**Authors:** Susan Spierre Clark[1], Thomas P. Seager[2], Mikhail V. Chester[2]

[1]Corresponding author: Susan Spierre Clark, PhD
UB RENEW Institute
112 Cooke Hall
University at Buffalo, North Campus
Buffalo, NY 14260
University at Buffalo
sclark1@buffalo.edu, 585-709-1366

[2]Co-authors: Thomas P. Seager, PhD and Mikhail V. Chester
School of Sustainable Engineering and the Built Environment,
Arizona State University
PO Box 875306
Tempe, AZ 85287-5306

**Title:** A Service-based Approach to the Prioritization of Critical Infrastructure Resilience

**Abstract:** As a consequence of the U.S. effort to increase infrastructure security and resilience, the Department of Homeland Security (DHS) and other U.S. federal agencies have identified 16 critical infrastructure sectors that are considered vital to the nation's well-being in terms of economic security, public health, and safety. However, there remains no articulated set of values that justify this particular list of infrastructure systems or how decision-makers might prioritize investments towards one critical sector over another during a crises. To offer a more integrated and holistic approach to critical infrastructure resilience, this research employs the Capabilities Approach to human development, which offers an alternative view of critical infrastructure that focuses on the services that infrastructure provides rather than its physical condition or vulnerability to threats. This service-based perspective of infrastructure emphasizes the role of infrastructure in enabling and supporting central human capabilities that build adaptive capacity and improve human well-being. Therefore, we argue that the most critical infrastructure systems are those that are essential for providing and/or supporting central human capabilities. This paper examines the DHS designation of criticality from a capabilities perspective and argues for a capabilities basis for making distinctions between those systems that should be considered most critical and those that might be temporarily sacrificed. A key implication of this work is that an across sector approach is required to reorganize existing critical infrastructure efforts around the most valuable infrastructure services.

**Keywords:** Critical Infrastructure, Infrastructure Services, Capability Approach, Human Development, Infrastructure Criticality, Maslow's Hierarchy of Needs

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## 1. Introduction:

In response to extreme weather events, terrorist and cyber-attacks, as well as other low-probability, high consequence technological catastrophes, recent policy directives and capital investments have exhibited a shift in priorities for critical infrastructure systems that emphasizes resilience. In general, a resilient system is one that minimizes both disruption and the time and resources required to recover from disastrous events by incorporating adaptive strategies. In particular, Obama's 2013 Presidential Policy Directive calls for an integrated and holistic approach towards critical infrastructure resilience that reflects its interconnectedness and interdependency (PPD-21 2013). However, as of yet there are no generalizable principles of resilient critical infrastructure design and operation that are applicable across multiple system contexts.

What is evident is that adaptive infrastructure will require increased flexibility, including the potential sacrifice of some system subcomponents for the sake of maintaining greater functionality of the larger system. The inevitability of failure in interdependent and complex infrastructure systems (Clark et al. 2017) requires a recognition that not all system functions or components can be protected at all times. For example, the inundation of the New Madrid Floodway in 2011 spared riparian communities along the Mississippi River from greater flood damage at the expense of prime farmland (Olsen and Morton 2012). The problem is that there is no agreement across infrastructure sectors and networks on what sectors or components are most essential to prioritize. Thus, a key impediment to infrastructure resilience is the lack of preferential objectives for utilizing scarce resources towards desired outcomes (Seager et al. 2017).

The current approach to infrastructure prioritization by the U.S. involves the identification of 16 critical infrastructure (CI) sectors that are considered vital to the United States because the incapacity or destruction of these systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters (DHS 2013). The Department of Homeland Security (DHS) and other lead agencies employ a risk-based approach to prioritize assets within each sector based on the likelihood of threats and infrastructure vulnerabilities, as well as the potential consequences the nation would face if it were to fail. However, this approach to critical infrastructure identification is too broad, given that not all 16 sectors can be protected at any cost. Moreover, the sector-based approach has resulted in inconsistencies among risk assessment tools, areas assessed for vulnerability, and the detail of information collected for each sector that has inhibited integration and coordination for prioritization efforts (GAO 2013, 2014). By organizing around distinct sectors, it also misses important dependencies and interdependencies in the infrastructure supply chain.

The view of resilience provided by the federal government is that of robustness, which emphasizes the physical condition (i.e., strength) of the infrastructure rather than the quality of services provided. This is problematic because infrastructure is not an ends unto itself but must be judged (in effectiveness) relative to its purpose, which is to provide services to the public. While confounding infrastructure resilience with robustness can help infrastructure respond more

effectively to expected or predicted disturbances, it can reduce the system's vulnerability to surprise events (Alderson & Doyle 2010). A more complete resilience approach would instead recognize the importance of infrastructure's extensibility or adaptive capacity for maintaining functionality in the face of surprise (Woods 2015), including the capacity of any sectors to substitute for, reinforce, or pose a threat to other sectors (Ganin et al. 2016).

