Sustainable IT Ecosystems: Enabling Next-Generation Cities

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In this paper, we describe an integrated design and management approach for building next-generation cities. This approach leverages IT technology in both the design and operational phases to optimize sustainability over a broad set of metrics while lowering costs. We call this approach a Sustainable IT Ecosystem. Our approach is based on five principles: ecosystem-scale life-cycle design; scalable and configurable infrastructure building blocks; pervasive sensing; data analytics and visualization; and autonomous control. Application of the approach is demonstrated for two case studies: an urban water infrastructure and an urban power microgrid. We conclude by discussing future opportunities to co-design and integrate these independent infrastructures, gaining further efficiencies.

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Introduction

The United Nations has estimated that about half of the world's population, 3.3 billion people, live in cities and towns, and projects that this figure will increase to nearly 5 billion people (60% of world population) by 2030 [WUrbnPr]. This growth in urban population will require the creation of new cities, and re-creation of existing cities around the globe. This new physical infrastructure will require significant amounts of materials and energy for construction and operation. The resulting risk to the carrying capacity of the biosphere – including threats of

climate change and growing scarcity of water, food, and fuel – necessitates a new approach to the design of city-scale infrastructures. This new approach must result in designs that emphasize the least and most appropriate use of resources such as material, energy, and water for construction and operation, while maintaining or improving the quality of life for urban populations.

Unlike the previous generation of cities built during the Industrial Age, next generation cities will be able to leverage current information technology (IT). We can now use IT, specifically computer-aided design, to optimize the design of new cities. What's more, we can embed information and communication technology into *everything* within a new city to achieve optimal operation of city-scale infrastructure. Researchers, city planners, and others have been working on such concepts as intelligent cities and spaces [IntSpace], as well as the integration of computing and sensing technologies with the physical world [PhyCSys], [PhyPNet]. Yet we still lack a concise framework for achieving optimal integration of IT into the design and operation of physical infrastructure. This paper introduces the concept of a *sustainable IT ecosystem* as one that employs key elements of information technology to improve the sustainability of compatible ecosystems. We apply this concept to the physical infrastructures that form the next-generation city ecosystem and introduce a framework that provides a more sustainable alternative to conventional physical infrastructures. Five principles comprise the framework:

1. Ecosystem-scale life-cycle design;

2. Scalable and configurable infrastructure building blocks;

3. Pervasive sensing;

4. Data analytics and visualization; and

5. Autonomous control.

As shown in Figure {CITY2ARCH}, our framework applies these principles across urban infrastructure functions. Using the same architecture in the design and management of all the different infrastructure components of a city

provides the opportunity to take advantage of interdependencies, while potentially eliminating many inefficiencies and redundancies. Such an approach has been previously reported to improve the sustainability of large-scale IT infrastructures, such as data centers [IntDSDC]. In this work, we describe how these principles can be applied to city-scale infrastructures.

Ecosystem-scale Life-cycle Design

A critical challenge in creating sustainable IT ecosystems will be ensuring that choices made at design time do not result in detrimental effects downstream during the life-cycle. Life-cycle assessment (LCA) provides a useful approach in such Design for Environment (DfE).

The notion of LCA is not new [HitchLCA] [ISO14064]; it has been successfully applied for many decades in various fields. Traditional LCA approaches have involved building detailed inventories of unit processes and products flowing across the entire life-cycle – from extraction of raw materials and manufacturing through distribution and retail to operation and end of life. Having aggregated these inventories through proxy indicators [Env6Meth] such as mass, energy, or exergy consumption of unit processes and products, standardized or documented impact factors can then be applied across the inventory to obtain the environmental impact along a multitude of impact categories [Imp2002], [EcoInd99]. Many off-the-shelf software packages [SimaPro]–[EcoLCA] are available for implementing LCA.

