Assessing Resilience as a Co-benefit of Sustainability in Urban Energy System

An integrated framework and two case-studies

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Sustainable cities

- Cities are responsible 70% of anthropogenic GHG emissions
- 6+ billion urban population by 2050

Bahrain twin tower

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REVIEW

City-integrated renewable energy for urban sustainability

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To prepare for an urban influx of 2.5 billion people by 2050, it is critical to create cities that are low-carbon, resilient, and livable. Cities not only contribute to global climate change by emitting the majority of anthropogenic greenhouse gases but also are particularly vulnerable to the effects of climate change and extreme weather. We explore options for establishing sustainable energy systems by reducing energy consumption, particularly in the buildings and transportation sectors, and providing robust, decentralized, and renewable energy sources. Through technical advancements in power density, city-integrated renewable energy will be better suited to satisfy the high-energy demands of growing urban areas. Several economic, technical, behavioral, and political challenges need to be overcome for innovation to improve urban sustainability.

Since 2007, a greater percentage of the global population has been living in urban areas than in rural areas. Increased urbanization is expected to continue, with two-thirds of the world's population projected to live in urban areas by 2050, a net urban influx of 2.5 billion people (*1*). Cities today are generally not equipped to address dramatic urban growth and strain on existing infrastructure in a sustainable way, especially with respect to their energy systems.

To be sustainable, cities must themselves, or in the resources that they command, become low-carbon, resilient, and livable (*2*). Although there can be considerable variation in methods for evaluating the emissions footprint of cities (*3*), with 54% of the population living in urban areas, it is estimated that cities are currently responsible for 60 to 70% of anthropogenic greenhouse gas emissions (*4*). The two main strategies for transitioning to a low-carbon city are to shift from fossil fuels to cleaner energy sources and to reduce urban energy consumption levels. The low-carbon transition can be accomplished through energy-efficiency measures, behavioral interventions, and incorporating carbon sinks such as urban parks. Cities and their energy systems should also be resilient to natural and human-made threats (*2*). The energy systems of cities are increasingly vulnerable to the effects of climate change and extreme weather, including storms, flooding, and sea-level rise, and also to natural and human-induced disasters. In addition, urban energy systems directly affect the well-being and happiness of urban inhabitants. Health conditions, economic competitiveness, cultural appeal, and social, gender, and racial equality are influenced by high-energy sectors such as transportation, food production, and water quality.

Here we evaluate some of the more promising recent technological advancements that could help urban areas become sustainable cities. Many opportunities exist, but focusing on city-integrated renewable energy—defined as distributed, non-fossil fuel energy generated locally in urban areas—has the potential to help cities meet several sustainability needs. Many of these renewable sources increase regional energy independence and can be redundant with other sources, thus increasing resiliency. Although there are several existing barriers to their adoption, solutions will involve increased power densities of renewable energy technologies, improved infrastructure capable of supporting widespread integrated energy generation systems, and increased urban energy efficiency, particularly in the buildings sector.

City-integrated renewable energy

About 75% of power generated globally is consumed in cities (*5*). Generating city-integrated energy at the site of energy use could substantially contribute to the environmental, economic, and social aspects of urban sustainability. Four characteristic advantages of such distributed energy systems include the ability to (i) offer low to zero carbon emissions, (ii) offset capital-intensive investments for network upgrades, (iii) impart local energy independence and network security, and (iv) motivate social capital and cohesion (*6*).

With limited available installation space, renewable energy generation within urban areas poses particular challenges. We use the balance between the high energy demand of cities and the available energy density supplied by renewable sources as a starting point for an analytic framework for decarbonized urban spaces (Fig. 1). However, in the waves of innovation that will be needed, strategies ranging from space-based solar energy to small modular nuclear power systems, deep geothermal systems, and other generation options could transform the energy landscape. In addition to reducing greenhouse gas emissions, these strategies may reduce the consumption of water, air, and other resources.

Solar energy

Recent economic and technical advances have made city-integrated solar technologies increasingly attractive. Since 2010, the installed price of solar energy has dropped by as much as 50% (*7*). Despite substantial economic progress and anticipated cost parity with fossil fuels, renewable energy technologies have often been criticized for their low power densities, making them inappropriate for urban applications. Conservative estimates of the power density of solar photovoltaics are around 10 W/m^2 (*8*), assuming an average direct solar irradiation of 100 W/m^2, which is typical for the United Kingdom, and a photovoltaic efficiency of 10%. However, the solar resource is highly region-dependent, and in some regions, annual direct solar irradiation can exceed 300 W/m^2 (*9*). Many of the regions expected to experience the greatest increase in urbanization are located in solar-rich regions. For example, the majority of the total land area of India experiences an annual direct solar irradiation of over 200 W/m^2 (*10*). Additionally, the efficiency of photovoltaics has increased steadily and has already surpassed 40% in the laboratory, using concentrated multijunction cells (*11*). Hence, under optimal conditions, the power density of photovoltaics could exceed 120 W/m^2.

Several studies have estimated the photovoltaic potential of existing cities. City-integrated photovoltaics have the potential to satisfy 62% of the current electricity needs of Oeiras, Portugal (*12*), and 66% of the electricity needs of Bardejov, Slovakia (*13*). High-efficiency commercially available photovoltaics only on suitable rooftops could satisfy 19.7 to 31.1% of the daily electricity demand and 47.7 to 94.1% of the morning peak electricity demand of Mumbai, India (*10*). With a 20% adoption rate, solar-powered urban microgrids could reduce the grid demand in Cambridge, MA, to almost zero at midday (*14*).