Alternatively, the United Nations Development Program (UNDP) recognizes the relationship between resilience and human development (i.e., human well-being), in which infrastructure plays an important role in providing basic services to people and society. In their view, resilience underpins any approach to securing and sustaining human development by stressing the role of people's *capabilities*, or available choices, in minimizing adverse consequences from shocks and persistent threats. In other words, the more capabilities or freedoms people have, the better their capacity will be for responding to and recovering from adverse events (UNDP 2014). The philosophy of human capabilities, known as the Capabilities Approach, is the foundation for the UNDP's Human Development Index (HDI), which is a widely used multi-dimensional metric for achievements in human development (Sen 1999a; 1999b; Nussbaum & Sen 1992; Jahan 2002). The HDI includes three key human development end points: a long and healthy life, being knowledgeable, and a decent standard of living. Although these dimensions represent essential human capabilities required for human development and human resilience, the UNDP does not explicitly relate these outcomes to the infrastructure systems that enable them nor mention the physical state of infrastructure. From this perspective, it is the ultimate services or capabilities that infrastructure provides that is important for achieving system resilience.

To offer a more integrated and holistic approach to critical infrastructure resilience, this research employs human development theory as an alternative view of critical infrastructure that focuses on infrastructure services, informs how we can prioritize infrastructure in a way that represents human values and capabilities, as well as recognize the interdependencies across systems. Whereas a risk-based approach would recommend policies such as insurance to manage people's risk, a human development approach informs broader initiatives, policies, and investments that improve the well-being of individuals and societies that can proactively build resilience as well as inform crises management. This paper specifically argues for a Capabilities Approach, which is the human development theory utilized by the UNDP's HDI, for justifying systems that should be considered most critical. We also employ Maslow's Theory of Human Motivation (1943) as a hierarchical guide for prioritizing the most essential capabilities during a crises. Furthermore, this approach emphasizes the importance of human and ecological dimensions of resilience for proactively improving adaptive capacity of infrastructure systems.

## 2. The Evolution and Prioritization of US Critical Infrastructure

In the context of public policy, the meaning of 'critical infrastructure' has been evolving for decades (see table 1). Successive federal government reports, laws and executive orders have refined, and generally expanded, the number of infrastructure sectors and the kinds of assets considered to be 'critical' for purposes of homeland security (see table 2). In the 1980's 'infrastructure' was primarily concerned about the adequacy of the nation's public works, which were viewed by many as deteriorating, obsolete, and of insufficient capacity. In the 1990s federal agencies were increasingly concerned about infrastructure protection. This concern led policy

makers to reconsider the definition of 'infrastructure' in a security context, primarily concerned with infrastructure protection (Moteff, Copeland, and Fischer 2003; Moteff 2015). In 1996, President Clinton's Executive Order 13010 was noteworthy for specifying particular infrastructure sectors considered to be 'critical', including sectors with high public involvement (typical of previously specified sectors of importance), but also those predominately owned by private companies (see Table 2). In 1998, Clinton signed Presidential Decision Directive 63 (PPD-63) with the goal of building national capability within five years to protect 'critical' infrastructure from intentional disruption, including cyber infrastructure, which hadn't been emphasized prior. Another Executive Order (E.O. 13228) came following September 11, 2001 by President Bush, which expanded the critical infrastructure list further to include nuclear sites, special events, and agriculture, which were not among the sectors identified in PPD-63. Later that year, Bush issued another Executive Order (E.O. 13231) that focused on information infrastructure and emphasized the importance of information systems to other critical infrastructure sectors, including telecommunications, energy, financial services, manufacturing, water, transportation, health care, and emergency services. In response to the September 11, 2001 terrorist attacks, Congress passed the USA PATRIOT Act, which is significant because its definition of 'critical infrastructure' was adopted by the 2002 Homeland Security Act, and remains in use by the DHS and other federal agencies today (see last row of table 1 for current definition).

**Table 1.** Evolution of critical infrastructure definitions (Moteff, Copeland, and Fischer 2003)

Although the definition of critical infrastructure has not been changed by the Administration since the Patriot Act of 2001, the list of infrastructures considered critical continued to expand (Table 2). For example, the President's *National Strategy for Homeland Security* (NSHS), issued in July 2002, added the chemical industry as well as a postal and shipping services to the critical infrastructure list. Not explicitly added to the list, NSHS also declared that it would place a high priority on protecting cyber infrastructure. NSHS also introduced the notion of 'key assets', which are distinct from physical critical infrastructure, defined as a subset of nationally important key resources (Moteff and Parfomak 2004) that included high profile events, symbols or historical attractions as well as local facilities worthy of federal protection because of their importance to national morale, destructive potential, or value to the local community. The Bush Administration's *National Strategy for the Physical Protection of Critical Infrastructures and Key Assets* (NSPP), released in February 2003, reaffirms the critical infrastructure sectors identified in NSHS and defined three categories of key assets: one for monuments, symbols and icons important to the Nation's heritage and values, a second for facilitates and structures representing the national economic power and technological advancement, and another for prominent commercial sectors, office buildings, and stadiums where a large number of people congregate. NSPP also specifically identifies nuclear power plants and dams as key assets. In 2008, DHS added another sector to the list, Critical Manufacturing, which includes primary metals, machinery, electrical equipment, and transportation equipment manufacturing industries. Most recently in 2013, President Obama's *Critical Infrastructure Security and Resilience* Presidential Policy Directive (PPD-21) did not make any major changes to policy, but did give energy and communications sectors a higher profile due to their importance to the operations of other infrastructures, and also expanded efforts towards cybersecurity.