Unfortunately, most of these LCA approaches are focused on product- or system-scale implementation (on the order of hundreds to thousands of components) using standard assessment methodologies. To create sustainable IT ecosystems, more advanced design tools that enable a higher degree of hybridization in LCA will be required; such tools will also need to deliver improved validation, rapidity and scale to the design methodologies. Such hybridization may include a combination of streamlined methodologies [StreamLCA], economic input-output techniques [EnvLCAIO], traditional process LCA [ISO14064], object-based modeling [ThermoOOA], and other approaches including Design of Experiment techniques [FundDesExp] along with innovations in computational LCA

approaches [CompLCA]. Once successfully integrated, such a toolkit would provide designers with a multi-stage, layered approach that allows an initial narrowing of the design space into discrete subsets of parameters, whose resolution is then gradually increased for the most sensitive objects as the size of the design space is expanded. While the analytical and computational complexity of such an approach previously prohibited its widespread deployment, we have now reached a point where IT infrastructure and methods – including software development, programming techniques, and computational hardware – enable large-scale analysis and design exploration using commodity systems. By using technology to create a library of domain-specific methodologies and metrics, an integrated approach for ecosystem-scale life-cycle design can be achieved, and be applied to the use of IT in urban infrastructures.

Scalable and Configurable Infrastructure Building Blocks

To take advantage of the resources consumed during construction of the physical infrastructure, the sustainable IT ecosystem must provide high utilization in spite of shifting population and resource availability patterns. An agile infrastructure will be required to effectively adapt to changes over an extended operational life-cycle. As population growth expands urban centers, including a rising number of megacities, scalability becomes a key attribute of infrastructures. Some examples of urban infrastructure components where scalability as well as security, configurability, and reliability are important characteristics include power supply and distribution [SecGrid], and public safety/civil defense [MeshPubSafty], [CommPubSafty]. We propose that the desired security, quality, reliability and availability for next-generation urban infrastructures be achieved by enabling integrated supply-side and demand-side management and the right-sizing of infrastructure building blocks. In many cases, resource microgrids can provide efficiencies and other benefits that cannot be obtained via centralized infrastructures.

Microgrids consist of multiple discrete sources and sinks interconnected to an available resource pool. These pools can be depleted or replenished as required to provide flexibility to meet user needs. The emergence of

smaller heat/power generating systems and other scalable technologies provide novel opportunities to create solutions that improve the reliability and scalability of supply-side infrastructures in the urban environment. A rich sensing system (more on this later) can provide information on the state of these entities. Resource management can be automated, and the automation can be driven by policies to remove humans and human error from the process.

As an example, a grid of regional reservoirs can store rainwater for energy and human use. Water can be supplied from these reservoirs based on usage patterns and current storage capacity, as determined by extensive sensing. Today's centralized systems consume approximately 1.2MWh of electrical energy for every million gallons of water delivered. This energy use can be significantly reduced through the use of distributed and coordinated water microgrids. This case will be developed further in a later example. The same approach can be applied with similar benefits for other goods and services such as power, transport, and food.

Pervasive Sensing

With recent advances in semiconductor technology and circuit design, we have seen the deployment of autonomous, low-power, low-cost, wireless sensor nodes throughout the environment and especially within urban spaces. These nodes are designed to form a robust, ad hoc network known as a wireless sensor network (WSN). The low cost allows for large numbers of nodes to be deployed widely and densely to achieve so-called "pervasive sensing".

These same economics allow for a reduced labor strategy to deal with node failure: *fail-in-place*. An intelligent networking stack, along with judicious over-provisioning and system software that "routes around" failed nodes, makes the system essentially maintenance free. This is imperative, as the cost to repair and/or replace deployed nodes would be prohibitive for many applications. Low power design and careful budgeting and scheduling of energy use throughout the system facilitate operation by *energy harvesting* [EnScavWSN]. This greatly extends the range of applications, as it eliminates the need for grid power or prohibitively labor-intensive battery replacement.

Where nodes are grid powered, they can help other nodes in the network conserve energy. The ubiquity of mobile handsets can be leveraged to augment sensing and networking.