Heating accounts for 40 to 50% of the global energy demand and 75% of the energy demand within the buildings sector (*15*). Urban solar thermal energy, specifically for space and domestic water heating, has been an area of particular research interest. With efficiencies up to 80% (*15*), solar hot-water systems offer a thermal power density up to 240 W_t/m^2 under optimal conditions (W_t, watt-thermal), whereas the global averaged thermal power density of solar heat collectors is 67 W_t/m^2 (*16*). Because domestic solar hot-water heaters are low-cost and compact, one study showed that 84% of urban households in China could install the system on their rooftops (*17*). Solar thermal energy is also used for passive and active space heating. A study of five Australian cities showed that the use of a Trombe wall could offer energy savings up to 17% (*18*). Seasonal solar thermal energy storage is an approach that stores solar thermal energy collected in the summer for heating in the colder months. This technology provides up to 91% of the total energy needs of a large residential building in Richmond, VA (*19*).

The exploitability of the solar resource is highly affected by urban form. Although taller buildings offer higher surface-to-volume ratios, allowing for increased facade-integrated solar technologies, they also increase the risk of vertical obstruction and shading (*20*). Although building facades provide almost triple the area of building roofs, they

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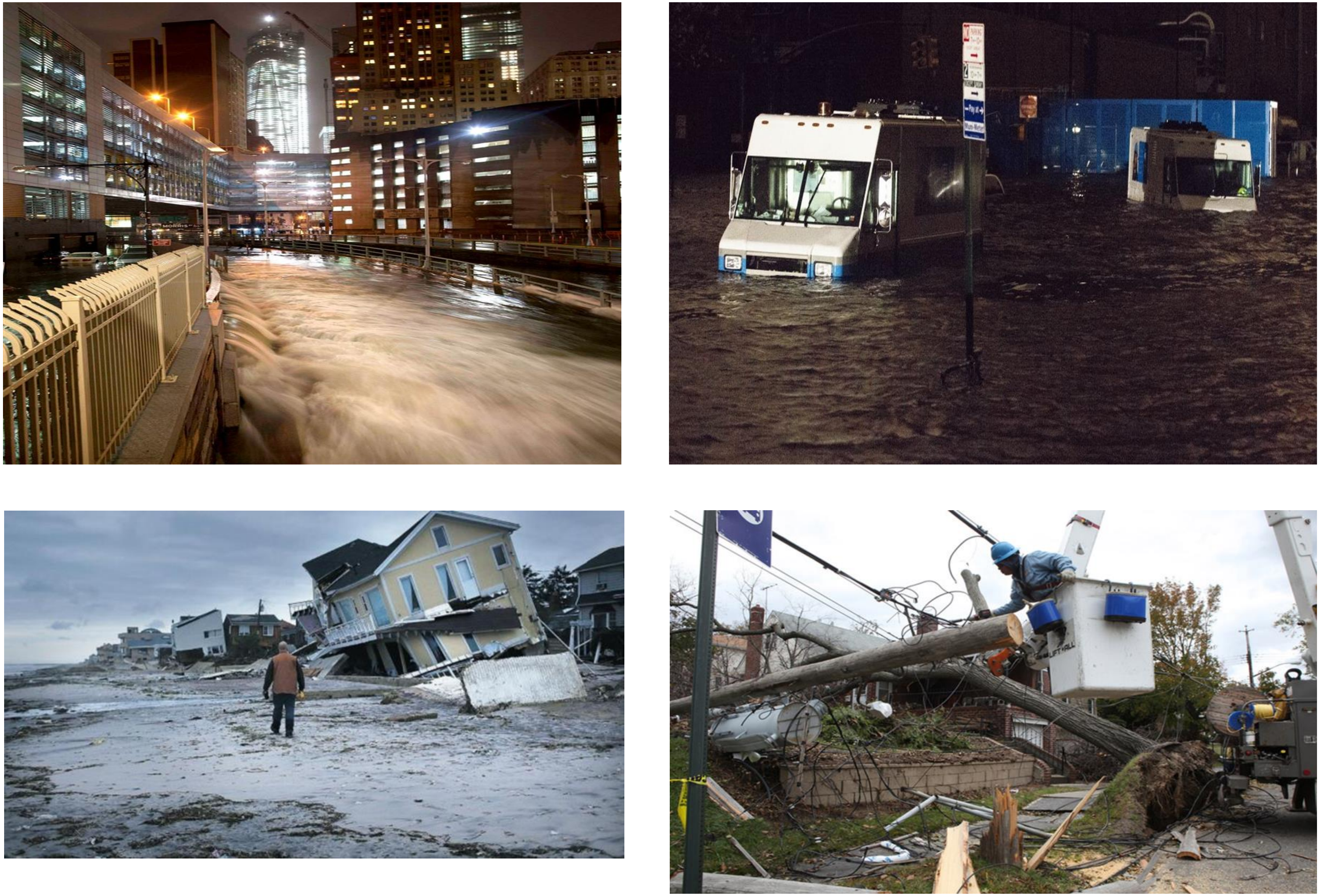
Diverse energy assets for cities

Real-time management of these assets can ensure energy independence, reliability and resilience


Pay at
Muni-Meter
LIFTALL

Gov. Dannel Malloy

- Tri-states area has been hard hit with severe weather
  - 2010 snowstorms
  - Tropical Storm Irene, August 2011
  - Freak October snowstorm, 2011
  - Hurricane/Superstorm Sandy, 10/22-11/2, 2012
  - Blizzard of 2013
- Storms have left hundreds of thousands without power for long periods of time, in some cases in excess of 10 days
  - large-scale devastation
  - threat to safety and security of residents
  - disruptions to everyday rhythms of 21st century life

- Policymakers scramble for ideas: somebody trots out a study on the cost of undergrounding power lines

“The most recent report in 2007 estimated the cost of placing the state's 1,330 miles of 345 kilovolt transmission line underground and maintaining it would be $27.8 million a mile compared to $6.8 million for the same length of overhead line.”— CTPost.com

