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Exploring Flexible Infrastructure Opportunities

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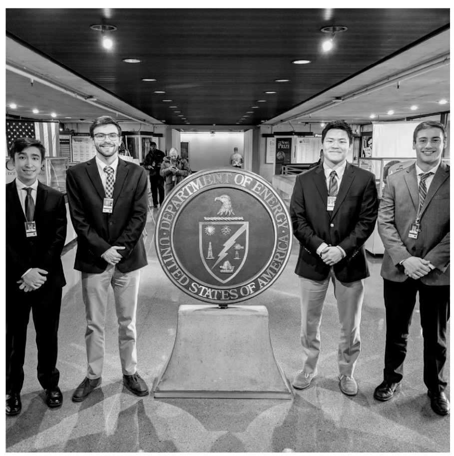

Abstract

America's infrastructure is in poor shape and requires substantial investment. An innovative approach termed flexible infrastructure promises to better meet the dynamic needs of communities in the future. Unlike traditional infrastructure, flexible infrastructure is multi-purpose and adaptable to changing demands over time and space. We explored the characteristics of a wide range of types of flexible infrastructure, including green roofs, electrical microgrids, and intelligent traffic systems. We characterized infrastructure based on stakeholder type, market maturity, and the risk and benefit streams. We concluded that federal, state, and local governments need to do more to incentivize and regulate the introduction of flexible infrastructure.

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WPI

Ivey (2005) defines infrastructure as publicly funded works that enable societies to grow and thrive. The term infrastructure is used typically to refer to roads and bridges but it also includes rail networks, ports, dams, levees, water treatment facilities, schools, and electric grids. Private infrastructure consists of works built by private companies for economic gain, however the line between private and public infrastructures has always been blurred. For example, broadband internet is an infrastructure that society needs to prosper, but it is owned and operated by private corporations (Ivey, 2005). The federal government was, however, involved in the initial research and development of the internet, and state and federal governments have subsidized its implementation to ensure access in rural and other underserved areas. Similarly, early electrical grids and the railroad networks were developed by private companies initially, but later their development was encouraged but closely regulated by government.

Traditionally, infrastructure has been developed and used for a single purpose (for example, roads are built to enable the transport of goods and people) and categorized based on purpose, such as transportation, energy supply, water supply and so on ("America's Grades", 2017). The American Society of Civil Engineers (ASCE) publishes a Report Card of America's infrastructure every four years that grades each of these categories with a letter grade A-F. A committee of 28 engineers with decades of experience evaluate reports and data, speak with technical and industry experts, and assign grades based on capacity, condition, funding, future need, operation and maintenance, public safety, resiliency, and innovation. In 2017, America's overall grade was a D+ (Figure 1). America's infrastructure is failing because of insufficient maintenance, the high cost of repair or replacement, and outdated designs that are no longer able to meet the dynamic needs of communities. ASCE estimated that over the next ten years America's infrastructure needs $4.59 trillion in investments to bring it up to acceptable conditions.

The Department of Energy (DOE) is one of America's many government organizations trying to fix America's infrastructure. The DOE promotes the development of energy efficient technology through research in various fields, including the development of infrastructure with energy-related consequences. The DOE is interested in exploring approaches to infrastructure that better meets changing conditions and demands.

Along with identifying promising types of infrastructure and their benefits, the DOE is also interested in assessing the potential markets for these examples. This includes finding methods to finance the development, operation, and maintenance of flexible infrastructure in both the public and private sector (e.g., tolls, user fees, and other revenue streams).

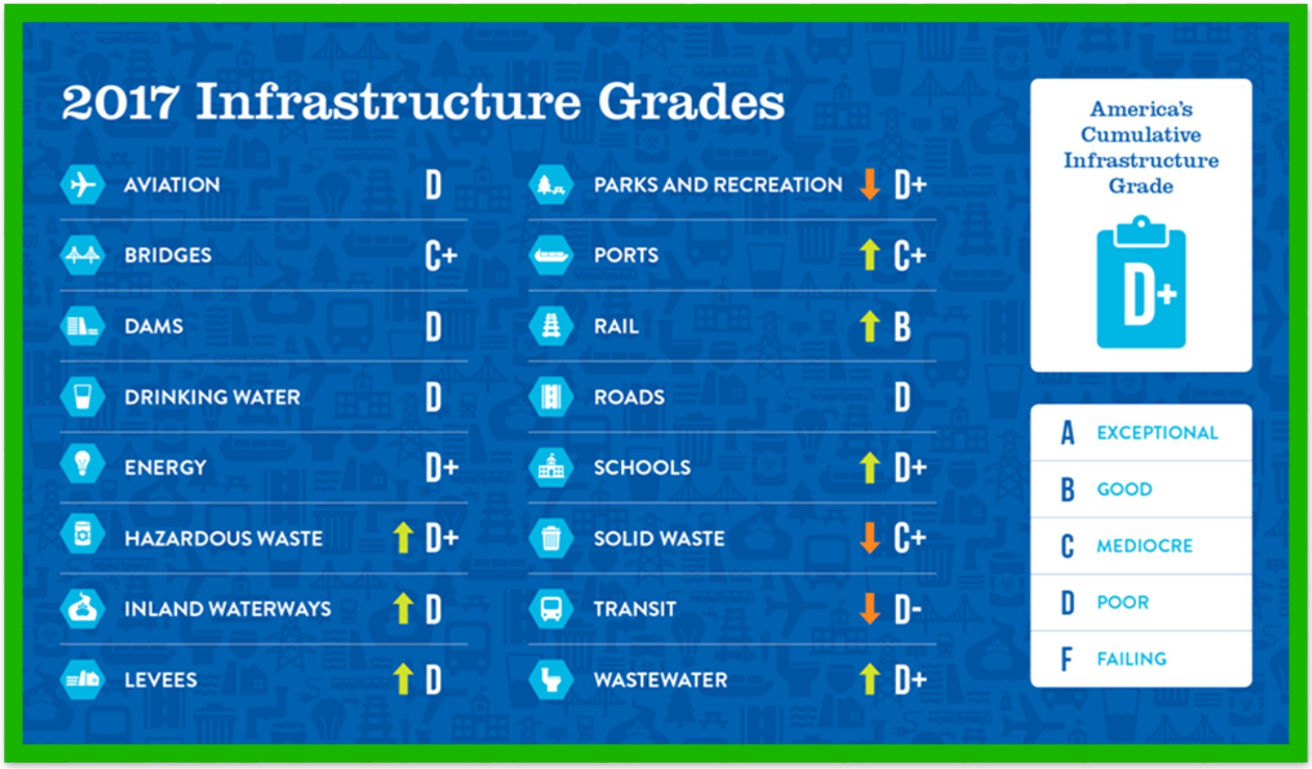

Figure 1. ASCE Report Card (American Society of Civil Engineers).

The DOE is currently researching how infrastructure systems can be designed to be flexible by meeting multiple purposes or being adaptable in time and location. Following Dispenza, Antonucci, Sergi, Napoli, and Andaloro (2017), we define infrastructure as flexible if it:

1. Serves multiple purposes;
2. Can be reconfigured or customized over time; and,
3. Is transportable to other locations.

Some forms of flexible infrastructure may meet all of these criteria, but we consider it flexible if it meets at least one.

Examples of flexible infrastructure include microgrids, green roofs, and water treatment plants. Microgrids are electrical grids that can operate separately and independently of the main electrical grid by generating and distributing energy from renewable and nonrenewable resources. Microgrids can be more robust in defending against cyber-attacks and dealing with changing energy production and demands by adding or removing energy sources at any time. A transportable microgrid system can easily be assembled and transported for communities without an active source of electricity. Green roofs combine sealant technology with natural vegetation to reduce the energy needs and stormwater impacts of the built environment. Water treatment plants can adapt to changing demands for different types of water quality to meet different needs at different times, such as for irrigation or drinking water. Conversely some traditional infrastructure may serve more than one purpose, but has not hitherto been called flexible infrastructure, such as dams which may provide energy, water supply, recreational opportunities, and flood control ("Multi-Purpose Water Infrastructure", 2017).

The goal of our project was to collaborate with the DOE to explore opportunities for integrated, flexible infrastructure that can equip communities with the tools to adapt to a dynamic world. We identified three objectives to achieve this goal:

1. Clarify the DOE's interest and role in developing, promoting, and implementing flexible infrastructure.
2. Conduct a comparative analysis of the advantages and disadvantages of flexible infrastructure types and funding mechanisms.
3. Develop profiles on the implementation of selected examples of flexible infrastructure within the United States.

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Approach to data collection and analysis

We engaged in an iterative process of literature review and brainstorming with DOE staff. We clarified the DOE's role and interests in flexible infrastructure (Objective 1) by researching examples of flexible infrastructure and discussing these in meetings with DOE staff. From these conversations and our review of the literature, we identified aspects of flexible infrastructure that were of interest to the DOE. These included: benefits, risks, stakeholders, life expectancy, and cost. These became categories we used to compare and assess the different types of flexible infrastructure we researched (Objective 2). These categories became the criteria which was the foundation for a matrix we used to document our analysis.