**Table 2.** Expanding list of critical infrastructure sectors. Adopted and updated from the Congressional Research Service (CRS 2004). Parenthesis in the final column indicate subsectors. Note that 'Education' and 'Monuments and Icons' are subsectors of 'Government Facilities' and 'Postal & Shipping Services' is a subsector of 'Transportation'

As the definitions of 'critical infrastructure' and 'key assets' have evolved in U.S. homeland security policy, responsible agencies have been seeking greater refinement and prioritization within these categories. In 1999, for example, the Critical Infrastructure Assurance Office (CIAO) determined that many federal agencies responsible for critical infrastructure protection lacked a clear understanding of what constituted a 'critical asset' within an infrastructure. As a result, the CIAO instituted the *National Critical Infrastructure Prioritization Program* (NCIPP) by which an agency could identify and assess its critical assets, identify the dependencies of those assets on other systems, including those beyond the direct control of the agency, and prioritize. Consequently, Bush's NSHS adopted the notion of critical asset differentiation and formally introduced the notion of critical assets as a way to focus critical infrastructure protection efforts on the highest priority sectors, an approach that is later reaffirmed by the NSPP. While the NSPP calls "for an objective assessment of critical assets it acknowledges that the 'criticality' of individual assets is potentially fluid" (CRS 2004, pp12).

Federal agencies and private companies have shared responsibility for identifying critical assets since PDD-63 was issued in 1998. That Directive required each lead federal agency to work with the private sector in their respective infrastructures to contribute to a sectoral National Infrastructure Assurance Plan by assessing the vulnerabilities of the sector to cyber or physical attacks, among other tasks. According to PPD-63 "these assessments shall ... include the determination of the minimum essential infrastructure in each sector". The responsibility of the private sector to work with federal agencies in developing and maintaining lists of critical assets, continues to be an essential part of the government's infrastructure protection strategy. However, individual critical infrastructure sectors implemented independent and often varying approaches for identifying their own critical assets.

In an effort to establish and implement a more consistent standard for what constitutes a critical asset, the NSPP required DHS to develop a consistent method for identifying facilities, systems and functions with national-level criticality and to create a critical asset catalog. The NCIPP approach consisted of identifying assets most critical to the nation based on the asset's exposure to threats/hazards, its vulnerabilities to those hazards/threats, and the potential consequences (including cascading impacts on other systems). The results populated a two-tiered data-base of critical infrastructure assets. Since 2006, the tiered prioritization system is consequence based. That is, infrastructure is categorized as either level 1 or 2 based on the consequences to the nation in terms of four factors: fatalities, economic loss, mass evacuation length, and degradation of national security. Most assets are identified at level 2, with a small subset of assets meeting the level 1 consequence threshold, those that could result in major regional or national loss or damage. This list identifies who DHS reaches out to for more thorough vulnerability assessments and to make further recommendations to reduce risk (Moteff 2015), it also helps to allocate Homeland Security grants.

Recently, questions have been raised about changes to the critical infrastructure prioritization approach, with some assets either dropping off the list or being assigned a new level of risk. There have also been questions on the impacts these changes may have on those that have developed and/or use the list. As a result, the US Government Accountability Office examined DHS' management of NCIPP and issued a report in 2013 summarizing their findings. The report indicated that DHS has made changes to NCIPP list criteria and has not identified or validated its approach (GAO 2013).

The implications of an unclear or changing list of critical infrastructures (or key resource) is a topic of debate among policy-makers. Ambiguity about what constitutes a critical infrastructure could lead to inefficient use of limited homeland security resources. For example, private sector representatives say they need clear and stable definitions of asset criticality so they will know exactly what to protect, and how well to protect them. Otherwise, they risk protecting too many facilities, protecting the wrong facilities, or both, and limiting the number of critical infrastructures due to resource constraints might miss a dangerous vulnerability (Moteff & Parfomak 2004). Creating resilient critical infrastructure therefore requires a clear definition of what constitutes infrastructure criticality as well as an explicit framework for identifying and evaluating key infrastructure systems and components.

## 3. A Capabilities Approach to Human Development

An alternative perspective is revealed when considering the infrastructure criticality from a human development perspective, which is broadly focused on human well-being. Although universally accepted definition of human well-being does not exist, in the context of resilience, a human development perspective generally identifies people as being vulnerable when they lack sufficient core capabilities because it severely restricts their agency, prevents them from doing things they value, and/ or undermines their ability to cope with threats (UNDP 2014). The UNDP considers human development as a process of enlarging people's choices or building human capabilities founded on the philosophy of the Capabilities Approach (CA), whose analytical framework is illustrated in Figure 1 (Robeyns 2003).