Peak Outage Levels and Duration of Restoration, by Company

Company	Peak Outage Level	Start of Event	Time of Peak	Time of **Majority** Restoration *(< **1,000** customers remaining)*	Duration of **Majority** Restoration
NGrid	37,588	10/29 @ 1330	10/29 @ 2130	10/31 @ 1530	2 days, 2 hours
RGE	26,580	10/29 @ 1430	10/30 @ 0730	11/02 @ 1930	4 days, 5 hours
CHGE	83,551	10/29 @ 1030	10/30 @ 0300	11/04 @ 0330	5 days, 17 hours
NYSEG	116,069	10/29 @ 1030	10/30 @ 1530	11/08 @ 1330	10 days, 3 hours
ORU	145,716	10/29 @ 1300	10/30 @ 2100	11/09 @ 1900	11 days, 6 hours
ConEd	824,991	10/29 @ 0700	10/30 @ 1730	11/12 @ 1200	14 days, ~5 hours
LIPA	950,943	10/29 @ 0630	10/30 @ 1600	11/15 @ 1200	17 days, ~6 hours
Statewide	**2,109,877**	**10/29 @ 0630**	**10/30 @ 1700**		
	2,185,438	*Sum of peaks*			

Company	Time of **Full** Restoration *(< **100** customers remaining)*	Duration of **Full** Restoration
NGrid	10/31 @ 2130	2 days, 8 hours
RGE	11/03 @ 1730	5 days, 3 hours
CHGE	11/04 @ 1930	6 days, 9 hours
NYSEG	11/08 @ 2100	10 days, 11 hours
ORU	11/10 @ 1500	12 days, 2 hours
ConEd	11/12 @ 1200	14 days, ~5 hours
LIPA	11/15 @ 1200	17 days, ~6 hours

Note: Flood affected customers are not included in this analysis.

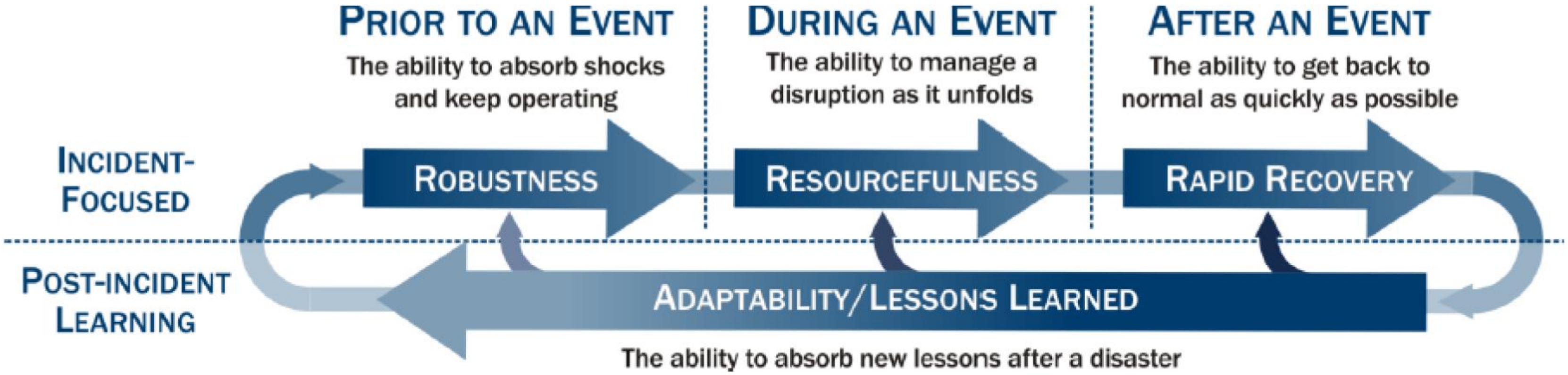
Sustainability + Resilience

Joint implementation of sustainability and resilience

- Two closely related but, especially in practice, distinct concepts
  - Both concepts express the most important goal for a system: its integrity and survivability when its internal conditions and external environments are normal or subject to disturbances
  - In the context of management practice, major differences include
    - Scales: sustainability focuses on larger spatial scales and longer temporal scales.
    - Equitability: Inter-generation and inter-region equity is at the core of sustainability concept, but resilience may be achieved at the expense of future generations and of connected systems.
    - Process vs performance: Resilience emphasizes process, and sustainability emphasizes system performance and outcomes.

- Three perspectives for the joint implementation of sustainability and resilience (Marchese et al, 2018):
  - Resilience as a component of sustainability: for a system to be sustainable as the primary objective, planning process needs to consider its vulnerabilities to disturbances. The sustainability of a system increases as resilience increases, but not vise versa.
  - Sustainability as a component of resilience, i.e. sustainability is pursued as a factor that can contribute to resilience as the ultimate goal of the system;
  - Resilience and sustainability as separate objectives (e.g., negatively correlated, uncorrelated, or positively correlated)