On the left side of this matrix we listed a range of flexible infrastructure assets and grouped them into categories drawn in part from the infrastructure types noted in ASCE's American Infrastructure Report Card. We omitted several types that did not directly relate to DOE's interests, such as schools and parks and recreation. Ultimately, we focused on three general types of infrastructure: Energy, Water, and Transportation (See Table 1). For each, we identified specific assets that demonstrated at least one of three types of flexibility (i.e., multi-purpose, adaptable over time, and adaptable to location). These assets are presented in Table 1, grouped by type and accompanied by a short definition.

Table 1. Examples of Types of Flexible Infrastructure

Infrastructure	Definition
Energy	
Standard Permanent Microgrid	A standard, permanent microgrid is a group of connected electrical storage and generation devices controlled by a single computer (Berkeley Lab, 2018). The computer optimizes the distribution of electricity and can disconnect the microgrid from the larger electrical grid in a process known as “islanding”.
Transportable Microgrid	Created by Prof. Nathan Johnson at Arizona State University, a transportable microgrid is a 40-foot shipping container that stores solar panels and a biofuel generator to supply electricity. The shipping container can be packed or unpacked in 30-60 minutes, moved and put to use wherever it is needed.
Flex Transformer	A Flex Transformer is a large power transformer connecting long distance power lines to local grids, and converting higher levels of energy to lower levels suitable for the needs of local grids (ABB Inc., 2018). A single flex transformer consists of a series of three smaller transformers that reside beneath large power line towers and local power lines. They are easily transportable and reconfigurable to convert different levels of electricity.
Combined Heat and Power with District Heating (CHP + DH)	A CHP facility provides power generation for an electricity grid and recycles the excess heat produced. Thermal energy is reused in the steam boilers of the power plant and delivers heat through a pipeline system (DH) to nearby buildings. CHP and DH have been implemented in many places, especially Nordic countries (Adjacent Open Access, 2017).
Transportation	
Smart Pavement	Smart Pavement is a slab of pavement that contains sensors and fiber optics. The sensors may be used for a variety of purposes such as monitoring traffic flow and opening or closing lanes. They can track vehicle speed and path of travel to determine if an accident has occurred. Smart pavement uses fiber optics to transmit information to transport agencies and nearby local emergency responders.
Adaptive Traffic Lights	Adaptive traffic lights differ from standard traffic lights because they self-adapt to reduce road congestion. Technologies, such as the Siemens Concert traffic sensors, allow traffic signals to adapt to traffic volume and congestion levels. Concert sensors are optimizable, help traffic flow more quickly and safely, and reduce CO_2 gas emissions by limiting idling (Siemens Industry Inc., 2017).

Infrastructure	Definition
Green Transit Building	Green transit buildings provide space for social gathering, reduce negative environmental effects, reduce energy consumption, and provide water transportation and collection. The Transbay Transit Center in San Francisco, CA serves these multiple purposes and includes bus transportation and storage, train transportation, green roofing, and green space (Transbay Joint Powers Authority, n.d.).
Water	
Hydroelectric Dam	Dams are very large structures that block water sources, typically rivers, creating a large reservoir of water for power generation, irrigation, recreation, and flood control. Exact configurations vary greatly from installation to installation, based on local needs and conditions.
Flexible Water Treatment Plant	Like standard water treatment plants, flexible water treatment plants treat water for human consumption and for irrigation. Flexible water treatment plants differ, however, in that they employ a modular design. They have a large, open customizable layout that allows for easy installation and the additional and replacement of components (Verdygo B.V., 2018).
Permeable Surfaces	Permeable surfaces allow water to flow through them. They reduce the volume of water runoff in urban areas which helps replenish aquifers, reduce erosion, and reduce contamination of streams and other water bodies (Green Building Alliance, 2016).
Green Roofing	Green roofs are designed with an impermeable membrane base that can be covered with vegetation. They help cool and insulate buildings, reducing energy consumption, and they reduce the speed and volume of stormwater runoff (Department of Energy and Environment, n.d.).

We created a table to expand our list of criteria for describing flexible infrastructure and their respective markets. This iterative process culminated in our final list of criteria presented below in Table 2. We organized our criteria into four categories: Features of Technology, Invested Parties, Asset Consequences and Asset Market. There are several subcategories within each, designed to help the DOE analyze and think about key aspects of any existing and new emerging flexible infrastructure. The matrix was developed by combining Tables 1 and 2, with the flexible infrastructure assets from Table 1 as the rows and criteria from Table 2 as the columns. Then we conducted brief background assessments of each asset to fill in the cells of our matrix.

As an example, consider how we used the categories described in Table 2 to describe and analyze one asset in Table 1—green roofs. When considering this asset, it is important to understand its many purposes, why it might be considered flexible, and its longevity. In this case, we determined that green roofs serve multiple purposes, for example green roofs provide insulation, reduce stormwater runoff, and reduce greenhouse gas emissions and that their longevity is around 60 years (Environmental Protection Agency, 2018) (General Services Administration, 2011).We found this type of information in publications by the Environmental Protection Agency (EPA) and reports they referenced. Next, it is also helpful to identify invested parties—those who pay or might be willing to pay for this infrastructure, and how they or others benefit from it. The answers to these questions may vary from one green roof project to the next,

Table 2. Examples of Types of Flexible Infrastructure

but we identified some of these answers through discussions with DOE economists, learning that many of the financial benefits are received by owners, but all the environmental benefits are received by all parties involved. The consequences of this asset can be described in terms of its benefits and risks. To identify these we again drew on EPA publications. When analyzing the market for green roofs, it is important to know the size of the market, what might prevent the market from growing (barriers of deployment), and what the asset costs in comparison to an alternative. We obtained this type of information from Green Roofs for Healthy Cities (GRHC) which conducts market surveys yearly, learning that green roofs are more expensive to install than other standard roofing options, but the market has been growing greatly in urban areas (Green Roofs for Healthy Cities, 2017). A list of all sources used to gather information for the matrix can be found in Supplementary Materials I our annotated bibliography.

Category	Definition
Technology	
Purposes	What service(s) is the infrastructure designed to provide?
Type of Flexibility	Is the asset multi-purpose, reconfigurable , and/or transportable?
Space	What is the asset's physical scale and location?
Life Expectancy	How long will it remain operable; will it soon be replaced by better technology?
Existing or Emerging	Does it already exist (is it in use) or is it emerging? Existing assets have already been installed and proven functional. Emerging ones have not been installed and are still being developed and tested.
Invested Parties	
Ownership Type	Who owns the infrastructure, is it owned directly or indirectly?
Investors	Who funds the design, development, operation, and maintenance of the infrastructure? Are these parties public, private, or quasi-private?
Other Stakeholders	What parties receive the benefits or bear the risks? Stakeholders include all interested and affected parties.
Asset Consequences	
Benefit Streams	What are the financial, social, and environmental benefits and advantages?
Risk Streams	What are the financial, social, and environmental risks, disadvantages, or downsides?
Revenue Streams	What are the sources of revenue from the asset?
Asset Market	
Market Size	What grouping of characteristics describes the value of installations in the market, the number of installations, and whether the market is growing or shrinking for a specific infrastructure? If the market is emerging, this may be blank.

Category	Definition
Initial Cost	What is the capital costs for design and installation?
Non-Flexible Standard Cost	What is the initial costs of older non-flexible infrastructure that is being replaced?
Market Competition	What is the number and valuation of companies competing to create this?
Payback Period	What is the time to recoup initial investment?
Incentives	Is there a supplemental reward that is motivation for constructing or using a type of flexible infrastructure?
Barriers to Deployment	Are there obstacles that prevent an infrastructure project from being implemented aside from risk streams?

Information about a single infrastructure asset can be found in the matrix by reading a row across and patterns and trends can be found by reading a column down which compares each asset by the same criteria. This allowed us to find assets with unique characteristics and allowed us to find patterns or commonalities amongst assets.

After completing this initial analysis of 11 different assets, we chose three assets (one from each infrastructure type) with unique characteristics, developing more detailed profiles of each (Objective 3). These included microgrids, smart traffic systems, and green roofs. To create these more detailed profiles we reviewed case studies and interviewed experts who had experience with the assets (See Supplementary Materials B for a list of interviewees and Supplementary Materials C-H for our interview questions).

Results

Our completed matrix (Table 3) provides a tool for the DOE's early research and development of flexible infrastructure. It provides a more organized way to analyze and talk about flexible infrastructure assets. It is designed to be a living document that is never truly completed, so when flexible assets emerge and/or evolve, the matrix can be updated. Its use will help the DOE decide what flexible infrastructure assets are worth researching and investing in.