The CA is a flexible and multi-purpose framework for understanding the underlying basis for the promotion of human well-being, sustainable development, and social justice. It is founded on the claim that the achievement of human well-being is of primary moral importance and emphasizes that the freedom to achieve well-being is understood in terms of people's capabilities, or their real opportunities to be and do what they reason to value (Sen 1999a, 1999b; Nussbaum and Sen, 1992; Nussbaum 2000, 2006). The approach emphasizes capabilities such as the ability to live a long and healthy life, engage in economic transactions, and/or participate in political activities. Unlike other development models that focus on the amount of resources available to individuals (i.e., traditional welfare economics), the CA is primarily concerned with people's ability to transform their resources into capabilities. That is, the CA emphasizes the intrinsic value of ends or outcomes of development, rather than the means or resources available, because people differ in their ability to convert means into valuable resources.

**Fig. 1** The Capabilities Approach framework considers the resources available to individuals and the conversion factors available to transform resources into capabilities, or opportunities and

freedoms. Based on the portfolio of capabilities available, functionings are the actual achieved capabilities that a person chooses to put into practice. Figure adapted from Robeynes 2003 and Verd and Lopez 2011

The distinction between resources, capabilities and functionings, as well as their relationship to infrastructure are described below:

- *Resources* are understood to be the set of rights, entitlements or commodities that are available to a person in a given context, such as the Bill of Rights in the US as well as basic resources like water, food and financial means. Resources are only useful when paired with appropriate *conversion factors,* which can facilitate the transformation of resources or means into effective freedoms. Conversion factors are unique to each person and include personal, social or environmental characteristics, such as a person's physical condition and intelligence, public policies and social norms, as well as available institutions and infrastructure. Infrastructure systems are considered an important conversion factor because they allow for distribution of resources that provide people with services that they might not otherwise have access too.
- *Capabilities* are a person's real freedoms, opportunities, or possibilities available that enable the pursuit of well-being. Capabilities reflect the valuable sets of options a person has based on available conversion factors. These include things like the ability to live a healthy life, the ability to be educated, and the ability to hold a job. Services provided by infrastructure, like access to water, food, electricity, transportation, and medical services, enable and/or support the ability of people to do things they value, and therefore can help to enhance the portfolio of a person's capabilities.
- Finally, *functionings* are realized capabilities, or the set of ways of being and doing that a person ultimately puts into practice. Examples include being well-nourished, being educated, traveling, and voting in an election. The availability of infrastructure influences functionings in the same way they influence capabilities, by providing people access to the services that they may ultimately choose to utilize. The distinction from capabilities is important because functionings take into account people's agency and freedom of choice as well as shows the flexibility of the CA for using across cultures and contexts.

An illustrative example of the CA framework that makes the distinction between resources, capabilities, and functionings is a bicycle. Having access to or owning a bicycle can be considered a *resource*, but the bicycle is only useful to get from one place to another if the person has appropriate conversion factors available, such as being able-bodied enough to ride the bike, having social norms that allow for that person to ride the bike without discrimination, and safe roads and/or bicycle lanes that enable the *capability* of mobility. Nevertheless, a person might have access to a bicycle and have the capability to ride it from one place to another, but may choose to not use the bicycle to achieve the *function* of being mobile, which may or not be of value to a particular person.

As the name implies, the CA ultimately focuses on the portfolio of capabilities or freedoms available to people because once they have these freedoms, they can choose to act on those freedoms in line with what they want to do and the person they want to be. The implication of

the CA for public policy is that policies should be assessed according to its impact on people's capabilities. For example, it focuses on whether people are able to be healthy, and whether the means necessary for this capability, such as clean water, access to healthcare, protection from infections and diseases, and basic knowledge on health issues, are available.

Employing the CA in the context of critical infrastructure resilience suggests that formal rights and freedoms are necessary but insufficient for enhancing human capabilities. In the US, formal rights are codified in the Declaration of Independence, the Constitution, and specifically the Bill of Rights, among other documents, which describe the inalienable human rights the US government is bound to protect. Such rights include the freedom of speech, freedom to bear arms, the right to privacy, and the right to peacefully assemble, among others. However, in a modern, interdependent world, protection of these rights is an empty, philosophical gesture without the affordances that acknowledge these rights as capabilities. The CA suggests that conversion factors, including institutions and infrastructure, are required for people to exercise their rights and realize their freedoms. Just as using a bike for mobility requires access to a road or a bicycle lane, getting an education requires schools and teachers, the freedom of speech requires access to a newspaper, cell phone, or social media, and living a healthy life requires access to health care, hospitals, water, and nutritious food. *Thus, from a capabilities perspective, the most critical infrastructures can be understood as those that are vital for protecting or providing essential human capabilities.*

An example of linking critical infrastructure and human capabilities is provided by a recent study by Day et al. (2016), which conceptualizes energy use from a capabilities perspective. The CA is used to identify multiple intervention strategies for addressing problems of energy deprivation in both developed and less developed nations. The goal for this research was to provide a framework for understanding the relationship between energy consumption, energy services, and what energy services enable or produce in people's lives, such as lighting, cooking, accessing information, washing clothes, heating and cooling (referred to as secondary capabilities) and ultimately outcomes like good health, social respect, maintaining relationships, and being educated (basic capabilities). Day et al. suggest that separating out secondary capabilities from basic capabilities is important because it recognizes that the relationship between energy services and capabilities are not fixed, but dynamic and context specific. That is, some people need more energy than others to reach the same level of capability based on individual and household factors, the needs of specific individuals, the local environment/climate, available energy services in other locations, as well as cultural norms and expectations. This an important point to consider for infrastructure planning and prioritization.

