Inter-Infra: On Data Centers and Infrastructure

A Thesis Submitted to the Department of Urban Planning and Design,
Harvard University Graduate School of Design
by

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In Partial Fulfillment of the Requirements for the Degree of

MASTER IN URBAN PLANNING

May 2023

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INTER
INFRA

On Data Centers and Infrastructure

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Thank you Professor Wang for agreeing to be my advisor and having faith in me despite only meeting once before I asked. You are the North Star who reminds me that this is a thesis, not an technical brief, that decodes a subject *for* establishing the propositions it makes. I hope that this work attains that. Thank you Alex, Sergio, Mitch and Chase for your critical perspectives that informed the development of this thesis.
Thank you Rongqing for building my computer when it came in spare parts.
Thank you Jie, Min, Zihao, for your overtime hours at the CNC lab for my models.
The gratitude I hold for the people who care, love, listen, endure, challenge, drive, catch, support, cheer, and embrace me is infinite.

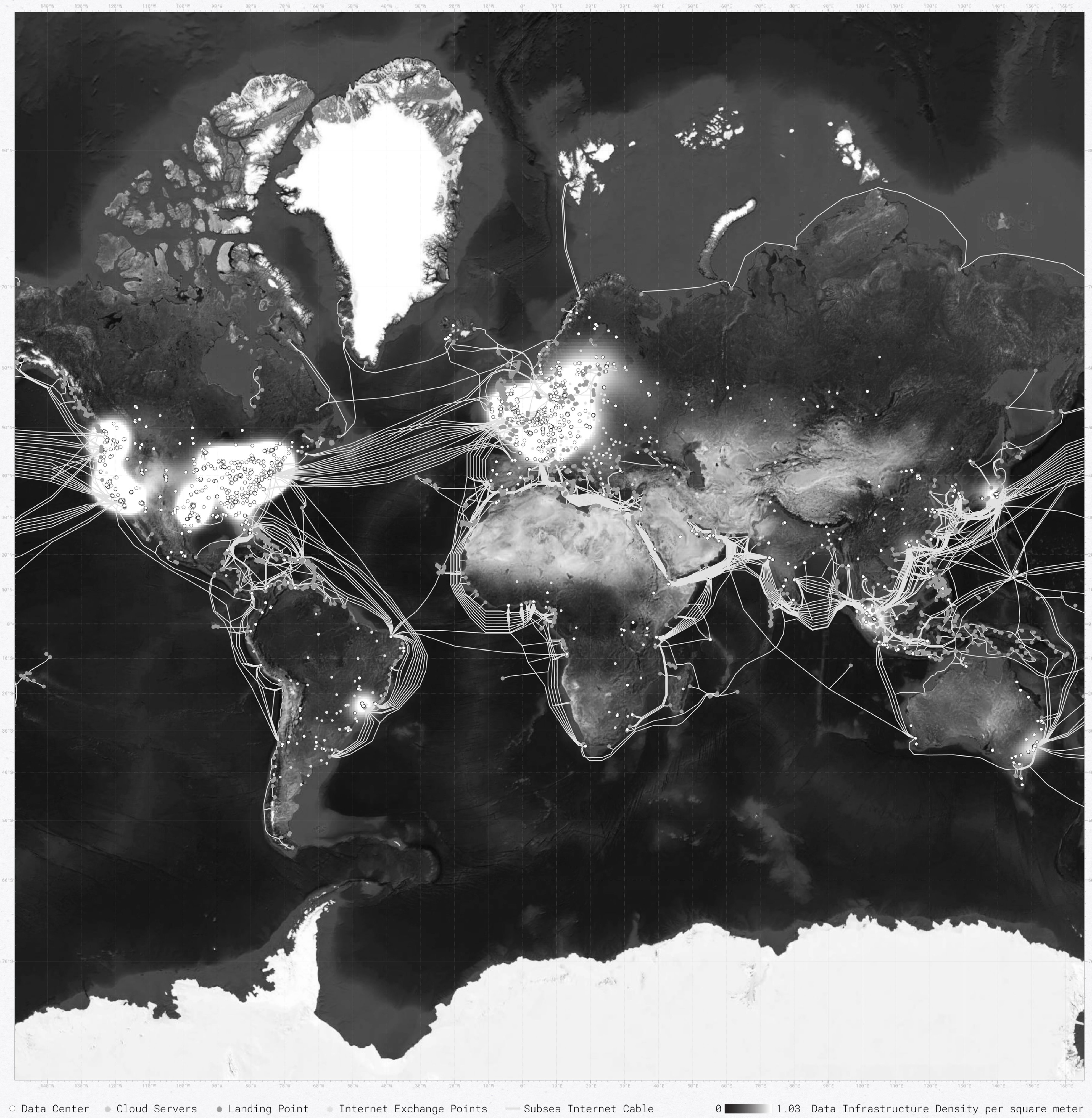
Thank you for being here.