Pervasive sensing has many applications throughout urban spaces. Though this is a nascent technology, the literature already describes numerous useful applications in fields such as intelligent transportation systems [DFutureITS], [WSNITS], air quality management [AirScope], homeland security [SensBalls], [SelfOrgWSN], flood control [ModelFlood], and the monitoring of civil engineering structures [WSNStructH]. Furthermore, the potential of nanoscale sensors [IQSL] raises the possibility of embedding such sensors in the infrastructure during the manufacturing process, eliminating the need for sensor installation. Such sensors could be inserted in the pavement at intersections for traffic sensing and control; injected in the concrete or paint of buildings, bridges and overpasses to measure stress and fatigue; affixed to the coating on water and sewer pipes to monitor flow and leakage; or embedded in the sheathing or insulation of electric cables to monitor and control power usage.

Sensing serves three broad purposes. The first purpose is to detect events of concern to the owners and managers of the infrastructure. Events can be normal or abnormal occurrences and may vary in severity. Many can be ignored, but some require immediate remedial action. Events can be simple and directly sensed, such as the case of a failed component, or they can be complex and even synthesized from other sensors. The second purpose of sensing is to supply data to tools that aid management. These tools include systems for visualization of operating conditions; data analytics algorithms for drawing inferences, developing learning models, finding hidden faults or poor operating points; and decision support systems. The final purpose of sensing is in the implementation of autonomic control systems. The volume of data generated by a true city-scale WSN would be enormous and poses a challenge of its own.

Data Analytics and Visualization

Data analytics refers to statistical, data mining and machine learning techniques that transform and analyze data collected from various sources – including pervasive sensing networks. Pervasive sensing for a city-scale

infrastructure would generate large volumes of data related to its physical and operational state, including environmental sensor data (e.g. temperature), operational state of systems and devices (e.g. utilization values), and user demand (e.g. user requests sent to a data center, or load at a power distribution site). Data analytics techniques, which can be applied to real-time data streams or archival data, can enable six classes of outcomes: (i) event and anomaly detection; (ii) diagnosis and causality inference; (iii) discovery of patterns, rules, and associations; (iv) predictive models for automated control; (v) automated planning and scheduling; and (vi) summarization and visualization of operational state and metrics through dashboards. These techniques have been widely applied to various components of existing urban infrastructures including transportation, power, water, telecommunication, and networking. For example, intelligent transportation systems [DFutureITS] rely heavily on data analytics techniques for achieving cost-effective, high performing, safe and sustainable systems pertaining to land, water, air and space travel. These techniques are also being applied to assist in agent-based autonomous and distributed control of traffic [DFutureITS], traffic flow prediction, inference of human behavior (e.g. if a driver is drowsy), identification of crash patterns for better future designs, and automated resource allocation and scheduling [ITSC05Trends]. In power systems, data analytics are used to forecast power infrastructure parameters such as peak and minimum demand levels, costs related to generation, fuel consumption, transportation and transmission of power; to diagnose faults; and to model power quality [IntAlPower], [KBSPower].

A key contribution of the current work is the recognition that – with the help of information technology – pervasive sensing and data analytics methods can potentially be integrally deployed across different infrastructure verticals to obtain a more unified view of the urban environment. For example, the discovery of trends sensed within the water infrastructure could potentially inform operational choices related to the power infrastructure, which in turn might alter fuel demand and supply patterns. Another innovation required in the creation of sustainable IT ecosystems will be the incorporation of sustainability metrics into data analytics techniques.

Autonomous Control

Ultimately, the goal of the physical infrastructure is to meet the needs of users. Realizing this goal requires continual attention to sensor data reflecting system behavior, and manipulation of actuators that modify that behavior to keep the system within a proper operating envelope. Failures in system regulation can result in disruption of services and even serious damage to the infrastructure itself.