As the matrix was developed, we began to see possible trends that warranted further exploration. For example, one hypothesis about the criteria that emerged in the matrix was that infrastructure directly owned by a single person or business seemed more likely to be developed than something indirectly owned by multiple parties. We saw this with green roofs and microgrids, both being developed and installed across the U.S. at high rates, and both typically owned by an individual entity. Contrast this with large power transformers for use in the U.S. national grid; these would be indirectly owned by investors and tax payers and have seen little to no development and implementation. This could be because of other criteria also, but ownership was the easiest to analyze with information available to us.

Another hypothesis we had about a pattern from the matrix is that multi-purpose flexibility may be valued more than flexibility over time or flexibility over location. Many forms of multi-purpose flexible infrastructure such as green roofs are being rapidly developed. Conversely, assets only adaptable over time or transportable, such as transportable microgrids, are seeing minimal or no development. Some forms of flexible infrastructure are both multi-purpose and adaptable to changing demands over time, such as standard microgrids, which are seeing development.

The last pattern we saw that prompted further examination showed that infrastructure assets that were incentivised seemed to develop at a faster rate than non-incentivised ones. Parties interested in installing a green roof in an urban area may receive aid (rebates or tax credits) from their local government which might contribute to their fairly rapid rate of development. Parties interested in installing a microgrid may have a harder time receiving such incentives as the incentives vary from state to state, which could be a factor in their slower rate of development.

Because these categories — multipurpose-flexibility, ownership, benefits and incentives — seemed like they might be important factors in the development of flexible assets, we chose to profile assets which varied across these specific criteria.

Table 3. The comparative analysis matrix

			Degree of Flexibility					Benefit Streams		
Classification	Infrastructure Assets ↓ ll Criteria →	Purposes	Multi-Purpose	Adapt (time)	Adapt (location)	Description	Stake Holders	Financial	Social	Environmental
Energy	Standard Permanent Microgrid(DERMS)	Provide electricity Store emergency power Optimize energy cost	X	X		Adapts to energy demand	Government Agencies Local Consumers Power Companies	Reduce cost of power for consumers Optimizes use of resources Reduces the impact of downtime due to power outages		Decrease greenhouse gas emissions
	Transportable Microgrids	Provide electricity Store emergency power Optimize energy cost	X		X	Adapts to energy demand Allows for reallocation based on need	Government Agencies Energy Consumers Military Non-profit disaster relief organizations	Provides power to an area without power Optimizes use of resources		Decreases greenhouse gas emissions
	Flex Transformer (Large Power Transformers by ABB)	Convert electricity from high to low power Converts electricity from long distance power lines to local power grids		X	X	Adaptable to meet demands Allows for reallocation based on need	Energy Consumers Power Companies Governments	Reduced downtime in case of failure compared to standard LPTs Temporary installation allows for reallocation		
	CHP with District Heating	Provides electricity Provides water heating for power plant operation Indoor and water heating for consumers	X				Government Agencies Local Consumers Power Companies	Reduce cost of operation High efficiency compared to other energy generators		Decrease greenhouse gas emissions
Transportation	Smart Pavement (Integrated Highways)	Provides information on vehicle accidents, traffic, speed. Can be used for network connectivity. Road transportation	X				Local Government Agencies Local Community Local Businesses	Life expectancy of smart pavement is longer than standard roads	Faster EMS response time	
	Self-Adaptive Traffic Light (Sensors)	Provides information on vehicle accidents, traffic, speed. Optimize traffic flow	X			Adapts to the changes in traffic patterns to help manage congestion	Local Community Local government, Commuters	Reduces commute time Reduce the amount of gas commuters use	Less wasted commuter time Decrease in accidents	Reduces vehicle emissions
	Transit Green Building (Transbay Saleforce Transit Center)	Transportation hub Green social area	X			Adapts to transit demands	Local Community Tourists Government agency Commuters	Provides business space Provides transportation jobs Convenient hub of transportation	Provides recreationalspace, shopping, eating	Reduced greenhouse gas emissions
Water	Hydroelectric Dam	Prevent Flooding Provide water for irrigation Provde water for recreation Generate energy (hydropower)	X				Local community Power Companies Government	Reduce cost of water Reduce cost of energy compared to standard options	Provides recreational water space	Provides habitat for wildlife
	Flexible Water Treatment Plant (Verdygo)	Clean water intended for human consumption Cleam water intended for industrial/agricultural use	X			Modularity in design of plant allows for easy removal and addition of new water purifying technologies based on changing needs	Local community Water treatment utility	Cheaper operating costs compared to standard WTPs Cheaper expansion		
	Permeable Surfaces	Walking and driving surface Retain stormwater	X			Adapts to climate and weather	Local community Local government	Reduces water treatment cost Less accidents due to decreased amount of ice		Reduce stormwater runoff impacts Reduces urban heat island Can be made out of recylced materials
	Green Roofing	Provide shelter Provide insulation Reduce CO2 emissions Retains stormwater	X			Adapts to climate and weather	Local community Local government	Increased life expectancy compared to standard roofing options	Venue for gatherings Can be used as a garden to grow certain herbs	Reduce stormwater runoff impacts Increase biodiversity in urban areas by creating spaces for wildlife

Risk Streams	Installation and Maintenance				Market Uncertainty						
Financial/ Social/ Environmental	Installation Description	Maintenance Description	Life Expectancy	Uncertainty of technology	Market Size	Type of Market	Initial Cost	Non-flexible Standard Cost	Payback Period	Incentives	Ownership
Significantly more expensive than alternatives	May reuse existing electric grid technology in installation	Check and replace faulty sensors or electric storage device like batteries, upgrade components	The whole system similar to the larger grids can last upwards of 60 years with maintenance	Computerized monitorization technology is relatively new with no replacement currently known (Low)	1,869 microgrids installed worldwide Current market value at $13 billion, forecasts expect $25 billion by 2025 Growing market	Existing	Varies based on installation size and needs from $250k to $100m	Varies too greatly to estimate	5-10 years	State based renewable energy tax credits	Direct or collective
Lack of a constant demand	Trained indivuals can install in as little as 30 minutes,deploy from storage crate		Varies as they aren't permanently installed and instead are only temporarily installed	Technology is new with no replacement currently known or theorized (Low)	No market currently, as it is in development	Emerging					
Significantly higher entry cost than standard LPTs	Installed in groups of 3, easy installation trained operators can install in one day	Maintenance is only required if one of the LPTs fails, requires failing one to be removed and new one to be installed	Around 40 years	Technology is new and no replacement can be found currently (Low)	No market currently Expected to be a growing market	Emerging		In the $ millions depending on individual case	5-10 years	Government grants for further R&D	collective
Longer return on investment	Large scale construction of building, also requires building district heating pipline system	Maintaining and inspecting major CHP equipment such as boilers and DH piping	Around 20-30 years	Technology has been around for a while and therefore other alternatives may be used (Medium)	Billions of USD	Existing	2-8 Million USD	2-8 Million USD	2-10 years	Sometimes	Direct or collective
Twice as expensive as normal pavement Privacy complaints	Individual slabs, sensors, and fiber optic cables installed over time	Requires upgrades to meet demands. Sensors must be checked and replaced over time.	About 100 years depending on location and climate	Technology is brand new and therefore there are no alternatives (Low)	$17 Billion in 2018 and estimated increase to $40 Billion by 2023 Two strips of pavement installed in US		$20/sqft	$10/sqft			
Cannot solve traffic issue alone, requires group investment	Installation requires prior analysis and investigations about traffic in area being installed	More often than traffic ligths that run on time schedule, less often than 4th-generation adaptive traffic lights	Same as that of a traffic light 15-20 years	Technology is relatively new, alternatives include 4th generation adaptive traffic lights that can analyze patterns but are not self-adaptive (Medium)	Millions of USD	Emerging	Tens to hundreds of thousands of USD	Tens of thousands of USD			collective ownership
High upfront cost	Construct large building that connects to transit lines such as train tracks or bus routes	Requires upgrades to meet demands Building failures in structure and safety Vegatation maintenance	Around 50 years or more	Technology has been around for a while and therefore other alternatives may be used (Medium)	Hundreds of billions of USD, more than 100 large scale transit centers in the United States	Existing	2.2 Billion - 6 Billion USD	0.41 Billion USD	Uknown - 20 million savings per year	Salesforce Transbay Joint Powers Authority - land formerly owned by the state	collective - group investment
Dam must be near consumers Displacement of communities May destroy entire ecosystem Reduce biodiversity	Dams require years and immense coordination and adherence to federal regulation to install properly	Dams require constant tests and analysis to ensure nothing catastrophic occurs	Around 50 years	Technology has been around for a long time(over 130 years) and therefore many alternatives are known that are less invasive. (High)	2,400 hydroelectric dams in U.S. Slow growing market world wide, but shrinking market in U.S.	Existing	Billions of dollars	Billions of dollars	10-20 years	Renewable energy tax credits	collective
Requires extra piping/sewage system	Installation requires modularity planning and constructing a large open water plant	Upgrades are frequent and common, happening every few years	flexible plant is a basis for newer technology, the life expectancy is as long as the company running it continues to do so	Technology is new, and no known alternatives are currently being explored therefore this technology is a safe investment (Low)							
More expensive to install than alternatives Require more maintenance	Can be installed by machine or hand. Requires more work to prepare area for installation. It can take up to a week to cure after installation.	Needs to be cleaned a couple of times per year. Replaced if surface becomes blocked and is not permebale	Around 20-30 years	Technology has been around for a while but no known alternatives (Low)	$12.13 Billion in 2015 increase to $22.17 Billion by 2026 Growing market	Existing	$4.00 - $6.00 per sqft	$2.50 - $4.00 per sqft		Many incentives across the US	Public roads are owned directly.
More expensive than standard roofing options	Plants need to be grown, in some cases done in a lab otherwise requires 2 growing seasons for plants to reach maturity	Plants requires watering and weeding every 2-3 months for the first year. 6 month intervals after	Around 60 years	Doesn't require technology and there are no known alternatives (NA)	$5450 million in 2017--> $9680 million by 2022 (worldwide) Growing market	Existing	$10/square foot for simpler extensive, $25/square foot for intesive designs	$3.50-$5.00 per s	6.2 years	Federal, State, City Tax breaks, Private donations, or incentives	Direct

Microgrid Profile

What is a microgrid?