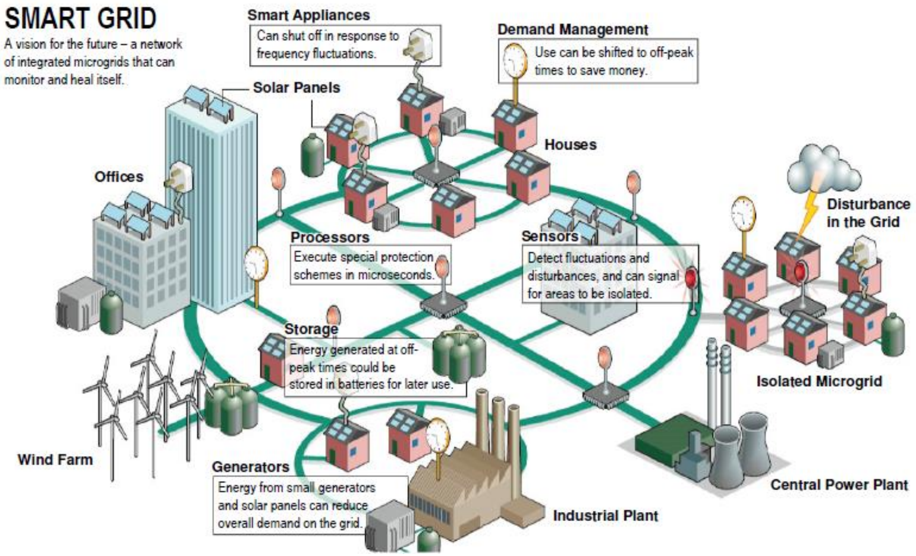
Four essential elements of resilience



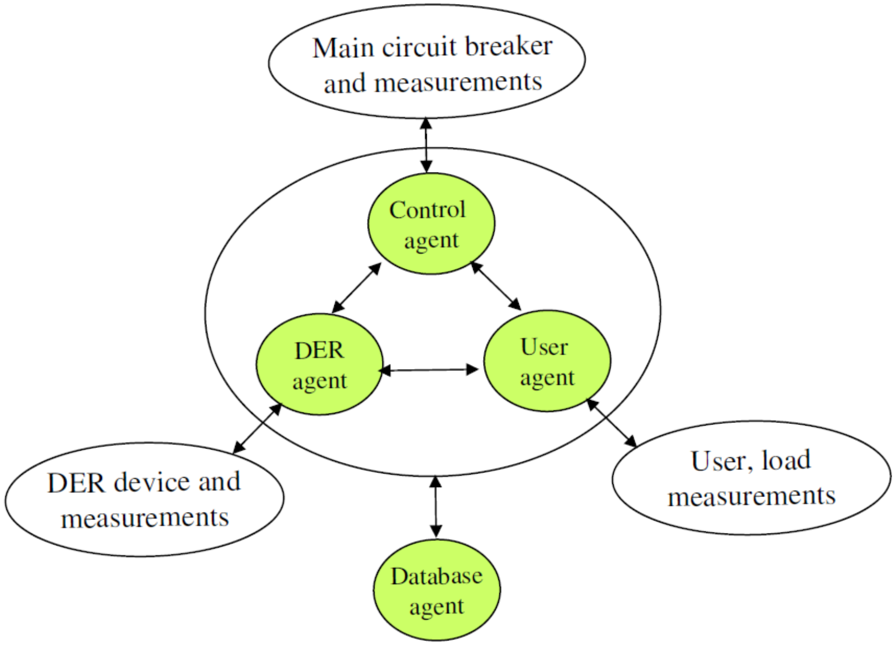
Smart city

- Internet of Things (IoT) leads to transformational changes in urban energy systems, as well as in buildings and transportation sectors
- Seven defining characteristics of smart cities:
  - sensible, connectable, accessible, ubiquitous, sociable, sharable, visible and augmented
  - Technically possible to close a loop critical to city operation: sensing, communicating, decision making, and actuating tasks in **automated** and **more accurate** manners
- Use military doctrine Network Centric Warfare to operate city:
  - respond to surprise and urgent adverse events
  - shared situational awareness and decentralized decision-making by distributing information
  - An example: dynamic islanding and dynamic microgrid
- New challenges associated “being smart(er)”
  - More complexity
  - Vulnerability to man-made adverse events (e.g., cyber-attacks)
- Cooperation from people as individuals and as organizations. Attractiveness of smart technologies depends on their own analysis of
  - feasible options
  - valued outcomes (comfort, cost, health, privacy)
  - uncertainties (controlled by utility? consumption data is protected?)