In traditional urban infrastructure components such as electrical grids or potable water systems, a control center staffed by humans monitors and controls the system. Given the complexity of such systems, human operators spend the bulk of their effort on maintaining the overall stability of the system. Their ability to optimize the system or to respond to local disturbances is limited.

Autonomous control is an attractive alternative. It is a mechanism by which an ecosystem can connect the sensed demands of users to the pool of supply-side resources available for consumption and can manage the infrastructure to deliver those resources efficiently. Autonomous controllers can often operate on larger volumes of sensor data, with larger numbers of actuators, and at faster rates than a human control center. This opens up the possibility of increasing efficiency and reliability of physical infrastructures, even to the point of being able to "do more with less".

To illustrate the applicability of autonomous control, we consider the vision of 'smart homes' – a key component of the urban infrastructure. Convenience is often mentioned as a benefit of control in a smart home (e.g., [MeshSmHome]), but ultimately the most compelling reasons for autonomous control would be management of expenses and conservation of resources. Sensors will be pervasive throughout this smart home: to monitor light, temperature, power and water consumption, room entry and exit (including unauthorized entry for security monitoring), and movement. The sensor network would likely be wireless and connected to one or more cooperating nodes to enable coordination throughout the home. Reducing heating or cooling in unoccupied rooms, detecting and controlling lighting, and control of instantaneous load are examples of benefits from distributed autonomous control in the smart home.

Case Study: Urban Water Distribution

To demonstrate the framework described above, we consider the case study of water distribution for a city with a population of 1.5 million spread over 1500 km^2. Our baseline case uses a single reservoir for the entire city. We compare this against an ensemble of micro-reservoirs. The EPA estimates that the fresh water consumption for such a city is upwards of 150 MGD (million gallons per day) [OutdoorH20US], including outdoor usage for swimming pools and landscaping with moderate evapotranspiration demand. As shown in Figure {WATERUGRID}, the phases of the water use cycle include *conveyance* from the source to the treatment plant, *treatment* itself, *distribution* from the treatment plant to the end users, and *wastewater treatment*. Summing the energy consumption per gallon across each of these phases determines the *embedded energy* for a gallon of water, of which distribution accounts for almost 30% in our baseline case and wastewater treatment including pumping is nearly 60%. While treatment plants benefit from economies of scale, distribution systems are generally less integrated. They can be optimized at design phase to reduce the embedded energy content and operational costs.

Small multi-purpose reservoirs are common in rural regions with highly variable rainfall that experience droughts and floods for domestic water use and small-scale irrigation. They are also common in some urban environments such as New York City. A reservoir ensemble can be hydrologically linked by the streams or aquifers that feed them. We propose that this approach can be applied on a city-scale, as shown in detail "A" of Figure {WATERUGRID}, to reduce the energy cost of water distribution. Such a configuration is scalable in the sense that additional reservoirs can be brought online to cope with growth in demand, improving variety and availability of water resources in the same network. Water can be traded between neighborhoods to balance supply and demand across the district. Moreover, since the proposed distribution system is tiered, there is no single point of failure, allowing water to be available during local power outages, assuming that each reservoir has sufficient static pressure head. Water microgrids also facilitate the isolation and containment of pathogens in the water supply.

The location and size of reservoirs can vary. In the present study we assume a total of 50 reservoirs, each with a capacity of 6 million gallons and servicing a population of 30,000. This microgrid approach enables the water to be

stored closer to the end-users so that small inline pumps can distribute water on-demand to local neighborhoods, as opposed to operating central pumping stations around the clock. Such a configuration has the potential to reduce the energy for distribution by about half (i.e., a 15% reduction in total energy embodied for conveyance), based on our estimates for pumping distances, which scale with the square root of the reservoir service area. Embodied energy could be further reduced by suitably locating the reservoirs at higher elevations. IT is an effective tool for simulating the results of design changes to large-scale infrastructures [CostRelAnytown].