Rising interest in energy management and energy optimization systems has led to the development of the microgrid, a group of connected electrical loads and generation devices that acts as a single entity (Berkeley Lab, 2018). The individual generation and storage devices may differ from one implementation to the next. Microgrids benefit communities where national electricity distributors become incapable or disadvantageous.

Microgrids have multiple purposes:

- Provide electricity to consumers
- Optimize cost of electricity generation and distribution
- Efficiently integrate distributed and renewable generation
- Act autonomously from the main grid

Key Findings

- Microgrids are an emerging flexible infrastructure that is both multi-purpose and adaptable over time.
- They provide unparalleled benefits in energy management, and not only to the owner but also to the government, electric utility, and local community.
- The definition of microgrid is in flux as this infrastructure is starting to scale down to communities.
- A specialized workforce of engineers is required to maintain and operate a microgrid which is not feasible for community microgrids.
- Community sized microgrids involve more invested parties which inhibits development by making financial planning complex.
- Incentives help to foster the development of microgrids by overcoming the stark upfront investment.
- Microgrids reinforce the larger trend of multi-purpose flexibility being valued more than adaptability over time.

Components of a microgrid

Microgrids have many different configurations but Figure 2 shows a general schematic, therefore not all microgrids will have the same components presented here. The microgrid manager found in the center of the figure represents the autonomous computer that operates the microgrid. This computer makes calculations every millisecond to determine the most efficient way to generate electricity. Some microgrids may not have an autonomous computer and instead use semi-automated systems supervised by live operating staff. Electricity is generated in three possible ways although microgrids are only required to have one. First, electricity can be generated from non-controllable sources, such as photovoltaic cells which produce electricity on an intermittent schedule based on location and weather. Second, electricity can be generated from controllable generation which generate electricity in a deterministic way. Third, electricity can be purchased from the utility grid which is connected to the microgrid through a coupling point. The microgrid is also connected to loads which are processes that consume electricity such as powering a light bulb. The microgrid manager has to provide enough energy for all the loads to be satisfied without wasting energy, so it turns on and off separate components when needed to minimize the cost of electricity. Excess electricity may be stored in battery storage and used at peak demand to decrease cost.

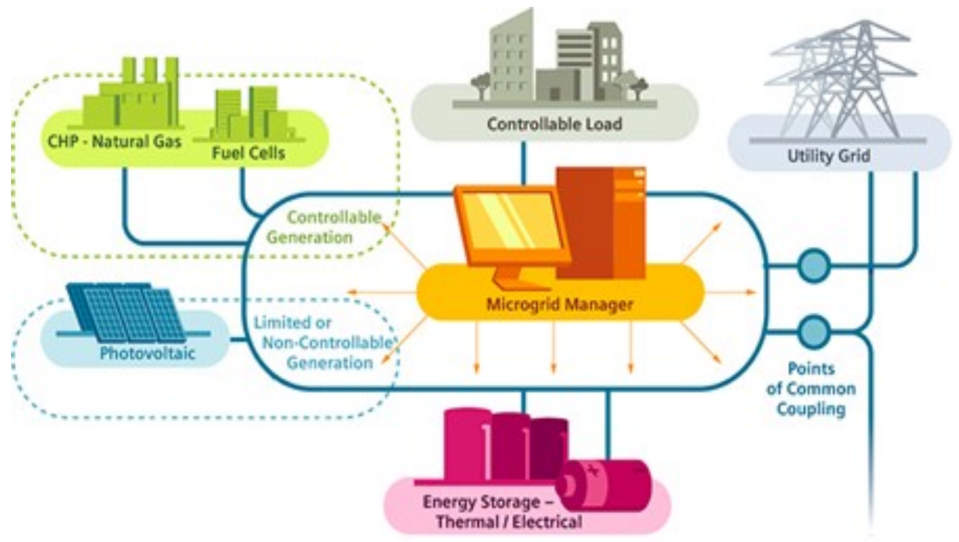

Figure 2. Generic microgrid design adapted from (ICICI Securities, 2018)

Cases

Figure 3. Blue Lake Rancheria solar array (Whiteside, 2018)

Blue Lake Rancheria (BLR) in Humboldt County, California is a Native American reservation with a microgrid that provides power for its government offices, critical infrastructure, outdoor lighting, security cameras, and economic enterprises. The microgrid at BLR was installed in 2015-2016 and achieved final commissioning in July 2017 according to their sustainability director, Jana Ganion (personal communication, November 20, 2018). The microgrid cost $6.3 million and was installed with financial assistance received through a grant from the California Energy Commission for $5 million dollars. A solar array was installed at the same time and is included in the cost estimate. BLR now receives 25 to 40% of their daily energy needs from their solar array, and excess solar energy is stored in batteries with a capacity of 950 kWh. Ganion estimates that the project saves the community $150,000 - $200,000 a year, reduces CO2 emissions by 150 tons a year, and has created 10% more jobs.

Princeton University since 1996 has used a microgrid with cogeneration to serve the energy needs of a campus with 8,000 students and staff (Leonhardt, Bourgeois, Bradford, Gerfow, & Martin, 2015). According to Ted Borer, the energy plant manager at Princeton (personal communication, November 19, 2018) the cogeneration system averages 75% - 80% efficiency, however the cogeneration plant cannot meet campus's peak electric demands, so during the peak of the day, some electricity is usually purchased from the regional grid. Unlike BLR's system, the Princeton mcrogrid has no electric storage but uses thermal storage instead. When electricity prices are low, electric driven chillers and cooling towers are operated to cool 2.6 million gallons of water down to 31ºF. The cold water is stored in an insulated above ground tank until electric prices are high, later in the day. When electric prices are high, Princeton shuts off the electric chillers and cooling towers and uses the stored cold water to cool advanced research devices, such as electron microscopes. Finally, the Princeton microgrid successfully 'islanded' during Hurricane Sandy and served as an emergency response shelter during the aftermath when surrounding communities were without power for days.

Figure 4. Princeton cogeneration plant (Cohn, 2015)

Figure 5. Alcatraz solar array (Office of Renewable Energy and Efficiency, 2017)

Alcatraz, a famous federal prison transformed into a national park, is located in San Francisco, California. Its microgrid powers lighting, a media office, and golf carts that traverse the island. The system cost $7.1 million to install and was completely funded by the United States American Recovery and Reinvestment Act (Office of Energy Efficiency and Renewable Energy, 2017). The microgrid was installed in 2012, and a large solar array was installed at the same time. Any excess power generated is stored in a 1,920 kWh battery system. The microgrid has reduced fuel consumption by 45% (Office of Energy Efficiency and Renewable Energy, 2017). This translates to 32,000 gallons of fuel a year and a reduction of 325 tons of CO2 a year (Boenig, Castellini, Genter, Milestone, 2015). According to Laura Castellini, the Sustainability Coordinator for the park, the microgrid is undergoing maintenance and will reopen in early 2019 with a goal of obtaining 60% of daily energy from the solar array.

Discussion

Microgrids are a type of flexible infrastructure that exhibits multiple types of flexibility. First, microgrids are **multi-purpose**. First and foremost, like larger grids, they **provide and transport electricity** to their consumers. But another purpose of microgrids is to **provide resilience** and continue supplying electricity if the larger power grid is down (Department of Energy, 2014). This fully autonomous mode of operations is known as "islanding". Another purpose is the **optimization of energy generation**, often integrating alternative energy sources previously deemed "unreliable for traditional grid use" such as photovoltaic cells or wind turbines (Department of Energy, 2014). Optimization is also achieved through purchasing electricity at night when electricity rates are cheap, and storing it for use when electricity rates are higher during the day.