The context-specific nature of human needs is a primary reason why economist and philosopher Amartya Sen, the founder of the CA, has refrained from developing a specific list of basic capabilities, arguing that the selection of capabilities on which to focus is value *judgement* that is to be made explicitly, and in many cases by a process of public debate (Sen 1992, 1999c). However, critics of the CA complain that Sen does not provide an operational framework to identify a list of basic capabilities (Clark 2005; Alkire 2002, Beitz 1986). However, Martha Nussbaum (2003), an American Philosopher and one of the pioneers of applying the CA to

human rights and justice, provides a list of ten capabilities that she claims are important because the activities and freedoms they enable are central to a life that is truly human (Table 3). She defends these capabilities as being the moral entitlements of every human being on earth and that the list specifies the minimum entitlements that a citizen should be guaranteed by their governments and relevant international institutions. Nussbaum formulates the list at a general, legislative level and advocates that the translation to implementation and policies should be done at a local level, taking into account local differences. Note that other multidimensional lists and conceptions of human well-being dimensions have been generated and vary according to the questions that each author seek to address and the context of operation; see Alkire 2002 and Hall et al. 2010 for a discussion and comparison of different approaches.

**Table 3.** An abbreviated summary of Nussbaum's (2003) list of central human capabilities and relevant U.S. critical infrastructure sectors (DHS 2013)

The capabilities Nussbaum lists clearly depend on infrastructure systems. Moving freely from place to place requires transportation systems, good health and living a life of normal length requires access to healthcare, engaging in critical thinking demands a quality education, relating to other human beings requires communication systems, and today, freedom of speech and freedom of association demand not only communication systems but also information technology. The right column of Table 1 identifies relevant DHS infrastructure sectors for each central capability that Nussbaum emphasizes, based on the descriptions of the sectors provided by DHS (2013). Note that only the most relevant systems are included in the table. Energy, Transportation, Water, and Communications (often considered life-line systems) are interdependent with most if not all critical infrastructure sectors but are only listed for those where they are directly relevant. Also, the most relevant infrastructure depend on other systems that are also not included. For example, Healthcare & Public Health and Emergency Services are directly related to enabling people to live a life of normal length, but some of components of the Chemical and Nuclear Sector support the materials and processes needed for medicine and medical equipment to function. The implications of infrastructure interdependencies and supply chains of human capabilities across sectors is discussed in Section 5.

Nevertheless, Table 1 helps us to justify the criticality of infrastructure sectors based on a philosophically generated and applied theory of human capabilities. It also highlights the apparent incongruity between the human centered approach emphasized by Nussbaum's central human capabilities and the focus on physical infrastructure by federal government agencies. Whereas some physical infrastructure sectors have clear relevance to capabilities, like the 'Healthcare & Public Health' sector to the bodily health capability, other capabilities are more difficult to align with physical infrastructure, such as the ability to play or live in relation to other species. In Table 1 we reason that parks and other recreational facilities included under the 'Government Facilities' sector would be an example of infrastructure that could support the ability of an individual to play and experience nature. However, it is clear that some capabilities, although can be supported by physical infrastructure, are much more relevant to social and ecological infrastructure, which are not sufficiently represented in the U.S. government's approach to critical infrastructure resilience. Recent research by Aldrich and Meyer (2014), who stress the critical role of social capital and networks in driving resilience support the lack of consideration for social infrastructure by current government-lead resilience approaches. Thus,

the CA framework informs a more holistic perspective of the types of physical, social, and ecological infrastructure systems that are important for providing services that support human well-being, as well as proactively building resilience in anticipation of possible catastrophe.

Although Table 1 offers a list of essential capabilities to consider overall, it does not offer guidance on how we might prioritize some capabilities over others, in terms of the infrastructure that supports them, during a crisis. For that, we look to Maslow's Theory of Human Motivation.

## 4. Developing a Hierarchy of Infrastructure Systems

There are many theories describing human needs and motivation (e.g., see McClelland's Acquired Needs Theory and Manfred Max-Neef's Fundamental Needs Matrix), but the most popular and widely used is Maslow's Theory of Human Motivation (1943). We employ Maslow's theory here because it offers a relatively easy to understand conception of human needs as well as provides a hierarchical ordering of multidimensional human needs that is useful in the context of prioritizing critical infrastructure. Although our understanding of this theory has become more sophisticated over the years (e.g., Koltko-Rivera 2006; Tay & Diener 2011), we provide a summary of Maslow's original proposed theory.

According to Maslow's theory, most people seek to fulfill needs in a particular order (Fig. 2), with the most urgent survival needs first, followed by less urgent needs that are important for one's satisfaction and happiness. The model takes the form of a pyramid and begins with *physiological* or survival needs that include things like food, water, air, and sleep. Once the physiological needs are met, people are motivated by *safety* needs, such as security of the body, employment, resources, mortality, family, health and property. The third level is *love and belonging* needs. If physiological and safety needs are met, people are motivated by their need for love and affection which could take the form of family, friends, intimate relationships and/or belonging to a club or group. Next is *esteem* needs, which is a desire for a high evaluation of themselves, for self-respect or self-esteem that is usually achieved through achievement and respect from others. The last and final tier is the need for *self-actualization*, which few people will actually achieve. Self-actualization is analogous to self-fulfillment or becoming everything that one is capable of becoming. Maslow gives the example of how a musician must make music, and an artist must paint to be truly fulfilled and happy in life. Self-actualization only occurs in people are satisfied by all other needs that come lower in the pyramid.