Although our current focus is on distribution only, other components of the water use cycle can also be implemented at the microgrid level. As the use of reclaimed water rises, a similar infrastructure of gray water microgrids can reduce demand for fresh water and the associated costs of conveyance and treatment. A water microgrid infrastructure also lends itself to integration with small-scale distributed energy resources. Such measures can reduce the emissions footprint of the water use cycle.

While reservoir ensembles store a significant quantity of water for convenient use, they also have an effect on downstream flows and need to be balanced against the tradeoffs resulting from the number and density of their structures. Multi-objective optimization using ecosystem-scale life-cycle design provides the framework to evaluate such trade-offs. For example, while a large number of different sources may provide higher operational flexibility, the material and energy required to harness and deliver the water also increases with the number of sources. If the final demand is usually much smaller than the overall water supply, the additional flexibility enabled by a large number of water sources may never be fully utilized, but the additional embedded impacts – constructing a dam, building and laying out the piping networks, providing electricity to the pumps – will lead to a sub-optimal solution from a life-cycle perspective. Ecosystem-scale life-cycle design may be required to balance between investing the appropriate amount of resources up front and obtaining the highest return-on-investment during the use phase.

Having designed the water infrastructure for optimal life-cycle trade-offs, the resource microgrids can then be instrumented for pervasive sensing. Parameters of interest include direct monitoring of water quality, storage levels, water consumption, evaporative loss, and biological processes; as well as inferred monitoring of aggregated

parameters such as hydrological impact and public health indicators. Enhanced sensing can help in improving the monitoring and management of these systems with quick turnarounds and minimal disruption of service.

Data analytics techniques applied to monitored data enable identification of historical trends and prediction for future consumption, as well as the recognition of consumption patterns from which improved distribution methods could be discerned. Data analytics can also diagnose and suggest remedial measures for faults in delivery systems, pump houses and treatment plants, including pipeline leaks, pump malfunction, valve failure, and corrosion-related failures. According to the United Nations Development Program, 30-50% of urban water is lost in leaks [Watergy], so tracking and maintenance of lines is critical as utility districts grow. Data analytics could be further extended to business and sustainability impact assessments.

Active management and control based on monitored and mined data ultimately enables the long-term sustainability of local water supplies and adequate downstream flows. Pumps and valves can be operated at points of peak efficiencies to reduce energy demands and operational costs. Large upstream pumps can run during off-peak hours to fill reservoirs for a predetermined demand period, and downstream pumps can maintain pressure based on real-time end-user requirements. Beyond improvements at the end-use level, the presence of water microgrids can also allow for coupled operation of the water treatment infrastructure, leading to opportunities for savings in the design and management of large plants. For example, water treatment facilities in New York City consume more than 3000 GWh of electricity per year [FocusNYH20]. Even a fractional improvement in operation can offset a significant portion of the municipality's energy bill. Isolation of solid wastes before pumping waste water for treatment can also save pumping power; sensing, monitoring, and ultimately controlled removal of solids in the water streams is an example of how the incorporation of IT can further benefit the physical infrastructure.

Case Study: Urban Power

As a second case study, we will examine the need for the reliable and efficient generation and distribution of electrical power. As an example of how a sustainable IT ecosystem can enable such an infrastructure we consider