感激不盡

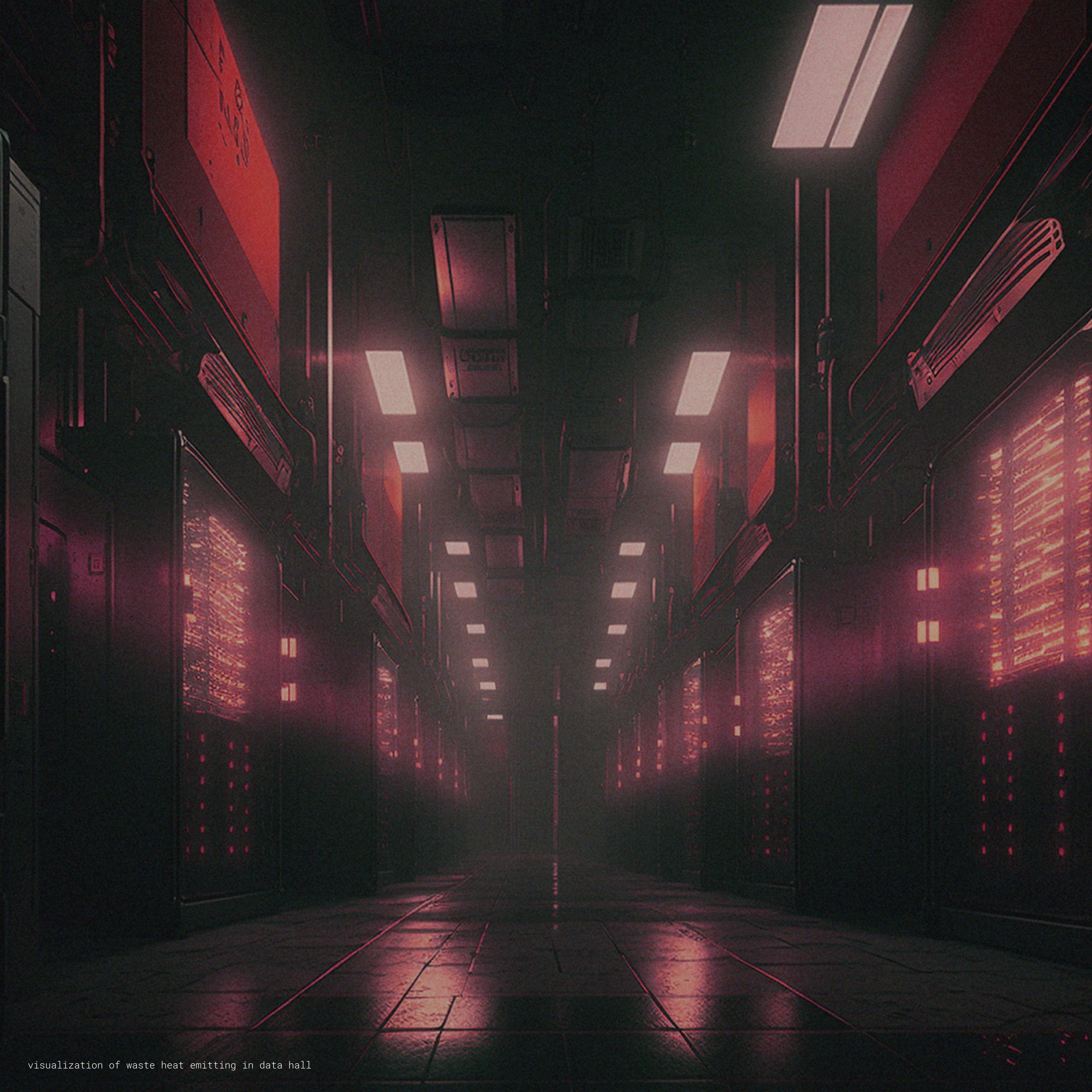
abstract 6
introduction 10
literature review 22
    on data centers 23
    on infrastructure 32
web hosting sites 42
    Mesa_AZ 44
    The Dalles_OR 44
    Chantilly_VA 46
    Secaucus_NJ 48
    New York_NY 48
design strategies 52
    power_grid_balancing 54
    hydrology 60
    heat_redistribution 65
    ecological_resilience 68
    modularity 70
policy considerations 72
    new_criteria 72
    sharing_expertise 73
conclusion 76
persons interviewed 84
bibliography 85