Moreover, Maslow explains that there are preconditions for basic need satisfactions at each level that include things like freedom to express one's self, freedom to seek information, freedom to act without harm, as well as justice, order in the community and fairness. These preconditions are not considered ends in themselves but important for achieving basic satisfactions (Maslow, 1943). According to Maslow, the higher needs on the pyramid require more preconditions, or better external conditions to achieve, whereas the lower needs are more tangible, localized, and limited. Also, the pursuit of higher needs tends to produce desirable social outcomes than needs lower in the hierarchy (ibid).

**Fig. 2** Maslow's Hierarchy of Human Needs (1943)

Maslow's hierarchy has resonated across many disciplines, from psychology, to education, business, engineering, and technology because it organizes a very complex topic into a cognitively appealing and intuitive model. Its popularity stems from the model's relative simplicity and hierarchical nature which allows for more practical application, yet these characteristics are also heavily criticized. Alkire (2002) argue that dimensions of human development should be *nonhierarchical* because what seems most important to an individual will change over time, depending on the situation and context. Others contend that people are capable of higher order needs such as love and belonging, even if their basic psyciological needs are unmet.

Nevertheless, Maslow acknowledges that his hierarchy has a degree of fixity, in that some people will be motivated by needs in a different order, such as an innately creative person whose drive for creativeness is more important than say love and belonging. He also discusses how the hierarchy does not usually occur in a step-wise fashion as the pyramid implies. He says a more realistic description of the hierarchy is decreasing percentages of satisfaction as one moves up the pyramid (Maslow 1943). For example an average person might have 75% of their physiological needs met, 60% of their safety needs, 50% of love and belonging needs, 35% of their esteem needs and maybe only 5% of their self-actualization needs. According to Maslow (1954), human psychological needs are like vitamins: having one vitamin does not reduce the need for other vitamins, just as all of our needs are individually required and contribute synergistically to our well-being. That is, just because we have water does not in any way help us fulfill our need for food, or shelter, or love, or esteem. What the theory tells us, however, is that having our most fundamental needs allows people to focus on achieving higher order needs. Maslow also claims that relative to superficial and conscious desires that are impacted by one's culture, the basic needs represented in his theory of motivation are more universal and common among all humans. The extent to which Maslow's theory holds across countries and cultures remains elusive, but a relatively recent study across 123 countries by Tay and Diener (2011) provides empirical evidence to support the notion that there is a tendency, although not a strong one, to fulfill needs in a specific order. The study suggests that societal conditions play an important role in determining the order of need fulfillment; The lower hierarchical needs in particular, like basic and safety needs had stronger correlations with country wide results when compared with psycho-social needs, like love and esteem, that are more unique to each individual.

Although the approaches are fundamentally different, the CA listing the minimal beings and doings that a just government should offer its citizens and Maslow's ordering of needs that motivate people's behavior, both conceptions of human well-being tend to recognize the multi-dimensional nature of what most people value in life. The two approaches can be integrated by conceptualizing Nussbaum's list of capabilities as a set of preconditions that are required to fulfill needs on Maslow's hierarchy, or achieve functionings in the context of the Capabilities Approach. Further, the supporting infrastructure systems can be conceptualized as conversation factors that allow resources to transform into capabilities. Integrating the CA and Maslow's Hierarchy together allows us to rank order infrastructure systems according to their role in supporting the most basic of human needs as described below and illustrated in Figure 3.

- Satisfying the physiological needs identified on the first tier of Maslow's hierarchy (water, food, shelter) is the capability of 'being able to have good health, nourishment and shelter' which are generally enabled and supported by the sectors of agriculture, water, and emergency services.
- Safety and security needs, which comprise tier 2 on Maslow's pyramid, require preconditions like the capability of being able to move freely from place to place, be secure against violent assault, and have a choice in matters of reproduction as well as the ability to hold property (both land and movable goods) and seek employment on an equal basis with others. Infrastructure categories that support these values are transportation systems, public safety (e.g., police and fire protection), national defense, financial services, and information technology.
- Further up Maslow's pyramid, we find the sense of belonging needs that that relate directly to Nussbaum's idea of affiliation or relationships with others (including nature) which are supported by communication technologies, schools and community structures, social clubs and institutions, as well as access to natural habitats.
- Next to last is 'esteem' or confidence, which relates to the capabilities of practical reason, having an adequate education, and control over one's political environment. These are enabled via education and political infrastructure and institutions.
- Finally, Maslow lists at the apex of his pyramid certain qualities of "self-actualization" like creativity and a capacity for moral judgement – activities that are related to Nussbaum's identification of "play" as a fundamental human capability and enabled by recreational and entertainment infrastructure services.