an Arizona city with a population of 48,000 that has an average electrical demand of 12MW. The city is powered from a grid primarily fed from coal-fired power plants. To reduce the impact of emissions and resource consumption, we propose a microgrid of sub MW photovoltaic (PV) installations and other micro power sources, distributed across the city and sized based on local utility demand. The microgrid will be grid-tied to provide excess power to the grid during the day and draw power from the grid during the night (or lean periods). Figure {PowerMicrogrid} shows a typical distribution of PV power plant installations, the inter-ties and the service area. During normal operation all power plants share the load. During outages or fault states, individual power plants can operate in islanding mode, disconnected from the region affected by a fault. Overall, the microgrid is connected to the power grid but retains the ability to operate in isolation within the limits of its generation capacity. Each PV power plant can be owned and operated locally with a level of oversight similar to how the ISO provides oversight today in the US. A service operator, regulated by the city, could manage the power distribution within the city. Metering at the inter-ties provides import and export data so that appropriate surcharges can be levied on power sold and consumed. Power from the network of micro PV power plants could be augmented by a Municipal Solid Waste (MSW)-based power plant. Considering average waste generation of 2kgs per person per day [EPA] with a lower heating value of 12.5MJ/kg, this power plant could generate around 4.5 MW of constant power. The balance demand in the city is managed by the network of 40 micro PV power plants each with a capacity of 600kW. Figure {SupplyDemand} shows the overall distribution of demand between the MSW-based power plant and the microgrid of PV power plants. Using current industry numbers for amortization, maintenance and cost per installed kW for MSW-based and PV-based power plants [MSWUS], in a grid-connected scenario, we estimate the cost of power at 5.3 cents per kWh. MSW-based power is 2.7 cents/kWh while power from a PV plant is 6.7 cents/kWh. The current rate for utility power in Arizona is 8.5 cents per kWh. Beyond reduced cost of power, implementation of such a microgrid would add flexibility to the distribution system, reduce transmission losses, and reduce carbon dioxide emissions by 0.13 MM tons annually.

Ideally, other modes of power generation can also be plugged into this system within agreed norms for power quality and availability. Local waste digesters or biogas units with generation capability can be added to the system.

Using methane storage, generation units can also be brought online during nighttime when the PV installations are offline. Local waste water treatment can also reduce water consumption by providing an opportunity for economical distribution of gray water, thus reducing demand for outdoor water use in landscaping, etc.

Future Work

We have discussed the case for ecosystem-scale life-cycle design, scalable and configurable infrastructure building blocks, pervasive sensing, data analytics and autonomous control for two city-scale infrastructure verticals: water and power. In future work, we will demonstrate the need for and the benefit of co-design of city-scale infrastructures. As our examples illustrated, multiple improvements are possible if the systems are designed and operated concurrently. For example, water should only be pumped, assuming usage allows, when excess power generation is available, and preferably from a renewable source. Furthermore, depending on geography, surface water can be pumped to higher elevation storage areas when excess power generation is available so as to provide power in periods when demand exceeds supply. Optimization of these types of joint systems will require sufficient sensing of supply and demand, and the use of IT techniques, such as data analytics, to predict likely supply and demand scenarios.

Conclusion

The ability to integrate IT into physical infrastructures provides a unique opportunity to improve the design and management of these infrastructures. This paper provides a framework for creating sustainable IT ecosystems: infrastructures wherein information technology is leveraged to achieve sustainability through need-based management of supply-side and demand-side resources. Future work will seek to apply and demonstrate the proposed framework to a diverse array of urban infrastructures.