all drawings, graphics, maps, models, photographs, and visualizations are by author unless stated otherwise.

Data centers stand as material structures of the digital world. Given the permeance and expanding necessity of digitalization, this thesis examines the notions of data centers as infrastructure and the contemplations required for such a definition. Despite being an emerging building typology, data centers are predominantly classified by their computing capacity, utility supply and business model. This project investigates data centers geospatially and the environmental and social complications of their presence. It analyzes five sites—(1) Mesa, Arizona, (2) The Dalles, Oregon, (3) Chantilly, Virginia, (4) Secaucus, New Jersey, and (5) New York, New York—based on site characteristics of environment, energy, land use, density, and economy. The endeavor (1) elaborates why data centers are infrastructure and the considerations required for such a paradigm and (2) posits design strategies that reimagine data centers as multifunctional infrastructure that serves beyond the cyber edifice and their futures post-decommission.



Data sources: Baxtel 2023; Earthstar Geographics; Data Center Map 2022; TeleGeography 2023



visualization of waste heat emitting in data hall

In a dark, tepid room lies
an array of blinking cuboid
machines speaking in code.
They compute, store, and
transmit immortalized memory
bytes - information of today’s
mortal lives. In this dark,
tepid room lie physical matter
supporting virtual terrains,
whose boundaries unremittingly
expand, transcending the
perimeters of this space.

The contemporary cyber realm is upheld by a network of physical subsea internet cables, landing points, inland cables, data centers, and more that operates 24/7. The embedded information and communication technology carries the new medium of communications infrastructure that also supports the digitization of systems that facilitate our social and economic conditions – the everyday[1].
In light of the unprecedented scale and scope of these developments, one might rightfully inquire whether the nature of these technologies implies that they are a new kind of infrastructure and how should we contemplate infrastructure in today's context.

With French roots from Latin parts in the late 19th century, infrastructure initially referred to "the substructure or foundation of a building, road, or railroad bed."[2]

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[1] Brown, "The Importance of Information and Communication Technology (ICT)."

[2] "'Infrastructure.'"

Infrastructure. it’s all around you (Merriam-Webster)

Infrastructure. the basic physical and organizational structures and facilities (e.g. buildings, roads, power supplies) needed for the operation of a society or enterprise.
“the social and economic infrastructure of a country” (Oxford Languages)

Infrastructure. The infrastructure of a country, society, or organization consists of the basic facilities such as transportation, communications, power supplies, and buildings, which enable it to function....improvements in the country’s infrastructure. (English Dictionary)

Infrastructure. 1: the system of public works of a country, state, or region also : the resources (such as personnel, buildings, or equipment) required for an activity 2: the underlying foundation or basic framework (as of a system or organization) 3: the permanent installations required for military purpose (Merriam-Webster)

Infrastructure. the fundamental facilities and systems serving a country, city, or area, as transportation and communication systems, power plants, and schools: Investments in infrastructure helped the U.S. economy recover from the Great Depression.
the basic, underlying framework or features of a system or organization:Over the years, as the incidence of cancer increased, the infrastructure of the hospital was developed to accommodate the new cases.
the military installations of a country:We could do much with just a fraction of the billions spent to maintain our robust overseas infrastructure.(Dictionary.com)

Infrastructure. Infrastructure refers to the physical and organizational structures that support a society or economy. This includes everything from roads, bridges, and transportation systems to buildings, power grids, and communication networks. Infrastructure can be publicly or privately owned and can be used for a variety of purposes, such as providing basic services like water and electricity, facilitating trade and commerce, and supporting social and cultural activities.