**Fig. 3** Nussbaum's central capabilities (center) and supporting critical infrastructures (left) mapped onto Maslow's hierarchy of needs (right). The three categories are also related to the terminology used by the Capabilities Approach analytical framework (conversion factors, capabilities, and functionings), shown in Fig. 1

Fig. 3 demonstrates how Maslow's hierarchy provides a framework from which we can begin to prioritize infrastructure according to the role that infrastructure systems play in enabling or supporting capabilities and ultimately human needs. Maslow's hierarchy suggests that during a crises, it is the human needs at the base of the pyramid that must be prioritized before those at higher tiers because they are essential for survival as well as required for people to have quality lives more generally. Thus, Maslow provides a guide for prioritizing infrastructure based on which infrastructure systems help people realize the services that fulfill their most basic physiological needs first, including the services of water, food, and emergency services. If possible, safety needs come next through services like security, mobility, healthcare, and finances.

Fortunately, it is the physiological and safety needs that infrastructure systems can most readily provide through physical water, food, energy, transportation, and medical systems. The role of physical infrastructure in supporting the needs higher up in the pyramid, like esteem and self-actualization, is less direct and are more relevant for social infrastructure systems in particular, like social networks and relationships. Still, physical infrastructure provides services that enable

people to communicate, be mobile, have access to knowledge, and be educated; Services that undoubtedly support people's belonging, esteem, and self-actualization needs. However, in the event of a crises, not all needs can be protected all the time. Maslow's hierarchy suggests that people's need for water, food, and emergency services must be prioritized first, while less urgent needs can be at least temporarily sacrificed.

## 5. Reorganizing infrastructure around critical services

Using the capabilities approach to inform prioritization of critical infrastructure emphasizes a shift from a sector-based approach to a service-oriented framework. Whereas DHS and other federal agencies employ sector specific plans and assign specific lead agencies for each of the 16 critical infrastructure sectors, a service based approach emphasizes that the provision of services requires subcomponents of multiple sectors. For example, emergency services requires aspects of the public health, transportation, communication, chemical, and energy sectors, among others. Also, water distribution systems require aspects of the water, energy, chemical, transportation, dams, as well as other sectors. Moreover, critical infrastructure systems are becoming increasingly interdependent at the same time as society is becoming increasingly dependent on these systems (Helbing 2013; O'Rourke 2007; Rinaldi 2001). A common example of infrastructure interdependence is that water distribution depends on electricity for pumping and treatment processes, and in return electricity depends on water for cooling power generating stations, all while people depend more on electricity and water systems to adapt to a warming climate (Clark et al. 2017). A service oriented framework for critical infrastructure could facilitate stronger and more effective collaboration across sectors.

Currently, the NIPP does recognize the importance of dependencies and interdependencies between sectors in one of its seven core tenets of consideration for planning. The plan also identifies particular lifeline functions, including communications, energy, transportation, and water, as essential to the operation of most critical infrastructure sectors and encourages each sector to identify and address sector reliance on lifeline functions to prevent cascading effects. Cross-sector issues are primarily addressed by the Critical Infrastructure Cross-Sector Council, which is comprised of the leaders of the Sector Coordinating Councils, who are self-organized groups that represent each sector and are responsible for coordinating with the government on a wide range of critical infrastructure security and resilience issues (NIPP 2013). In this way, information sharing across the critical infrastructure community is key to increase situational awareness between sectors. Nevertheless, the NIPP's strategy is organized around sector-specific goals for infrastructure security and resilience. A service-based plan would alternatively organize around the critical services that infrastructure provides, with goals and plans primarily structured around the infrastructure required to deliver those critical services that the public values the most.

This recognition of critical infrastructure interdependencies in conjunction with the hierarchical infrastructure results from the CA framework above enables a methodology for prioritizing components within sectors that provide the most essential services to support human needs. According to the framework, the existing infrastructure sectors that directly support the most basic physiological needs of the public during a crisis are Emergency Services, Water &

Wastewater, as well as Food & Agriculture. Indeed, resilience investments in these sectors are warranted to build disaster resilience, however the framework can also help prioritize the sub-sector infrastructure components across all sectors that are import for delivering these essential services. In other words, prioritizing Food & Agriculture because it supports access to food oversimplifies and reduces the supply chain of food to a single sector. When in reality, providing communities with food requires water, transportation, energy, chemicals, and commercial facilities in addition to agricultural assets. Moreover, broad investments in agriculture will not necessarily improve food security resilience if they are not strategically channeled towards access to food or secure food supply chains. In summary, multiple interdependent systems that span across sectors support critical services and not all components of each critical infrastructure sector are equally important for providing critical services.

Consequently, we argue that a service-based view of infrastructure should identify the minimum infrastructure needed *across* sectors to ensure people have their most basic needs met during a disaster. This would mean not protecting energy in general, but prioritizing the aspects of the energy sector that are critical for providing the services we care about most, like electricity for pumping drinking water, imminent medical procedures, refrigeration for food supply, and transportation fuel for ambulances and first responders. Rather than the current practice of investing in efforts to strengthen the most vulnerable systems to prevent failure, a service-based resilience approach would alternatively focus infrastructure investments towards enhancing safety measures around infrastructure that provides the most valuable services.

