions to city management. In order to reach these solutions, the public sector must collaborate with industry and academia. Public-private and public-academic partnerships can provide the public sector with access to state-of-the-art technologies, while providing the private and academic sectors with a living testbed. Insights from these collaborative pilot projects can be used to inform city-level tactics for utilizing IoT for sustainability. One example is UC Berkeley professor Greg Niemeyer’s interactive street lighting system in collaboration with the City of San Leandro, California that projects colored lights on the sidewalk when a pedestrian walks by, collecting data on foot traffic patterns and increasing public safety.[13]

12 https://iotuk.org.uk
13 http://www.modernluxury.com/san-francisco/story/san-leandro-pedestrians-walk-the-light

6.3. THE ROLE OF PEOPLE: EQUITY, ACCESS, PARTICIPATION, AND BEHAVIOR CHANGE

The potential for IoT technologies to improve sustainability in cities is contingent on engaging citizens and enabling them to participate in IoT initiatives. This means that parties interested in driving change must put people first by addressing critical barriers to individuals' ability to utilize IoT sustainability technologies. Providing cutting-edge IoT for enhancing conservation and efficient use of energy, water, and transportation resources is ineffective if citizens lack the means to use it. Disparities in broadband access between rich and poor—even within the same city—are well documented and persistent across the United States. For example, studies of communities such as Cleveland, Houston, and San Bernardino have shown that access stops when incomes drop (Holmes et al., 2016). As part of creating sustainable IoT infrastructures, cities should work with internet providers to expand access to broadband internet to ensure that low-income residents are not left out of the IoT revolution. Cities should also ensure that the IoT tools they develop are conceived with a diverse constituency in mind. For example, programs such as Boston's Street Bump app, which uses data from smartphone accelerometers and GPS to detect where roads need repair, can unintentionally neglect neighborhoods where residents are more likely to walk and smartphone ownership is less common.

Finally, IoT for sustainability initiatives will likely struggle to gain sustained behavior change, thus cities must devote resources to develop effective strategies for changing behavior and ensuring that residents appreciate the environmental gains. Some private programs, such as Zero Footprint, offer a system of tangible rewards for measurable behavior changes, and it is possible to develop and/or communicate financial incentives to encourage shifts in behavior.[14] Some evidence suggests that lasting behavioral changes are most effectively achieved with a "whole systems" approach used in projects such as the Cool City Challenge, a pilot project in San Francisco, Palo Alto, and Los Angeles.[15] The Cool City Challenge will launch in Fall 2016 and will recruit community block leaders to identify and tailor solutions that will incorporate community-level needs. Community members will be engaged within a network to support accountability and shift cultural norms to conservation (Lebeck 2016; Lawrence Berkeley National Laboratory and Empowerment Institute, N.D.).

6.4. DEVELOPING A FRAMEWORK FOR TRUST AND RELIABILITY

Cities should develop a framework for documenting and ensuring the reliability of IoT deployments in order to gain the trust of those investing in and benefiting from these systems. Because the data derived from these systems will serve as the basis for actionable decisions, including potentially millions of dollars in infrastructure investment, it is essential that the data be valid and replicable. We recommend that city-level officials collaborate with academia and industry early on, to evaluate not only the accuracy and reliability of the data but also the capacity of IoT systems to safeguard the security of the infrastructure and the privacy of individuals affected.