In general, infrastructure is essential for the functioning of modern societies and economies, as it enables people and goods to move around more efficiently and reliably, and it supports economic growth and development. Good infrastructure can also enhance quality of life by providing access to essential services and amenities, such as healthcare, education, and cultural facilities. (ChatGPT)

Information and Communication Technology (ICT)
Includes all categories of ubiquitous technology used for the gathering, storing, transmitting, retrieving, or processing of information (e.g., microelectronics, printed circuit boards, computing systems, software, signal processors, mobile telephony, satellite communications, and networks). (CNSSI 4009-2015 from DoDI 5200.44)

Encompasses the capture, storage, retrieval, processing, display, representation, presentation, organization, management, security, transfer, and interchange of data and information.
(NIST SP 800-161r1 under Information and Communications Technology from ISO/IEC 2382:2015 – adapted; NISTIR 7622 under Information and Communications Technologies from ANSDIT - Adapted)

Encompasses all technologies for the capture, storage, retrieval, processing, display, representation, organization, management, security, transfer, and interchange of data and information. (NISTIR 8074 Vol. 2 under Information and Communications Technologies)

By comparing the definition of infrastructure and the role of information and communication technology (ICT) in our lives today, it is apparent that this is the new communications infrastructure paradigm succeeding telecommunications. Meanwhile, data centers are indispensable today in the present ICT infrastructure. They are spaces for the hardware that the "network of computing and storage resources that enable the delivery of shared applications and data" inhabits[3]. As we shift from the age of telecommunication to internet technology, which extends beyond communication, data centers are nodes for processing information transmitted wirelessly through the internet. Physically, they are buildings that store machines whose components include "routers, switches, firewalls, storage systems, servers, and application-delivery controllers.[4]"

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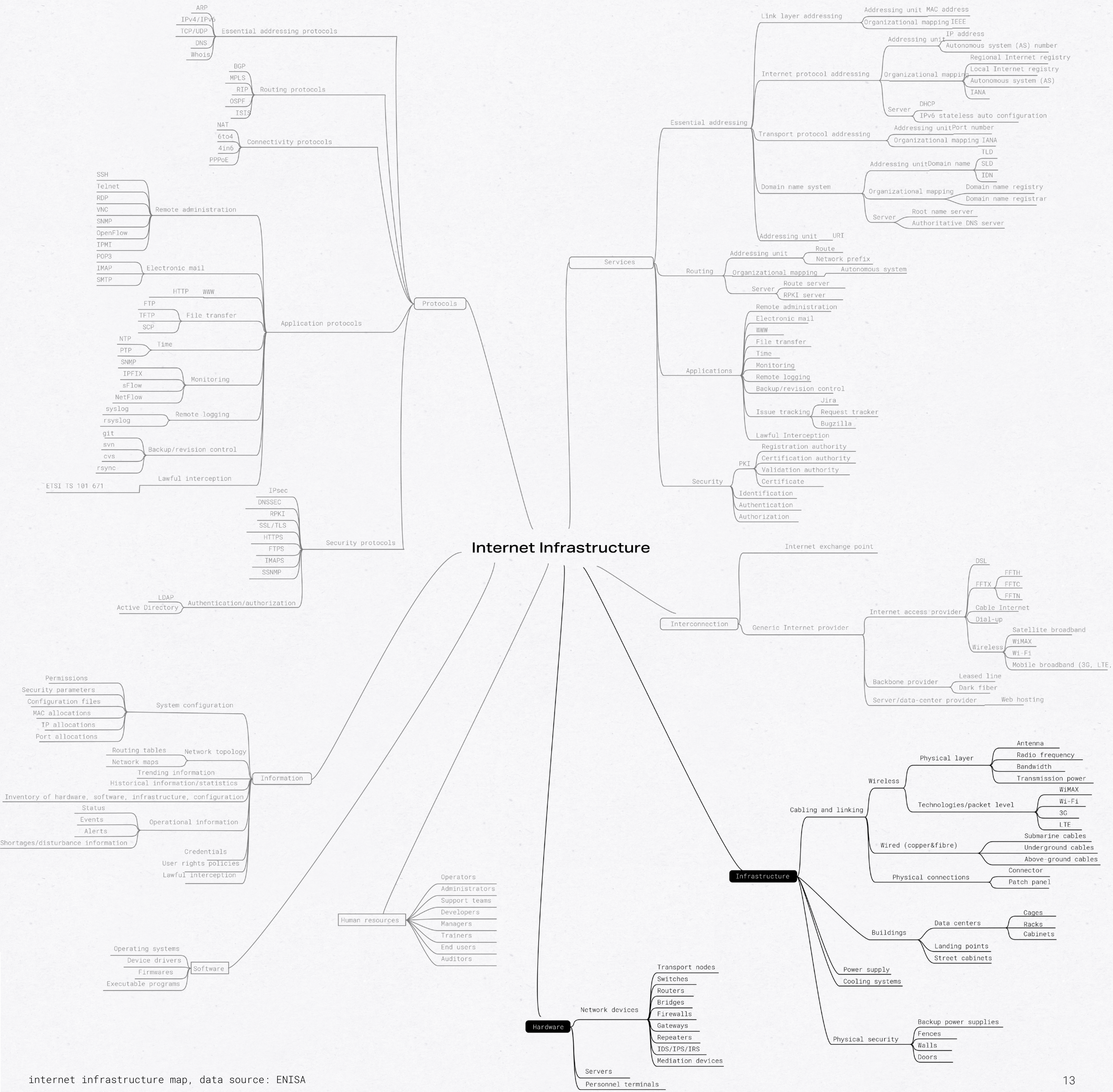
[3] "What Is a Data Center?"