Second, microgrids are flexible because they can **adapt to changing demands over time**. Microgrids installed today may use fossil fuel generators, but as fossil fuels are phased out and become more scarce, other forms of electricity generation such as solar arrays can help meet demand by connecting to the microgrid.

The benefits of microgrids are valued differently depending on the context. Parties interested in decreasing their greenhouse gas emissions typically value the optimization of energy generation because their typically unreliable renewable energy sources can be used to their maximum potential. Other parties may value microgrids in that they **allow independence from the national grid**. Parties in rural areas without access to power lines or in places where the larger grid is unreliable due to natural disasters, would value islanding capability. All are likely to value the economic benefits; microgrids **decrease the cost of electricity** by optimizing its generation and distribution.

The microgrid owner receives the benefits mentioned above, but many other parties also receive benefits. By optimizing energy generation and distribution, cost and fuel use for general operation decreases, **indirectly benefiting the local community and environment** by decreasing greenhouse gas emissions. The ability for the microgrid to island may indirectly benefit the local community, as places with microgrids can **serve as emergency centers**, providing a base of operations for emergency response and providing shelter for people temporarily displaced by the event. Another consequence of islanding is that the larger grid becomes more **resilient to natural disasters and cyber attacks** (Department of Energy, n.d.). This directly benefits the government at state and federal levels, and benefits electric utilities by creating a more reliable grid that may be able to recover more quickly from disasters and return power faster to consumers (Department of Energy, n.d.). This faster restoration is done by larger microgrids that could "black start" the local utility grid plants according to Borer.

Microgrids are an **emerging set of technologies** in an existing market. Their main purpose is to replace the local distribution of energy that larger grids already achieve. However, the technology itself is still being developed and tested. The concept of energy optimization is not new (e.g., many may know to run washers and dryers at off-peak times), but the technology has finally advanced to the point that optimization can be more readily automated. Microgrids are not intended to displace the larger national grid, but they are changing the endpoints that the larger grids connects to.

Since microgrids are an emerging set of technologies, they lack clear consensual definitions. Some argue that systems without centralized computers can be called "microgrids" while others see computers as a necessary defining feature. As showcased above in each of the three cases, the microgrid may be configured different ways. Individual implementations may have different loads and different combinations of generation, and storage devices.

Microgrids may also vary in size. For example Princeton's microgrid provides power for thousands of students, whereas Blue Lake Rancheria's microgrid provides power for only a few hundred guests at the casino. Microgrid researcher Miguel Heleno noted that microgrids were first developed on college campuses, but as this technology has become more feasible, other communities and neighborhoods of various sizes are looking into the implementation of microgrids (personal communication, November 19, 2018).

A lack of clear information on this asset may be one of the barriers to widespread development and deployment. Both Borer and Heleno agreed that there is little clear and publicly available information about microgrids. Better defining and explaining consumers' options and documenting best practices for installation would greatly help with the acceptance and development of microgrids. Heleno explained that providing reliable information is difficult, though, as the technologies are currently in flux.

Another barrier for parties interested in installing a microgrid is the **sheer complexity involved**. After installation, microgrids require human oversight and maintenance to make sure the microgrid is operating as efficiently as planned, according to Heleno (personal communication, November 19, 2018). Microgrids require not only a large financial investment but also a significant time investment. Moreover, qualified engineers and operators are required to maintain and operate a microgrid to maximize the benefits. Operators are typically skilled tradespeople, and electrical engineers specializing in medium voltage lines and integration engineers with knowledge of all individual components connected to the microgrid are required to manage the microgrid. Even in smaller communities such as Blue Lake Rancheria, microgrids require a specialized workforce for proper maintenance and optimization, according to Ganion. Castellini also emphasized the need for a specialized workforce. She explained that the Alcatraz microgrid shutdown in early 2018 because of improper maintenance of the batteries during the previous 5 years. This barrier is not as significant for campuses and universities that already have experts on site, but for other communities this can pose challenges and be costly.

Despite these barriers, some state government agencies such as the California Energy Commission (CEC) are giving **incentives in the form of grants to foster the development and deployment** of microgrids. The Blue Lake Rancheria microgrid received a grant of 5 million dollars from the CEC in order to showcase how effective a microgrid can be for a small community. By creating this microgrid Blue Lake Rancheria is hoping to inspire and show other prospective owners how well microgrids could work for them. The CEC hopes to see an increasing number of microgrids in California in order to increase energy reliability in an area that is prone to natural disasters. In addition the CEC aims to reduce greenhouse gas emissions in California to meet the state's zero net emissions goal by 2045 (Leila Mead, 2018). Blue Lake Rancheria shows this is possible, according to Ganion, since it will be zero net emissions by 2025-2030.

Much could be learned from a larger study of microgrids across the United States, but in our own brief analysis, three important issues emerged:

1. **The benefits of a microgrid are unparalleled among energy management systems**, but microgrids come with a large overhead, including the need for a specialized workforce to install, operate and maintain these systems. Government incentives might offset these and other costs. Currently, only a few states are offering incentives, however more incentive programs at the state and national level might jump start more widespread development.

2. **Multi-purpose assets may be valued more than those adaptable to changing demands over time**. Although microgrids in all three cases had both forms of flexibility, those we interviewed said they were installed mainly to optimize energy use and generation. The microgrids at Blue Lake Rancheria and Alcatraz aimed to increase the efficiency of their solar arrays, while the microgrid at Princeton aimed to increase the efficiency of their cogeneration plant. The prospect of being able to adapt to changing demands of time was not irrelevant, however, as all three cases had plans to develop their microgrid further. According to Ganion, Blue Lake Rancheria aims to install a microgrid that operates their water treatment plant more efficiently which will be integrated into their main microgrid (personal communication, November 20, 2018). This adaptability to changing demands was not the reason they installed the microgrid in the first place, however. This may be due to the inability to evaluate adaptability over time as compared to the evaluation of direct multi-purpose benefits which can be quantitatively calculated prior to installation. From the cases we reviewed, it appears that those choosing to install microgrids emphasize the multi-purpose flexibility of the asset and the ability to adapt over time is an afterthought.

3. **The large number of stakeholders in a microgrid makes development and financing complex**. All microgrids examined in the three cases had a single owner and a relatively defined consumer base. Financing was complex, but relatively straightforward. As microgrids are installed

in larger communities, the business models will become increasingly complex with direct ownership, multiple owners, and multiple consumers. This offers new opportunities but will also pose a variety of barriers. Questions such as who will pay for maintenance and who will own the equipment no longer have simple answers. We expect that a variety of business models for microgrids will emerge in the next several years, and have started to see development of a utility owned model in places such as Rutland, Vermont where the electric utility owns and operates the microgrid and shows that this issue can be overcome through collaboration between invested parties (Clean Energy Group, 2018). However, widespread adoption of microgrids is likely to be slow until the utilities, communities, and other investors have a clearer picture of the likely risks and benefits.

In summation, microgrids are at a pivotal step in development. Microgrids are now becoming scalable for smaller communities. The benefits that microgrids bring maximize the effectiveness of renewable energy sources and increase grid resilience across the United States. These benefits come with a few downsides, most notably the complexity of a microgrid is too large for most small municipalities to handle. In order to develop more microgrids more incentives need to be given out and utilities need to take an active role in shaping the standard economic model for communities.

Smart Traffic Systems Profile

What is a smart traffic system?

Research to remedy traffic issues, such as congestion, has lead to the development of smart traffic systems, which have varying configurations and therefore no clear definition. We present the definition that a smart traffic system is an interconnected system of sensors, configurable traffic lights, and a centralized computer that collects data from the sensors and allows personnel to make decisions that will solve a traffic problem (Smarter Cambridge Transport, n.d.). There are a wide variety of sensors used in smart traffic system but in this analysis we will only consider two groups, intrusive and non-intrusive road sensors. Intrusive sensors require implementation into or on a road which requires costly installation, but provide more accurate information (Ibanez, Zeadally, & Castillo, 2018). Non-intrusive road sensors are found around the road such as at road level, above the road, or on poles nearby and are cheaper but provide less accurate information (Ibanez, Zeadally, & Castillo, 2018).

Smart traffic systems may have a range of purposes:

- Reduce traffic delays
- Reduce greenhouse gas emissions
- Improved accident response

Key Findings

- Smart traffic systems are an existing infrastructure in an existing market.
- The benefits that smart traffic systems provide reduce traffic congestion, emissions, and fuel consumption.
- Emerging technologies are competing with the need for smart traffic system sensors.
- The lack of a standard for performance of traffic lights creates a barrier to implementation.
- Smart traffic systems aren't being heavily implemented due to rapid advancements in technology.
- Due to rapid advancements in technology, resources will not have the expertise or skills to maintain these technologies.