Smart Grid: a network of integrated microgrids that can monitor and heal itself



Source: Kurt Yeager, Galvin institute



Source: Pipattanasomporn et al, 2012

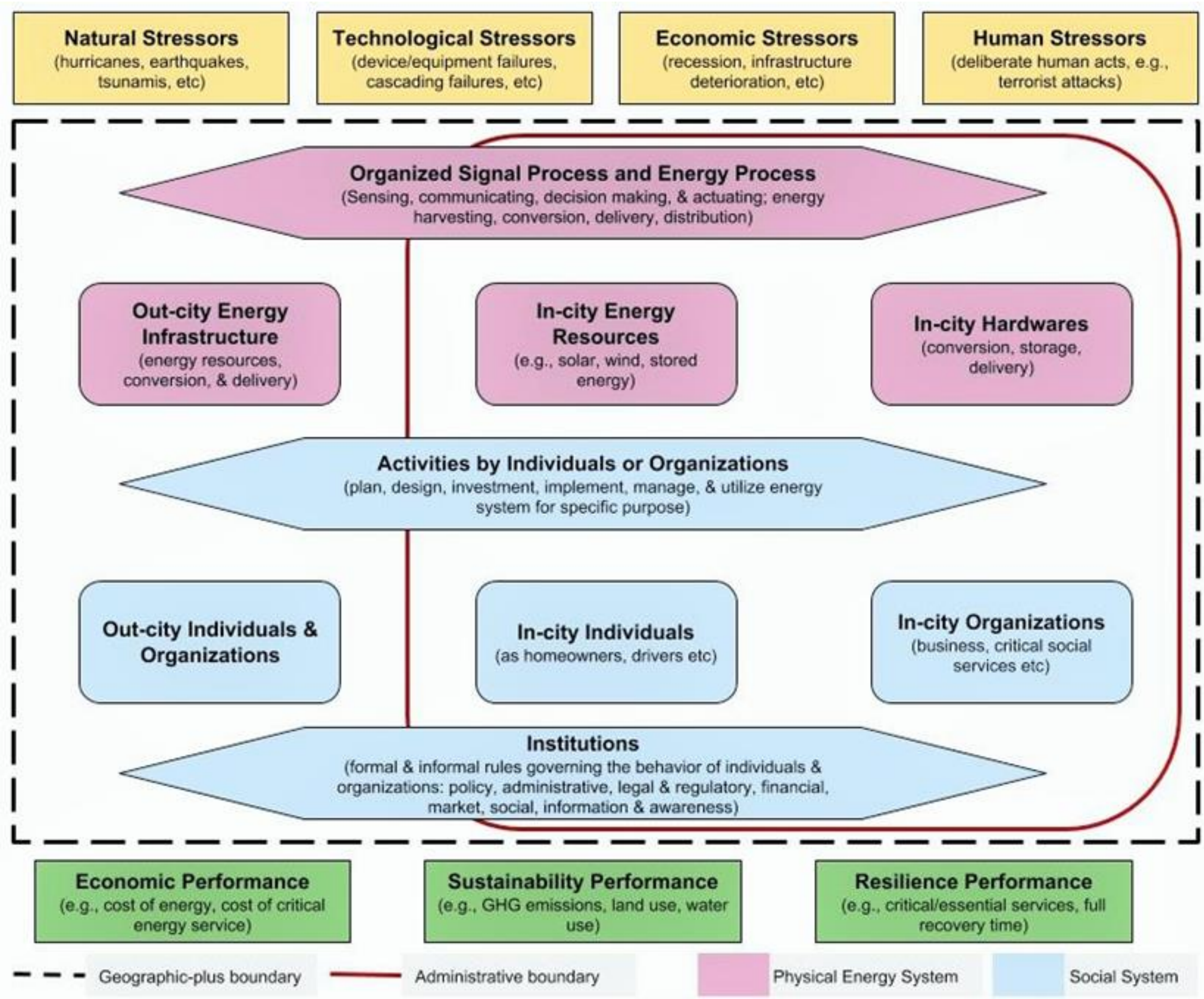
Energy systems in smart cities

- Enormous benefits
  - the availability of energy-use information with high spatial and temporal granulations
  - reduction in total energy use and carbon emissions
  - lowering peak demand
  - mitigating load pocket, and
  - quicker restoring power supply (especially to critical services).
- Research questions
  - What are the new energy problems in smart city?
  - What are the appropriate interventions (e.g., technologies, policies) to address these problems so that best energy services can be provided?

Need new framework for urban energy system

- City as a complex adaptive system, and the six elements
  - Energy resources: solar, geothermal, wind…
  - Hardware: energy use and generation/harvesting devices, pipes, wires….
  - Processes: "organized collection of signal tools" (i.e., generation, detection, and perception) to govern energy importing & harvesting, and the installation and operation of energy hardware
  - People: individuals involved in energy activities (e.g., harvesting, use, and storage) as homeowners, building occupants, drivers and passengers
  - Institutions: formal and informal rules governing the behavior of individuals and organized individuals
  - Activities: tasks including plan, design, invent, implement, manage, and utilize energy system for specific purposes

- City boundary: geographic-plus boundary
  - All within the administrative boundary, plus
  - substations, transmission lines, and central power stations connected to city but located outside the administrative boundary


Natural Stressors
(hurricanes, earthquakes, tsunamis, etc)
Technological Stressors
(device/equipment failures, cascading failures, etc)
Economic Stressors
(recession, infrastructure deterioration, etc)
Human Stressors
(deliberate human acts, e.g., terrorist attacks)
Organized Signal Process and Energy Process
(Sensing, communicating, decision making, & actuating; energy harvesting, conversion, delivery, distribution)
Out-city Energy Infrastructure
(energy resources, conversion, & delivery)
In-city Energy Resources
(e.g., solar, wind, stored energy)
In-city Hardwares
(conversion, storage, delivery)
Activities by Individuals or Organizations
(plan, design, investment, implement, manage, & utilize energy system for specific purpose)
Out-city Individuals & Organizations
In-city Individuals
(as homeowners, drivers etc)
In-city Organizations
(business, critical social services etc)
Institutions
(formal & informal rules governing the behavior of individuals & organizations: policy, administrative, legal & regulatory, financial, market, social, information & awareness)
Economic Performance
(e.g., cost of energy, cost of critical energy service)
Sustainability Performance
(e.g., GHG emissions, land use, water use)
Resilience Performance
(e.g., critical/essential services, full recovery time)
Geographic-plus boundary
Administrative boundary
Physical Energy System
Social System