[4] "What Is a Data Center?"



internet infrastructure map, data source: ENISA

“HARDWARE” building

MACHINE

COMPUTING

POWER

CLIMATE

HUMAN

ADMINISTRATIVE

Computing Equipment
Servers
Switches
Routers

Operations Center

Climate Control Equipment

Main Power Systems
Power Distribution Units
UPS Systems
Backup Generators

Office +/ Security Room

Data source: TierPoint

“SOFTWARE” systems

Onsite Operations System
Carrier-Neutral Networking
Multi-tenant Cloud Pod
Compliance Certification

Cyber Security

Building Management System

Building Security System

Programmatically, a data center can be dissected into four main sections: computing, power distribution and storage, climate control, and physical security[5]. Auxiliary programs such as small office space may be present.

As critical components of this connectivity network, data centers are naturalized components of a new generation of infrastructure that supports our integrated physical and digital realms. Spatially, they occupy a spectrum of geographies and scales, ranging from urban to rural and one server to a mega warehouse estate. Operationally, they require immense energy and utility support such as electricity and water. A large-scale data center can occupy 1.3 million square feet[6] and consume as much power as a “medium-sized town.”[7] Like prior generations of infrastructure, data centers are necessary and resource intensive. They belong to a global information technology communication network that includes subsea internet cables, landing points, inland internet cables, and internet exchange points. In light of the integration of internet technology in our economy, society, and even culture, the construction of data centers and other internet infrastructure components is anticipated to increase.

On the other hand, data centers, as a new building typology that mostly houses machines instead of humans, pose challenges for the geographies they occupy. Key complaints include its extensive power and water consumption, noise pollution in residential neighborhoods, and inequity. These issues fall well under the purview of planning. This analysis categorizes the complications into ones of environment, quality of life, its current ambiguous status as infrastructure, and its role in the international territory of electronic waste pollution.

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[5] Ellsworth, “Infographic.”

[6] Moss, “Amazon Web Services Owns 11.9 Million Square Feet of Property, Leases 14.1 Million Square Feet.”

[7] Choo, Galante, and Ohadi, “Energy Consumption Analysis of a Medium-Size Primary Data Center in an Academic Campus.”

First, regardless of their size, data centers are exorbitantly energy-intensive[8], "consuming 10 to 50 times the energy per floor space of a typical commercial office building.[9]" Another common complaint is their high consumption of water[10]. This is specific to data centers, typically those above one hundred square feet[11], which use liquid cooling technologies such as evaporative cooling systems as it is a more efficient and often cheaper method for cooling than non-liquid technologies. These two factors substantially impact on the environment, with high carbon emissions and excessive water use that disrupts local hydrology.