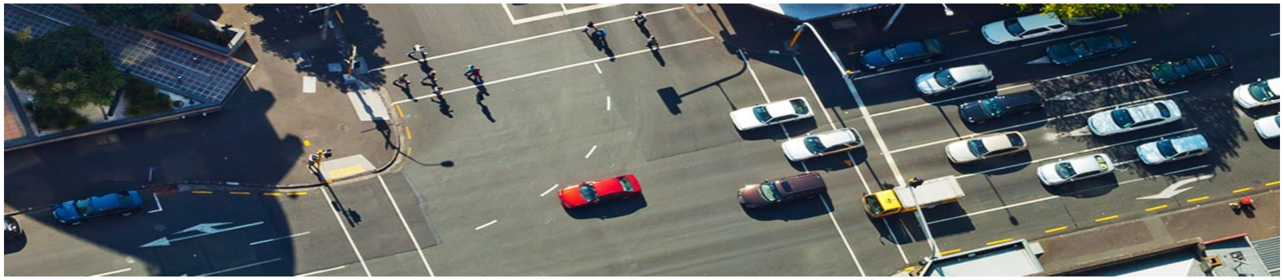

Figure 6. Adaptive signal intersection which changes light based on traffic needs (Curtis, 2017).

Discussion

Smart traffic systems (STS) are a type of **flexible infrastructure that is adaptable over time** and can be reconfigured or customized. These optimizations are tailored to the changing needs of commuters, and may **cover a wide variety of purposes**. Purposes may include reduced traffic congestion, reduced greenhouse gas emissions, and reduced emergency response times. Over time newer sensors are being developed and traffic patterns are susceptible to change. New sensors can replace older ones, and different types of sensors will be added to STS to reduce traffic delays for new traffic patterns. The algorithms used to reduce traffic delays can be altered to interpret data from different sensors and continue to perform the same task. Greg Barlow, Chief Technology Officer of Rapidflow Technologies, commented that the underlying technology of Sutrac, an intelligent traffic signal control system made by Rapidflow Technologies, can be used to reduce wait times for other forms of transit (personal communication, November 26, 2018).

Benefits provided by STS affect the traveling public, different levels of governments, and travel agencies. **Reduced traffic congestion** is the primary benefit that commuters are interested in. This benefit allows commuters to reach their destination faster by reducing the amount of stopping, starting, and idling during ones commute. Barlow said that in Pittsburg, Pennsylvania, Surtrac optimizes traffic light scheduling to ease traffic congestion. This reduction provides commuters with benefits such as reduced fuel consumption, emissions, and time spent in traffic (Snow, 2017). The **savings in energy consumption of commuters provides monetary savings** for the public. Updated and innovative technologies that can communicate more descriptive and accurate data reduce traffic congestion for emergency response services allowing them to reach accidents with a faster response time (Global Traffic Technologies, 2017). Another benefit that Barlow mentioned was **public transit agencies receive travel time reliability**, which can lead to more commuters using these services.

STS are an **existing technology in an existing market**. Smart systems are comprised of a central computer that collects and presents data from multiple sensors. These systems have been implemented in various transportation infrastructures and microgrids. Eddie Curtis, a traffic operations engineer at the Federal Highway Administration, discussed that inductive-loop sensors, detection cameras, and radar have been used in roads within the past decades; sensors which can communicate through the centralized computer in a smart traffic system (personal communication, December 3, 2018). Through the existence of old sensors and the creation of new sensors, STS remain in a small existing market.

Emerging technologies are competing with the need for STS sensors and reducing the desire for STS implementation. Curtis and Joe Molinaro, a traffic systems engineer at Albeck Gerken, agreed that smart cars and smartphones may have the potential to collect and provide enough data to decrease the number of sensors needed in STS, but with so few implementations there is not enough data collected to support this claim (personal communication, December 4, 2018). One type of emerging technology that Molinaro commented on is connected vehicles. The idea behind this technology is vehicles will have sensors in them that can collect and transmit traffic data to other vehicles. These vehicles will then adjust their courses or provide drivers with this data in hopes to reduce traffic congestion.

Another barrier is the lack of a **standard of performance for traffic lights**. Curtis talked about how the lack of a standard means that governments (local, state, and federal) do not have a basis to determine the efficiency of a traffic lights. Therefore communities may not understand that their traffic lights aren't functioning at optimal levels. Without this understanding the community will be disinclined to spend the government budget or acknowledge the benefits of installing a STS.

The **layers of complexity involved in sensor placement** is another barrier that Curtis mentioned. Curtis explained that the first step in implementing STS is for the customer to consider the purpose of the STS as that purpose decides the location, number, and types of sensors for that intersection. One example that Curtis described was that on a main road, lights could be set to green, while intersecting empty side roads remained red. The risk associated with this was when both side roads and main roads had traffic, traffic on side roads would experience more congestion. As seen in Curtis' example the purpose affects the area positively and negatively. This raises questions such as will customers consider adding more sensors to combat negative side-effects and whether or not to implement multiple sensors over time or all at once.

Molinaro affirmed that incentives are distributed by the Department of Transportation and the Federal Highway Administration. Molinaro also stated that some states or organizations may provide grants for STS. Funding typically comes from federal government budgets or city bonds that are transferred into state and local government budgets.

There are many trends seen in STS but here we showcase two significant ones. The first trend is there are many **different forms of STS that have different capabilities, therefore many aspects must be considered when choosing the best STS**. The variations and number of sensors used in an STS affect or change the types of data collected, the best fit area of implementation, and the ability to redesign or relocate the system. With varying types of data collection sensors such as microloops or cameras, different forms of data are collected. By changing the sensor configuration of an STS the system's purpose can also change. This change in purpose can make STS become better suited for a specific area. One example that Molinaro explained was the use of thermal cameras for environments that have heavy rain or snow that would prohibit normal cameras from monitoring an area. A smart traffic expert who wished to remain anonymous said that micro-loop sensors have provided better results in rural areas over urban areas (personal communication, November 27, 2018), and Barlow talked about Surtrac providing more benefits to an urban area over a rural one due to the sensors in the system. Variations of STS do not only include different combinations of sensors but can also include being built to accommodate additions of more sensors after initial installation, or to have the ability to be relocated. When implementing STS there are many aspects that must be considered to find the pertinent configuration.

The second trend is **widespread implementation of STS are inhibited due to rapid advancements in technology**. The cost of widespread STS implementation is expensive, and new technologies are being developed all the time; therefore, it is difficult for investors to choose a technology which may become obsolete by the time of installation. As Curtis mentioned new combating technologies are being developed that could reduce the amount of sensors needed in STS. Molinaro also explained that resources, such as contractors, operators, and maintenance crews, **will not have the expertise or skills to maintain these technologies** due to the rapid advancements in technology. Without these resources and information implementation is decreasing as the STS become more of a liability and uncertainty that customers do not want to deal with.

One of the reasons we chose to research STS further is because we thought it was an emerging technology. When we asked Curtis he revealed that this was not the case. Smart sensors are individual technologies which make up the STS, therefore the market for sensors (part) is different that the market for the smart traffic system (whole). STS has both emerging and existing **technologies in an existing market** that contain one or more sensors that have varying purposes which made it difficult to fit into a STS sensor specific market. Sensors on the other hand are an existing/emerging technology in an existing market. Curtis explained that inductive loop sensors are as old as 60-70 years, but new technologies are being developed that can detect multiple data types. Also, the market for these sensors is fairly small across the United States, causing smart traffic systems appear as if it were in an emerging market. Research on this topic was difficult because of the lack of information and data.

"The cost of widespread STS implementation is expensive, and new technologies are being developed all the time; therefore, it is difficult for investors to choose a technology which may become obsolete by the time of installation."

Green Roof Profile

What is a green roof?

Green roofs are a combination of layered sealant technology and permeable layers that are well equipped to absorb water and reduce stormwater runoff. Green roofs have existed for centuries, mainly for their aesthetic or social properties, but have risen to new levels of popularity especially in cities partly due to incentive programs recognizing their water management benefits.

Purposes:

- Reduces greenhouse gas emissions
- Reduce stormwater runoff and water treatment costs
- Increases roof lifespan
- Provides insulation and reduce building energy usage
- Social/recreational venue

Key Findings

- Green roofs are an existing, multi-purpose flexible infrastructure asset.
- They provide multiple environmental benefits to a community and financial benefits to an owner.
- Governments have introduced legislation or incentive programs to foster widespread development across the United States.
- There is a competitive market for urban roof real estate to provide:
  - Energy Production,
  - Stormwater Reduction, and
  - Amenities.
- Proper maintenance is essential to receive all of the benefits of a green roof.

Layers of a green roof

Green roofs consist of successive layers stacked on top on another. The top layers, the vegetation and soil layers, are capable of absorbing stormwater. Filter and drainage layers collect any water that seeps through the media layers (Environmental Protection Agency, 2009). Next, the root barrier prevents roots of the vegetation from growing into and damaging the structural and insulation layers. The thermal insulation layer reduces the energy flow out of the building trapping heat inside and keeping the internal temperature of the building regulated. Finally, the vapor barrier prevents moisture from seeping through the structural support which is the traditional roof section that holds all other layers up.