Integrated assessment and usefulness

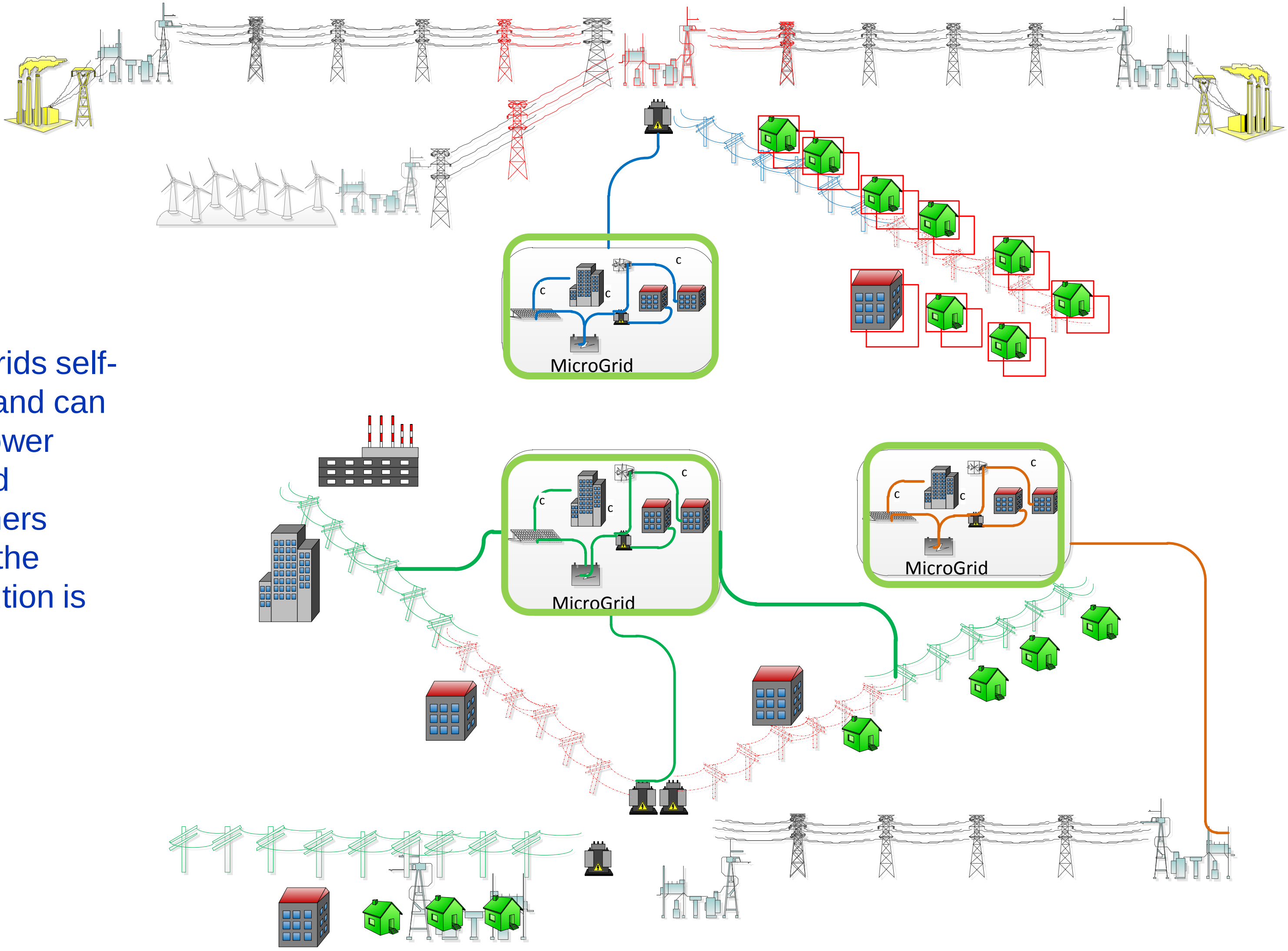
- As a process connecting knowledge and actions, usefulness (or effectiveness) measures:
  - issue defining and framing,
  - identifying and evaluating options for interventions, and
  - ultimately actions adopted by society to address the issues

- Three attributes of effective/useful assessment
  - Saliency: How relevant to the changing needs of targeted users?
  - Credibility: Are the technical arguments true? and
  - Legitimacy: Is the assessment process fair and respectful to stakeholders?

List of guiding questions

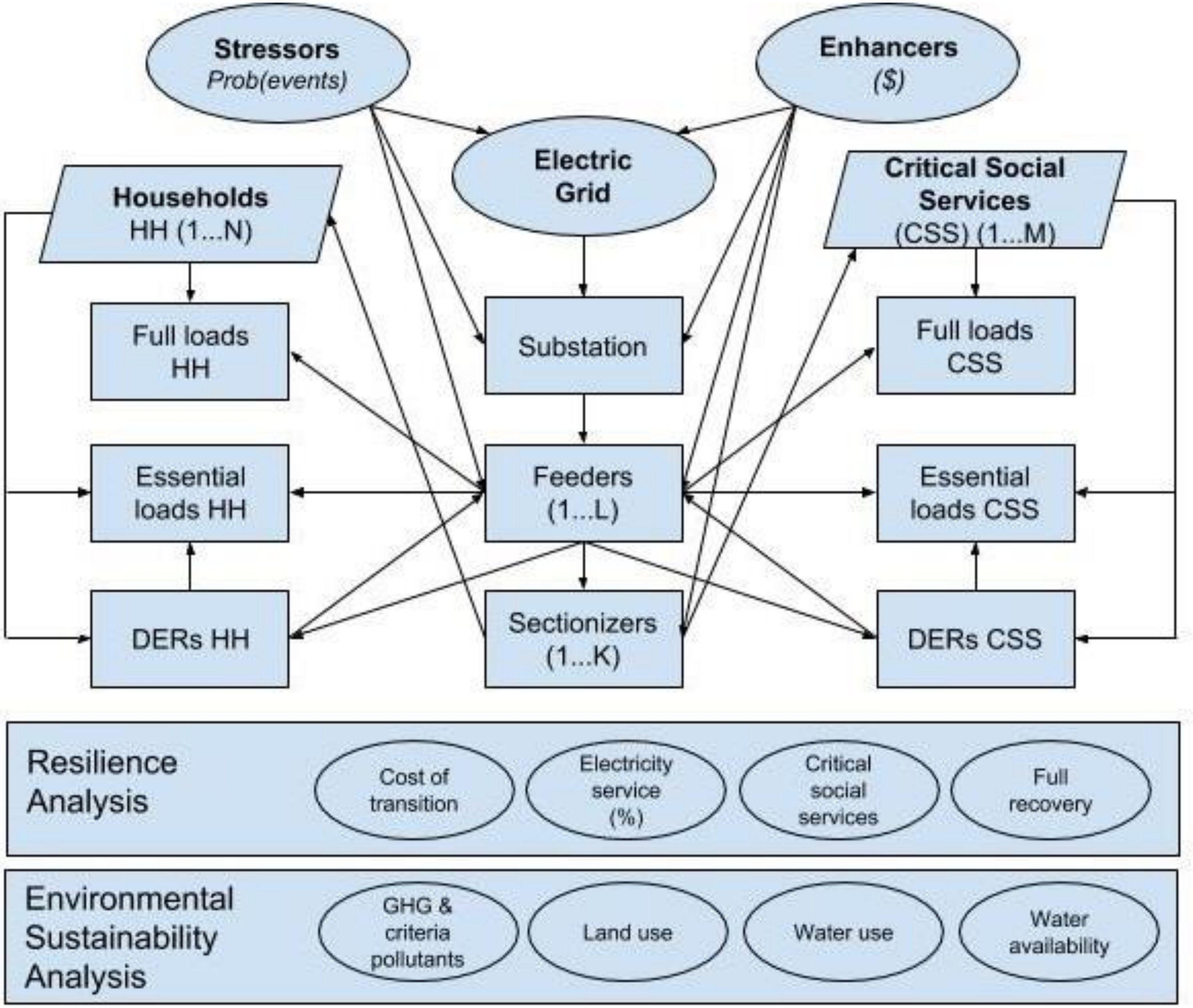
- Who are within (and outside of) the city boundary? Whose needs for energy services have higher priorities? Whose energy services are vulnerable to stressors? Who are the decision makers determining the desirable energy services? Who can influence decision makers?
- What issues decision makers concern about? What are the desirable energy services in smart cities? What are the technological and policy options to improve the sustainability and resilience of smart cities? what are their valued outcomes and uncertainties?
- Where are the severe impacts of stressors?
- How are key decisions influenced (automatic, individual decision making, and through political process)?