Data centers impact the quality of life in terms of noise pollution and aesthetic incoherence. They generate a lot of noise from HVAC systems[12], disrupting the physical health and well-being of residents. Additionally, as a building predominantly occupied by servers, switchboards, and other hardware, the building often takes the form of a windowless cuboid distinct from its local architectural language and may ignore qualitative aesthetic considerations. This results in a visually disengaged structure that disrupts the neighborhood and landscape[13].

The ambiguous status of data centers as infrastructure causes loopholes in emergency events when they are overlooked in the power supply hierarchy. As critical nodes of ICT, an inoperable data center may paralyze the communications functions required in disaster management. On the other hand, as commercial property, the investment, and placement of a data center in a community does not necessarily create a proportional number of jobs per square foot. Additionally, its technical specificity may hinder local employment[14].

Finally, data centers serve as institutional actors in the production of electronic waste. However, it is recognized that they have expertise in the management of electronic equipment and waste. As such, they can play an integral role in global initiatives to address this matter.

This thesis will examine the abovementioned implications of data centers and refer to some more in its investigations. The material from this effort will consolidate into as a translation guide for data center developers and urban planners to reconcile the language barrier between industry and field to build better data centers as a new and unique typology of infrastructure that can integrate more sensibly into our environment. Meanwhile, the agenda of this thesis is to resynthesize and reinterpret infrastructure today. As a nascent building typology to support communication and the cyber verse, data centers serve as a proxy to reconceive the notion of infrastructure. To explain, this discussion turns to global challenges and infrastructure today.

The infrastructure paradigm needs to shift as global challenges such as climate change call for a sustainable approach to developing them. Climate change, a consequence of excessive carbon emissions, global warming, and depletion of natural resources, is a chronic international emergency that has demanded a change in how we produce and consume.

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[8] Glanz, "Power, Pollution and the Internet."

[9] "Data Centers and Servers."

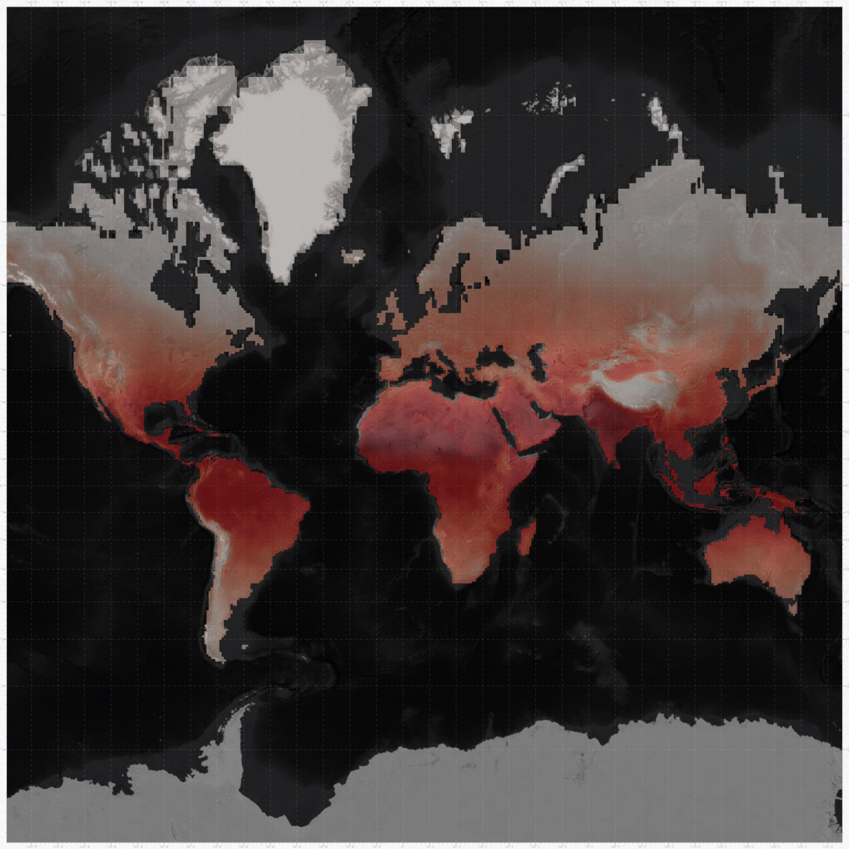
[10] Mytton and Ashtine, "We Are Ignoring the True Cost of Water-Guzzling Data Centres."