Trade-offs among the priorities of privacy, security, and interoperability will need to be considered on a case-by-case basis. Data at the individual or household level may need to be anonymized or aggregated to ensure privacy and support systems-level security. IoT systems that prioritize security may not be interoperable, resulting in data silos and redundancies, and an IoT system that prioritizes personal privacy and collects data at an aggregate level may result in missed insights at the granular level. Still, not all IoT deployments for sustainability purposes merit the same security and privacy restrictions. For example, security and privacy measures for smart electricity meters and grids should be held to a higher standard than sensors monitoring leaks in municipal water pipes.[16] Civic IoT policy should use a balancing test for these priorities, gauging them

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14 http://www.zerofootprintsoftware.com

15 http://www.coolcitychallenge.org/what-it-is

16 Smart meters can collect highly detailed information on energy consumption, including what appliances are being used, when, and for how long. This data can be used for real-time surveillance on the occupants of a home by tracking and profiling energy-consumption patterns, making smart meter data highly susceptible to third party monitoring and theft. (see http://fas.org/sgp/crs/misc/R42338.pdf).

against the necessity for trust and data reliability. We recommend that cities engage in open conversation with the various stakeholders (utilities, vendors, customers, and rate-payers) to arrive at the most appropriate configuration for each case.

Because IoT technologies will create vast troves of data, city-level officials should create strategic agreements with private and academic partners concerning policies for data stewardship, ownership, and public access. Data collected and generated for and by the public should, to the extent advisable for privacy and security reasons, remain within the public domain. The opportunities offered by the dynamic exchange of data among public and private actors can yield great advances in sustainability. Thus, it is recommended that city-level officials take initiative to support the cyberinfrastructure for sharing de-identified open data and develop strategic outreach efforts to share data insights to support changes in public behavior and further IoT for sustainability initiatives.

City-level leaders would benefit from participating in ICT standards organizations such as buildingSMART International, the International Organization for Standardization (ISO), the National Institute of Standards and Technology (NIST), the Open Geospatial Consortium (OGC), and the World Wide Web Consortium (W3C). Cities can also avoid “reinventing the wheel” of standards development and avoid the need to create bespoke IoT services and applications by participating in and learning from the National Institute of Standards and Technology’s Global Cities Team Challenge, which creates IoT systems according to uniform standards of security that can be deployed in multiple cities (Rhee, 2016; NIST, 2016).[17]

17 http://www.nist.gov/cps/sagc.cfm

7. CONCLUSION & FUTURE AREAS OF RESEARCH

Cities stand at a pivotal confluence of trends: rapidly developing technology and growing urbanization. These streams may be brought together through IoT technologies that enable leaders to better manage urban systems, conserve natural resources, and improve quality of life.

While the landscape of stakeholders and considerations is complicated, city-level officials have an opportunity to shape the way residents experience and influence their environment. In the energy sector, sophisticated sensor technology and data analytics in public buildings, combined with advances in microgrids, may reduce overconsumption and increase clean energy use. Publishing water and energy consumption data and the corresponding environmental and financial impacts in an easily understandable format can serve to educate the public on the value of IoT for sustainability. Within transportation, IoT technologies can streamline transportation management and empower commuters' decision-making on transportation choices, reducing commuter stress while obtaining sustainability objectives.

Additional research is needed to assist city-level decision-makers in identifying the most appropriate IoT technologies for sustainability initiatives. Future research should be conducted to create a matrix for city-level decision makers indicating the different types of IoT technologies available for sustainability initiatives in energy, water, and transportation; the potential security and privacy risks of these technologies; and best practices or resources required to mitigate negative impacts if the systems or data are compromised. Furthermore, additional research on the relationship between broadband internet availability at the city- and residential-level and development of IoT initiatives for sustainability should be conducted. Findings from this research could be used to inform federal-, state-, and city-level broadband investment initiatives.

Taking into account the relationship among demands for energy, water, and transportation to support a healthy ecosystem, while also preserving privacy and security for city residents, is a tall task—and an enormous market, estimated to grow to nearly $150 billion by 2020.[18] Citizens themselves should stand at the center of these considerations. City officials should explore public-private-academic partnerships to support mutually beneficial collaborations on behalf of the people—residents, workers, visitors—who sustain the vibrant, challenging atmosphere of growing cities.

18 http://www.marketsandmarkets.com/Market-Reports/iot-smart-cities-market-215714954.html

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