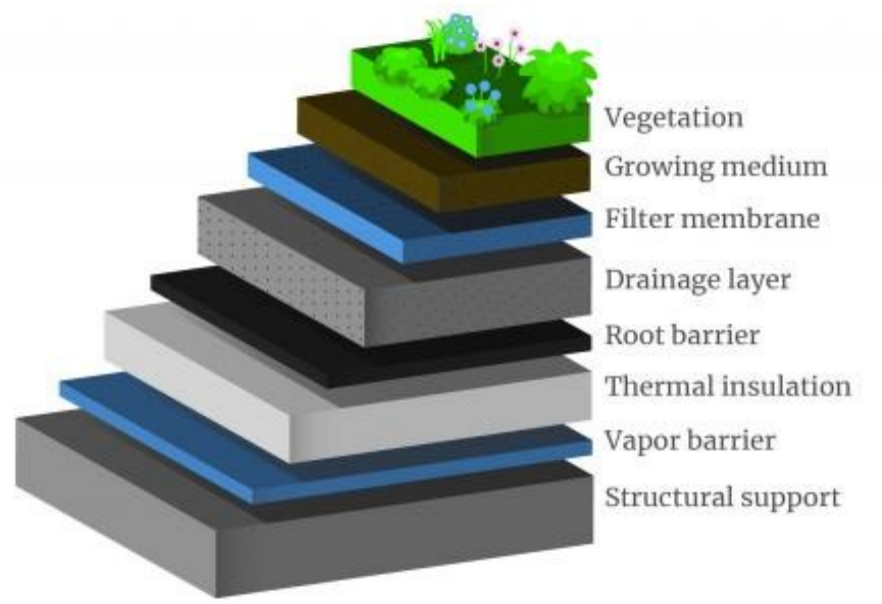

Figure 7. Schematic of common layers in a green roof (Environmental Protection Agency, n.d.)

The College of Agriculture, Urban Sustainability, and Environmental Sciences building at the University of District of Columbia in Washington D.C. boasts an impressive 20,000 square foot green roof. The green roof is semi-intensive containing a variety of extensive and intensive plots. It is used for both educational and agricultural purposes, holding a greenhouse and over 100 planter boxes. Several different resilient species of produce are grown on the roof including tomatoes, cucumbers, and sweet potatoes. The produce is grown and maintained by the student and faculty of the agricultural college and is donated to charities and soup kitchens around D.C. In 2015, 4250 lb of produce was borne from the green roof at UDC according to Sandy Farber, the green roof manager and master gardener coordinator at the University of District of Columbia (personal communication, November 28, 2018). The system also contains multiple cisterns for stormwater collection and irrigation. Stormwater collected by the cisterns is redistributed to the roof's irrigation system.

Figure 8. University of the District of Columbia green roof (University of the District of Columbia, n.d.)

The ***American Society of Landscape Architects*** headquarters has a green roof in Washington D.C. This green roof features a social space and supports diverse types of plant life over an area of 3,300 square feet. The roof includes two 'waves' on the roof designed to increase surface area of vegetation and a cistern that ensures 100% of runoff is captured. The green roof is used mainly for social purposes, but it has also helped save ASLA 10% on energy costs during the winter since 2006 (American Society of Landscape Architects, 2007). In the summer, ASLA was not originally saving on energy costs. After further investigation they found the building was being over-cooled during the summer, and after changing the cooling of the building they now save 2-3% on energy costs during the summer (American Society of Landscape Architects, 2007). ASLA is working on expanding their green roof and plans to conduct another study upon its completion.

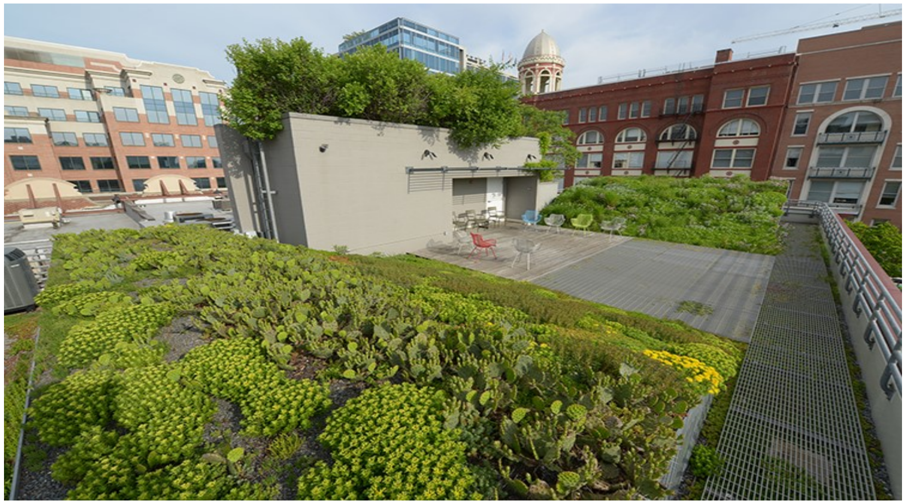

Figure 9. American Society of Landscape Architects green roof (American Society of Landscape Architects, 2014)

Discussion

Green roofs are a **multi-purposed form of flexible infrastructure** falling under the category of green infrastructure. In Section 2800 of America's Water Infrastructure act of 2018, the definition of green infrastructure is described as:

> ...[T]he range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evap-o-trans-pi-rate stormwater and reduce flows to sewer systems or to surface waters (America's Water Infrastructure Act of 2018, 2018).

Green roofs are used to collect **stormwater and manage runoff** by reducing water flow while controlling the destination of remaining stormwater. The retention of stormwater reduces strain on local water management systems, while **reducing water utility costs** for the community (Environmental Protection Agency, 2009). Stormwater runoff can cause flooding and water pollution. Stormwater management purposes are directly beneficial for the government, since they would be heavily involved in the cleanup of the aftermath of severe weather (National Geographic Partners LLC, 2018). Green roofs can reduce flooding in cities that do not have proper drainage systems, and reduce the costs of water and sewage treatment systems.

Along with stormwater management, green roofs serve multiple purposes and provide many benefits for the local environment and community. Green roofs can **reduce CO2 emissions** through the natural process of photosynthesis, and by reducing energy consumption. This makes green roofs a financially viable option in locations with carbon taxes. Another issue green roofs can mitigate is the urban heat island effect. Large amounts of dark flat surfaces can cause unnatural rises in temperature. Green roofs combat this by replacing dark flat surfaces with vegetation. They benefit the community by replacing a dark flat surface with a green space that absorbs less heat from the sun, resulting in **cooler temperatures in the summer** and financial savings (EPA, 2018).

Chase Coard, CEO of Ecospaces D.C., explained that vegetation and the thick layers of soil act as a layer of insulation, resulting in the **reduction of heating and cooling costs** for indoor temperature regulation (personal communication, November 29, 2018).

Socially, green roofs have substantial **recreational value**. Cecelia Lane, an environmental protection specialist at the Department of Energy and Environment (DOEE) in Washington, DC, mentioned that she had come across many different ways green roof spaces could be utilized recreationally (personal communication, November 28, 2018). Homeowners might use it as a patio or a yoga studio, while office buildings might use it as a break room, and hospitals might use it to create an aesthetically pleasing space for their patients. Well-maintained green roofs provide **aesthetic benefits**, another selling point for their implementation. Chase Coard indicated that the motives of roughly one-half of his clients interested in voluntarily implementing a green roof were driven by aesthetics.

Incentive programs are often created by government organizations to launch an innovative technology with communal benefits so that a market for that technology can be developed. These **incentive programs can foster widespread deployment** of this technology. In Washington D.C. the DOEE) started a green roof rebate program called RiverSmart Homes to reduce stormwater runoff. It incentivises green roofs by offering a $10-$15 rebate for each square foot of voluntarily installed vegetated green space. The rebate varies on which sewer system you are connected to (combined or separated). The difference in incentives is motivated by Washington's layout, as approximately two-thirds of the city is connected to the separated sewer system and one-third is connected to the combined sewer system. In the early stages of the RiverSmart program, the DOEE targeted federal buildings, universities, and other large properties connected to the separated sewer system. The separated sewer system is connected to a larger portion of the District of Columbia, therefore containing a high supply of stormwater, making it more susceptible to overflows. The original push from the DOEE expanded the green roof market in the D.C. metropolitan area, and there is now over 3 million square feet of green roofs in the District of Columbia (DOEE, n.d.).

Another way Washington D.C. has incentivised the installation of green roofs is through the Stormwater Retention Credit Trading Program. Through this program, property owners can install green infrastructure (green roofs, permeable pavements, rain gardens) to acquire Stormwater Retention Credit (SRC). This credit can then be sold on an open market to other properties that have government-mandated stormwater requirements.