[11] Rochlin, "What Are Data Centers?"

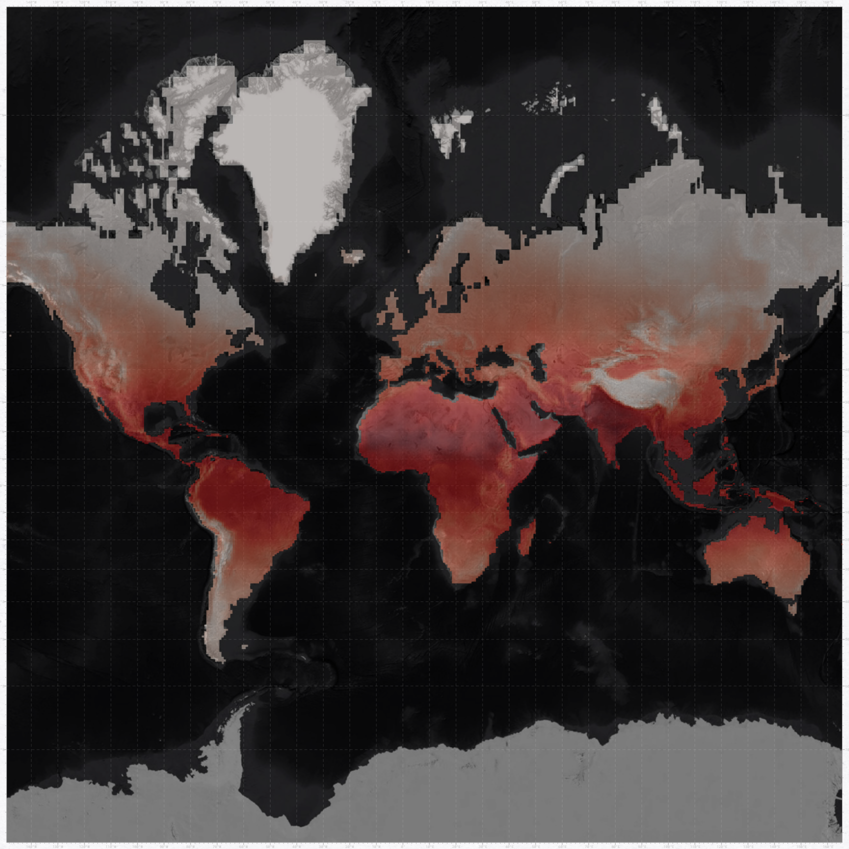
[12] Olivo, "Northern Va. Is the Heart of the Internet. Not Everyone Is Happy about That."

[13] Cutieru, "Architecture Without People."

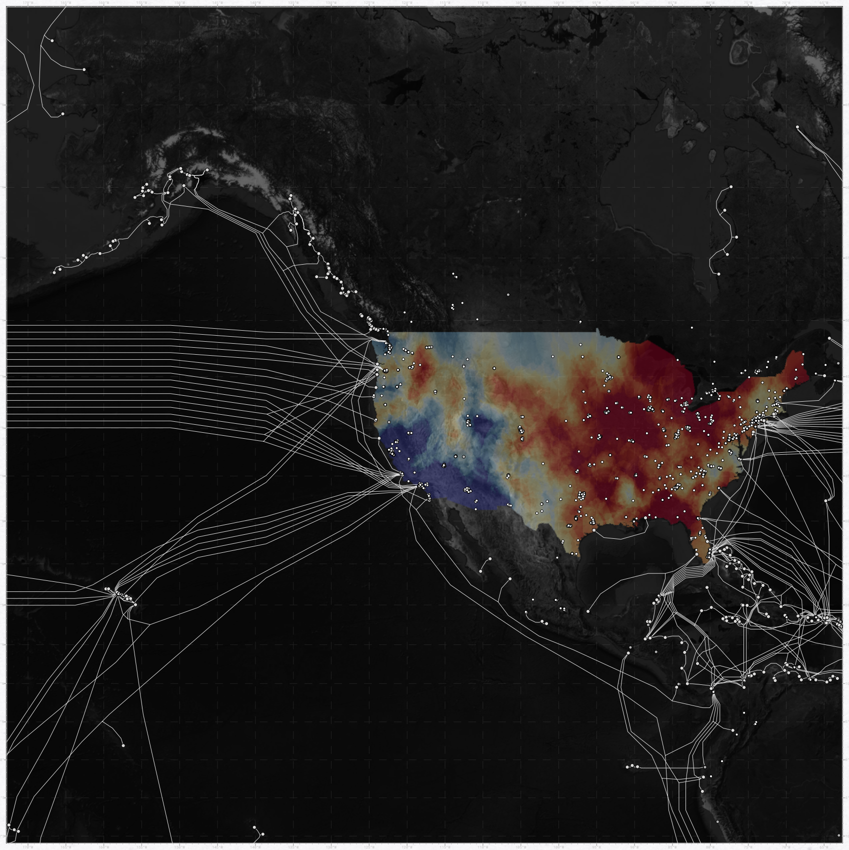
[14] Jeans, "Data In The Dark."