Dynamic MicroGrids – Generation which is self driven to find the best fit load to serve at the distribution feeder level



Microgrids self-island and can also power isolated customers where the distribution is intact

From structure to a relational framework



Stressors
Prob(events)

Enhancers
($)

Electric Grid

Households
HH (1...N)

Critical Social Services
(CSS) (1...M)

Full loads HH

Substation

Full loads CSS

Essential loads HH

Feeders (1...L)

Essential loads CSS

DERs HH

Sectionizers (1...K)

DERs CSS

Resilience Analysis

Cost of transition

Electricity service (%)

Critical social services

Full recovery

Environmental Sustainability Analysis

GHG & criteria pollutants

Land use

Water use

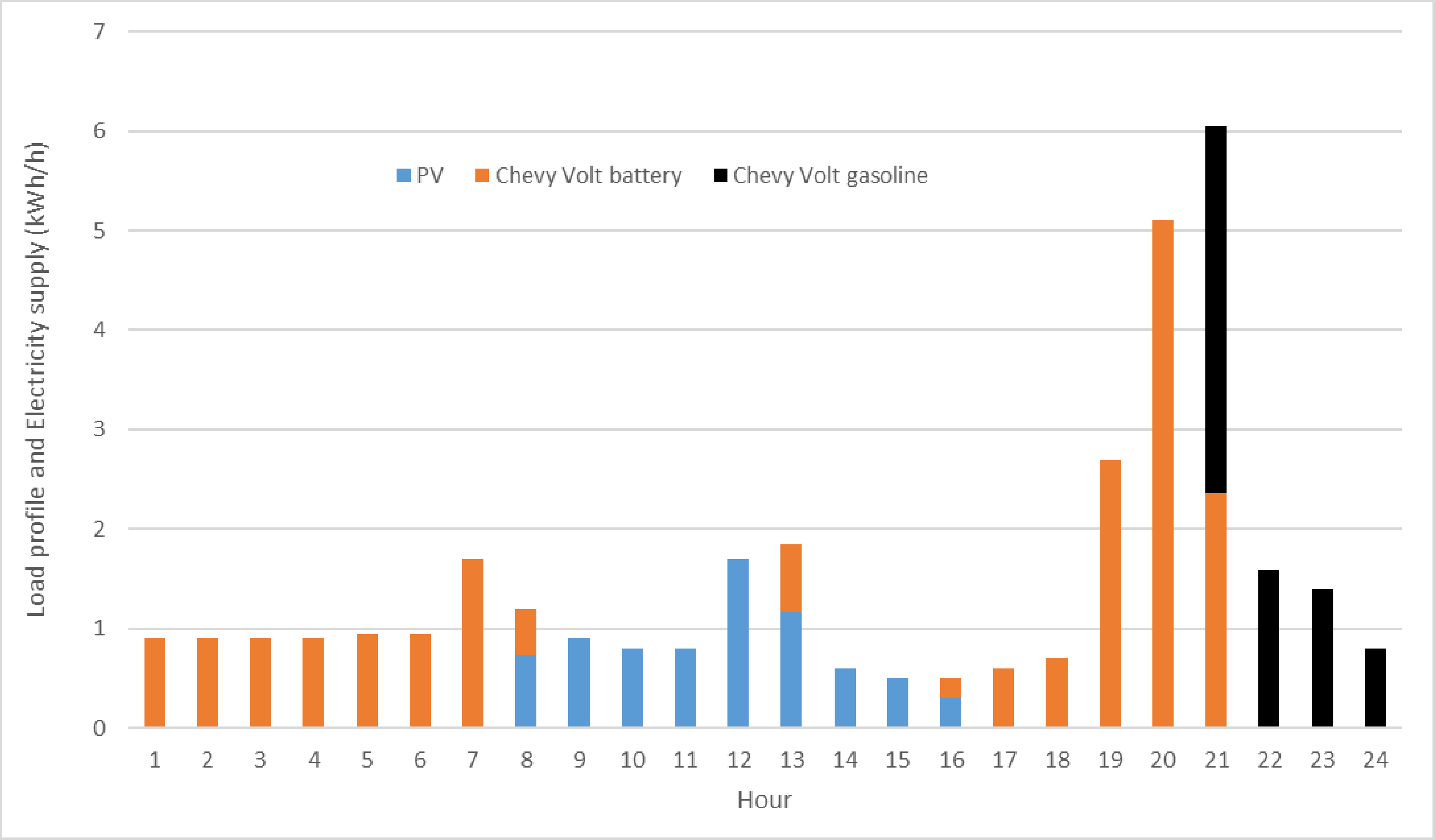
Water availability

Scenario in the two case-studies

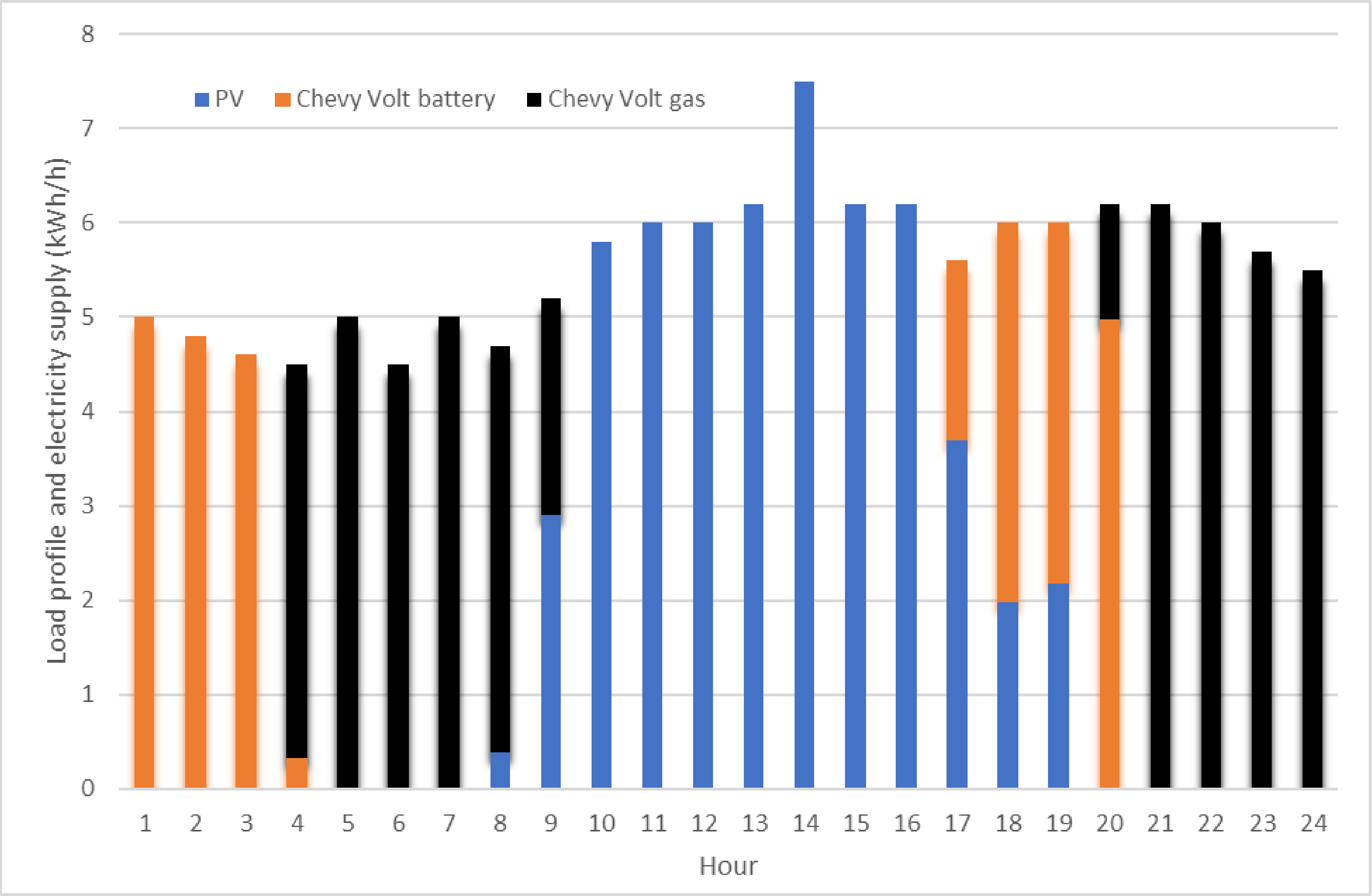
- Context: extended period of power outage
- Typical residential buildings
- Sustainability: PV system that meet all the electricity needs of the households
- Resilience: capable of disconnecting from grid and operating at “island” mode
- Households maintain normal load as much as possible
- Dispatching priority during the outage: 1st PV, 2nd car battery, 3rd gasoline
- The household has 1 plug-in hybrid electric vehicle (Chevy Volt, or Chevy Bolt, or Toyota Prius Prime)

Vehicles	Battery capacity (kWh)	Fuel tank capacity (gallon)	Electricity equivalent (kWh)
Chevy Volt	18.4	8.9	243
Toyota Prius Prime	8.8	11.3	316
Chevy Bolt	60	0	0

Case study 1: Long Island, New York



Case study 2: Villa in Riyadh, Saudi Arabia



Summaries and implications

- Without DER (i.e., PV and PHEVs/EVs), no power supply, miserable life
- With PV only,
  - LI house can have full power supply for 6 hours, partial supply 2 hours;
  - Riyadh villa full supply 7 hours, partial supply 5 hours,
- With PV and PHEV
  - LI house has full power supply all day (24 hours), and gasoline in the tank is needed
  - Same to Riyadh villa, but gasoline is essential.
  - Implications: PHEV
- Future work
  - Feeder-level simulation
  - Power outage for multiple days
  - District cooling