To accomplish this, the supply chains for providing the public with water, food, and emergency services (at a minimum) should be identified within each critical infrastructure sector and the classifications of infrastructure types should be reorganized around those key services. Instead of the existing 16 critical infrastructure sectors that are classified by specific types of physical infrastructure, (e.g., transportation, energy, dams, chemicals, commercial facilitates, etc.), we would have categories of infrastructure identified by the critical services they provide the public (e.g., drinking water, food security, shelter, and quality healthcare). For example, enhancing food security would entail investments all along the supply chain of food systems, including farms and farming equipment, water for crop irrigation, chemicals for necessary fertilizers and preservatives, electricity for refrigeration, transportation fuel and vehicles for food delivery, and facilities for food retail or distribution, etc.. The result would be a more resilient food system to supply the public with the service of food, but would simultaneously build resilience of important aspects of interdependent infrastructure systems like water, energy, transportation, and communication systems that are necessary for supplying food. Where possible, investments towards the sustainable aspects of service supply chains should be prioritized to advance both resilience and sustainable practices. For example, investments in local and organic food supply chains should be prioritized over industrial farming pathways.

Investments along the supply chains of critical services will not only make current supply chains more robust, but could also enable more adaptive strategies for meeting human needs. Because the focus is on services, it takes the emphasis away from particular components of physical infrastructure. The CA to critical infrastructure instead focuses on maintaining the supply of

services, even if only part of the system is functioning, or by using infrastructure systems in non-conventional ways. For example, to effectively provide the service of food, not every tractor or farm must be prioritized. In fact, a resilient food system would not be dependent on any one particular food source or facility to maintain access to nutritious food and may mean either depending more heavily on locally produced food or through importing food from other locations. For water, even if the pipelines or water treatments fail to deliver clean water, having the ability to boil water or truck in water from other locations would still satisfy basic needs temporarily. In addition, using buses or other forms of public transportation could help keep people warm or offer cooling services during weather extremes and power outages. These latter examples show how the interdependent nature of critical infrastructure could be an asset for alleviating failures or disruptions in other areas. On the other hand, during cascading failures the ability to disconnect essential services from failing interdependent systems is necessary. In these situations, decentralized services are ideal. Thus, having the flexibility to connect (i.e., interdependent and centralized systems) or disconnect (i.e., independent and decentralized) the supply chain of our most essential services would ultimately make these systems adaptable to changing operating conditions.

Furthermore, the service-based approach and supply-chain methodology for prioritizing aspects of critical infrastructure systems would integrate well with existing business supply chain resilience and management practices. The goal for businesses that invest in supply chain resilience strategies is to ensure business continuity in the face of supply chain disruptions, which ultimately ensures that the products and services they sell are available to their consumers (Sheffi 2015). This approach would help facilitate and strengthen public-private partnerships around U.S. critical infrastructure, which are essential for achieving national goals because a majority of the nation's infrastructure is owned by the private sector. Companies are incentivized to develop their own resiliency plans for their products and services, but public policy at the federal level could channel efforts towards broader, systemic, and collaborative critical infrastructure continuity plans for the most valuable public services. Future research should explore how best practices used for creating resilient supply chains in businesses and industry could be applied and extended to the context of U.S. critical infrastructure.

## 6. Conclusion

The current approach to critical infrastructure prioritization by the federal government is problematic for three primary reasons: 1) it has a misplaced focus on the physical condition of infrastructure instead of the services infrastructure provides, 2) it is too broad in its attempt to secure and protect all 16 critical infrastructure sectors, and 3) its sector-based approach has inhibited cross-sector integration. Alternatively, the CA to human development suggests that the services that infrastructure provides are important for building people's adaptive capacity to adverse events, including services provided by social and ecological infrastructure that are beyond the scope of the current, physical infrastructure-based approach. This perspective allows us to redefine critical infrastructure as the systems that are vital for protecting or providing essential human capabilities. Relating the CA to Maslow's Hierarchy of Needs provides further guidance for prioritizing infrastructure that supports essential human capabilities during a crisis.

According to the hierarchy, the services that are most critical are those that allow people to fulfill their physiological needs, including water, food, and emergency services. Focusing on these services demands a cross-sector approach towards critical infrastructure resilience, because protecting the infrastructure that provides these services stem from multiple physical infrastructure categories and interdependencies between sectors is important to consider in terms of both preventing cascading infrastructure failures as well as adaptive infrastructure recovery.

A service-based approach towards the prioritization of critical infrastructure represents a paradigm shift in the way critical infrastructure is currently understood, and could consequently have significant implications for the way we design and manage infrastructure. Prioritizing services would mean understanding resilient infrastructure in terms of its ability to maintain functionality of those services, even when faced with surprise events. Consequently, it demotes the importance of prediction and prevention of failure among vulnerable systems, and instead focuses primarily on protecting those systems that we consider most valuable. We think that a service-based approach will ultimately remove barriers to infrastructure resilience by providing a way to systemically prioritize infrastructure based on the collective values of the public. This type of approach will also consolidate efforts and resources towards the resilience of a few essential services, which are both important for disaster recovery as well as overall human wellbeing.

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