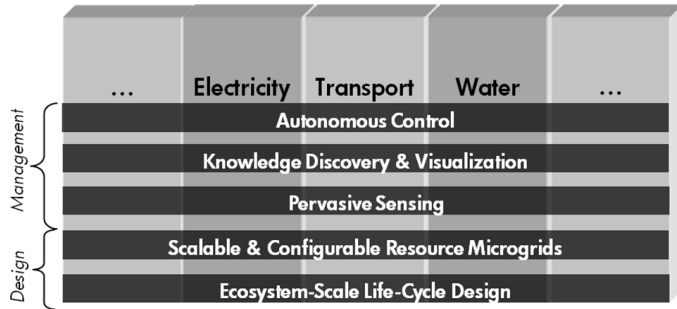# Figure {CITY2ARCH}: City 2.0 Architecture for a Sustainable IT Ecosystem
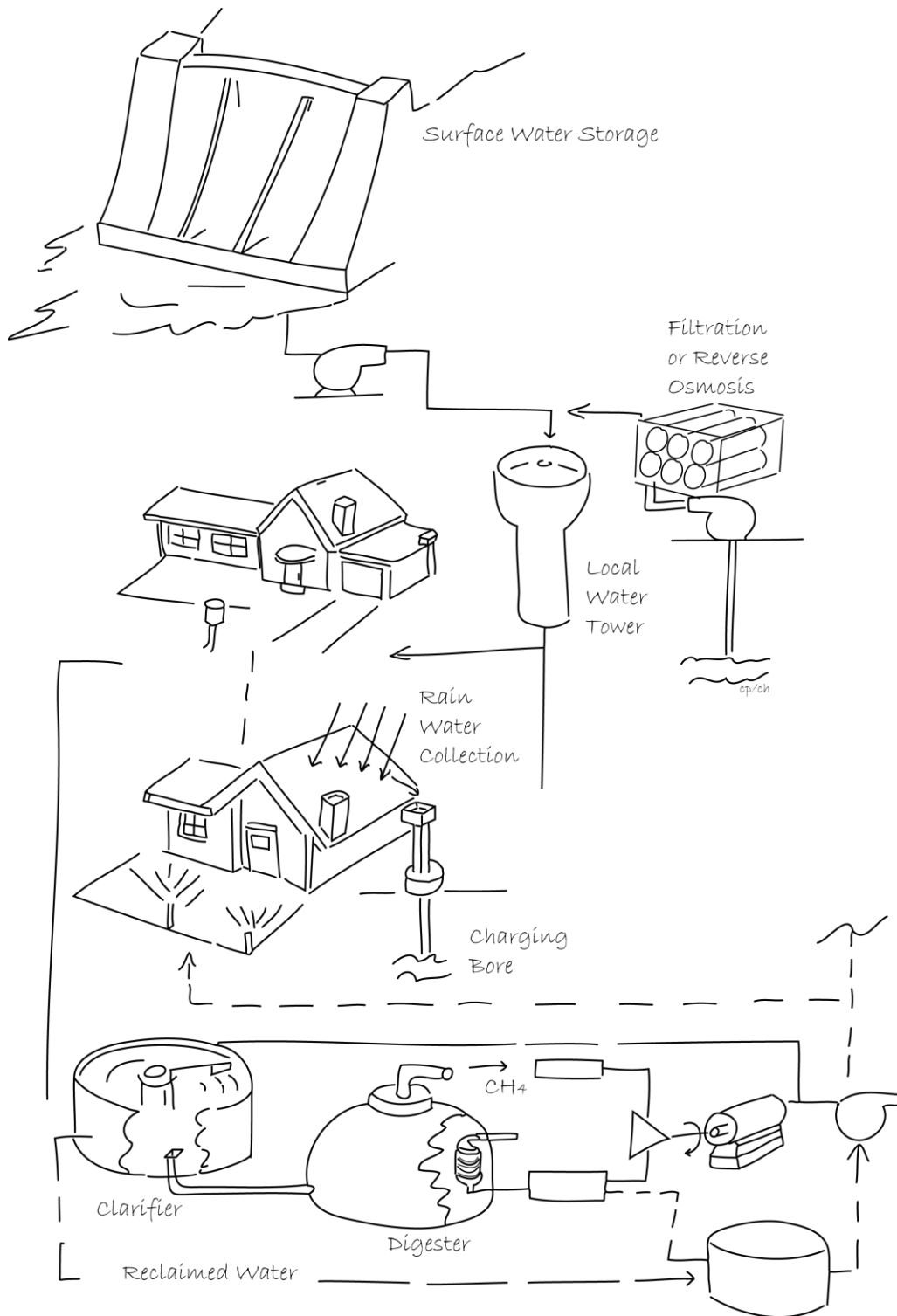
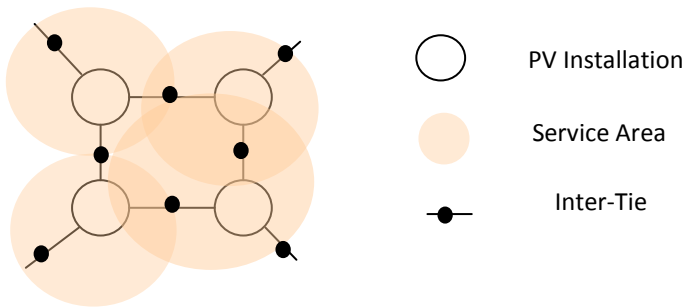# Figure {WATERUGRID}: Water Microgrid Architecture