Green roofs have an **existing market**, meaning there is an industry of businesses and contractors who install and maintain them in many locations all over the world. However, many cities have different rates of green roof implementation. Cecelia Lane mentioned that some city **governments have introduced legislation or incentives** which jumpstarted the market of green roofs in the area. Moreover, Lane said that the governments in Portland, Oregon, and Chicago, Illinois have recognized the benefits of city stormwater management, and have implemented such programs. These **government programs have resulted in the development of a market** for this infrastructure with a high rate of installation amongst property owners. Rebecca Stack, a leader of the RiverSmart Green Roof incentive program in Washington D.C., explained that Washington D.C. is currently using a similar program, and the implementation rate of green roofs has jumped in the most recent year (personal communication, November 16, 2018).

As important as government incentive programs are to the implementation of green roofs, it can also be a barrier. Cecelia Lane mentioned that the **incentive application process can be complicated** and has many requirements. The tedious application and permitting process may dissuade some property owners from implementing a green roof.

Another barrier of green roof installation is the **high cost of implementing a green roof**. The multiple benefits and **increased lifespan** of the roof can prove to be worth the investment, but it is a riskier financial investment compared to alternative roofing options. The payback period for a green roof is difficult to calculate prior and therefore may be off putting to some.

There is also **competition for rooftop real estate**. Solar panels have proven to be a competitor of green roofs because of their shorter return on investment and transparent payback period. Solar panels can still provide a property owner the feeling of doing something environmentally beneficial.

One risk to green roofs after their installation is an owner's **neglect of maintenance**. Farber explained that green roofs are often advertised as being low maintenance, which some owners may read as no maintenance. This leads to other issues that some green roof owners face, such as maintaining weeds or experiencing leaks in their building. If weeds take over a green roof it can hurt both the aesthetic and water retention benefits by choking out the vegetation and irrigation system. A small leak can lead to structural damage of the roof and require thousands of dollars in repairs.

During our brief analysis of green roofs, we came across two significant trends.

1. Government involvement plays a role in the growth of flexible infrastructure markets.
2. There is a competitive market for urban roof real estate.

The **government plays an important role in the growth of flexible infrastructure markets** through the use of legislation and incentive/rebate programs. When infrastructure can no longer meet the demands of a community, government will create legislation to enforce higher infrastructure standards to ease the burden of its current infrastructure or promote its replacement. When a flexible infrastructure asset can meet the growing demands of a community, government can incentivise the private implementation of the asset.

In the early 21st century, a major problem with D.C.'s infrastructure was its inability to manage stormwater runoff. To combat this issue, D.C. government passed legislation requiring stormwater retention technology on private property. The government promoted the growth of the green roof market by offering incentives for green roof implementation.

Urban roofs are becoming an increasingly valued space in today's society. Green roofs are not the only option for property owners looking to make better use of the space. Three large players in the urban roof market are energy production, stormwater reduction, and amenity space. According to our sources the most valued benefit of a green roof for the average homeowner is the feeling of doing good for the environment/the aesthetic value. Green roofs are not the only way to satisfy this benefit, and are certainly not the cheapest. Green roofs **compete for urban roof space with other options** such as solar panels or recreational space. Green roofs have to compete with these cheaper alternatives putting the market of green roofs at a disadvantage.

Conclusions and Recommendations

Our initial task to explore flexible infrastructure opportunities to equip communities with tools to adapt to a modern world turned out to be a much larger task than we expected. Comparing and contrasting the many different forms of flexible infrastructure in our matrix provided several generalized insights. The insights gained from our matrix were unique, however, as during our course of research we found no other study that attempted to compare this many different forms of infrastructure. More insights came from our profiles where individual scenarios could be examined and individual benefits could be seen. The most important conclusions we draw from analyzing the matrix and profiles were:

1. **Information communication technology (ICT) is creating integrated infrastructure systems by converting isolated elements into networks**. Many forms of flexible infrastructure use ICT to communicate between entities that used to be separate or discrete. Microgrids and smart traffic systems (STS) are the most prominent examples of this trend. Microgrids use a centralized computer in order to optimize energy generation and distribution. STS similarly use ICT to optimize traffic flow. Although traditional traffic lights together form a system of traffic control, STS use multiple sensors and ICT to create more sophisticated traffic control systems that can respond to a greater array of conditions and needs in real time.

Furthermore, this trend may continue with the integration of multiple forms of flexible infrastructure into a network. The trend of ICT connecting components of an infrastructure can be abstracted one level higher, and soon ICT will be connecting different forms of flexible infrastructure into one system. These integrated flexible systems are known as "smart cities" as they use many different forms of flexible infrastructures to automate tasks that a single infrastructure cannot complete alone. For example, smart cities will use ICT to coordinate the services of many different infrastructural assets, such as transportation, water, power supplies, and district heating systems.

2. **There are two types of additive flexibility: discrete and integrated**. Green roofs exemplify the idea of discrete additive flexibility. Installing more green roofs does not increase or decrease the benefits of previously installed green roofs. Therefore green roofs always add the same 'flat' value to the system in an additive way. Installing more green roofs will provide more value to the urban system as a whole, but the benefits of each additional green roof are independent from the state of the larger system of green roofs. By contrast, in more integrated systems of flexible infrastructure, such as STS, the benefits of adding new sensors may be more difficult to assess because they are not simply additive. Installing STS sensors and lights at a single intersection has benefits, but installing more STS nearby may not provide the same amount of additional benefits. In some cases, the marginal benefits of each additional expansion in the network may actually decline. Thus, the benefits are not discrete and rely on the state of a larger, integrated system they interact with. Therefore integrated flexible infrastructures require optimization of the entire system, simply adding more does not guarantee the benefits will be maximized.

3. **Lack of specific information about flexible infrastructure inhibits development and analysis**. Many aspects of a flexible infrastructure must be examined prior to installation. Knowledge about costs, benefits, and configuration of components are necessary to formulate an informed decision about the value of installing such an infrastructure. Unfortunately, this information is not readily available or of a sufficient quality to guide decision making for many forms of flexible infrastructure. By their very nature, there is little available information about best practices for the installation, operation, and maintenance of emerging infrastructural assets. This may lead to a tendency to overstate the benefits and underestimate the costs, and the uncertainty over costs, benefits, payback periods, etc. may hinder the development of emerging flexible infrastructures. Reflecting the nascent state of these types of infrastructure, different studies and reports on the same infrastructure use different terminology and metrics that impair analysis and institutional learning.

Future research into flexible infrastructure is necessary as this infrastructure will enable all communities to adapt to the uncertain demands of the future. We found that the benefits of these flexible infrastructural assets are unparalleled compared with traditional infrastructure, but matched with high upfront costs and considerable market uncertainty. We had very little information about transportable infrastructure and therefore it had to be left out of our analysis. We also had issues with attempting to examine what benefits adaptability over time provided as opposed to multi-purpose. Multi-purpose flexible infrastructure provides immediate benefits that were easy to evaluate whereas adaptable over time flexible infrastructure provides one immediate benefit based on the state of the system they interact with but the future of this system cannot be evaluated.

As with the development of all types of infrastructure, the federal, state, and local government play key roles in the promotion and development of flexible infrastructure. We offer the following set of recommendations to governments aiming to foster development of flexible infrastructure. At the federal level, we recommend; the passage of **legislation** to ensure the infrastructural assets meet appropriate standards of service delivery at reasonable costs, **regulation** to ensure the protection of health, safety, and environment, and the **promotion of research** of emerging infrastructure through national labs and federal agencies. At the state and local level, we recommend offering **tax breaks and incentives** to emphasize the integration of flexible infrastructure in strategic and urban planning processes. We recommend all levels of government to be involved with **planning and guidance** to encourage the development of flexible infrastructure and serve as exemplars for new types (e.g., installing green roofs on government buildings).

Next, we recommend to the National Labs and other federal government agencies researching these flexible infrastructures to disseminate valuable findings to the decision makers involved with flexible infrastructures. To do this we recommend **coordinating with urban planners and city officials** to examine the unique benefits that flexible infrastructures may provide to their specific areas. We consider it important to make information about these flexible infrastructures readily available on public websites with accessible language.

Finally we offer these following recommendations to the DOE to continue research on flexible infrastructure opportunities:

- **Develop metrics or a framework to evaluate the cost and benefits associated with a specific flexible infrastructure**. This could be done by continuing to develop the criteria we created to examine flexible infrastructures. When new flexible infrastructures emerge this framework could be applied to gain an initial understanding.
- **Create a database or central repository that details the cost and examines specific benefits provided by individual implementations of flexible infrastructures across the United States**. Case studies could be included, with executive summaries for each that could be found through a keyword search. This will be invaluable for decision makers by providing a repository where they can compare cost and benefits with exact quantitative information.
- **Further analyze the funding models used to build flexible infrastructures**. As these flexible infrastructure scale towards communities, older financial models are no longer relevant. Instead newer financial models that appease a variety of invested parties need to be developed and evaluated.

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Supplemental Materials for this project may be found at https://digitalcommons.wpi.edu/studentprojectsandresearch/ by entering this report's title in the search bar. When the window appears, click on the appropriate project title and scroll down to "additional files".

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