Surface Water Storage

Filtration or Reverse Osmosis

Local Water Tower

cp/ch

Rain Water Collection

Charging Bore

CH₄

Clarifier

Digester

Reclaimed Water

Figure {PowerMicroGrid}: Power Microgrid

◯	PV Installation
⬤ (service area)	Service Area
●—	Inter-Tie

Figure {SupplyDemand}: Supply and Demand throughout the Infrastructure

Popln: 48000
Demand: 12MW

Waste Generated
98.2 MT per day

Power Produced
7.4 MW
6.7 ¢/ kWh

Power Produced
4.6 MW
2.7 ¢/ kWh

Waste to Energy Power Plant

Microgrid of PV Power plants
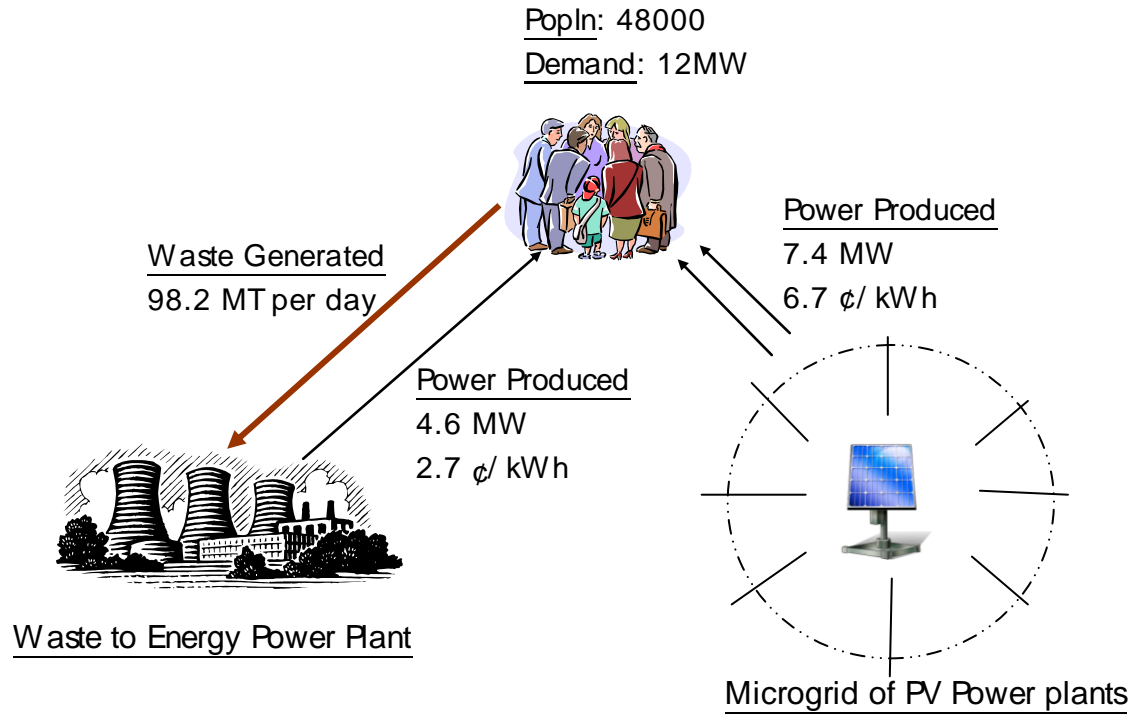
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