Median Temperature in May (1981-2010) 36.0°C -1.2°C
Data Source: Esri Earth Observations, Global Historical Climate Network - Daily v. 3.24.,HadUK Grid, Met Office



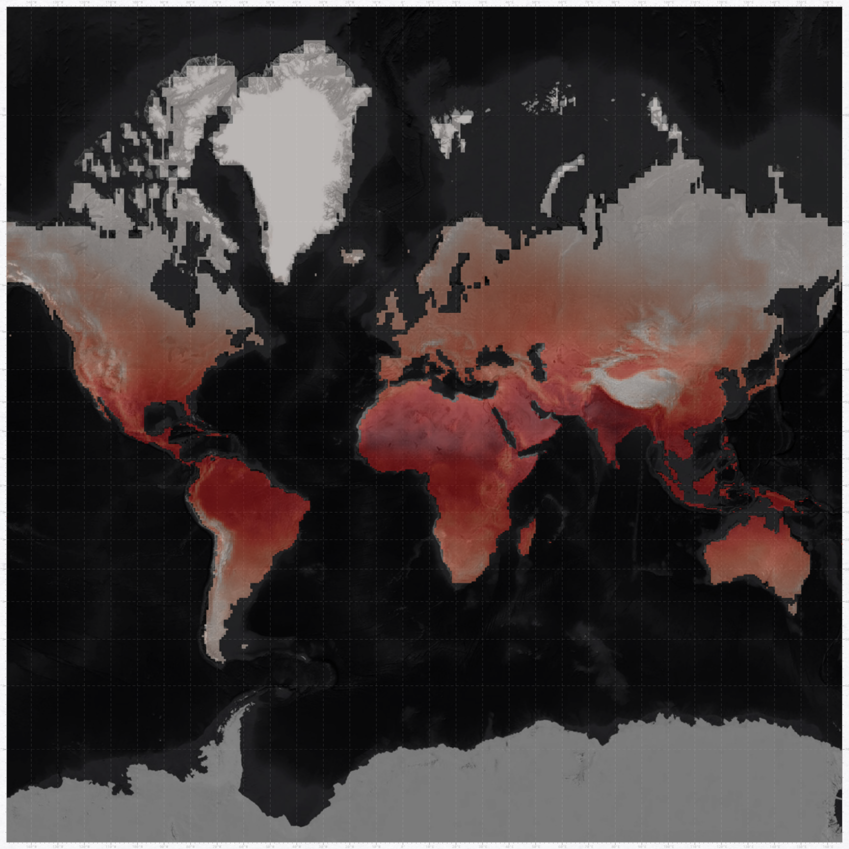
Projected Temperature in May (2040-2069) 38.0°C 1.4 °C
Data Source: Esri Earth Observations, Global Historical Climate Network - Daily v. 3.24.,HadUK Grid, Met Office



∘ Data Center
∘ Internet Exchange
∘ Landing Point
∘ Cloud Server
— Subsea Internet Cable

Percent Change in Temperature (°F)
7.52905
-34.1689

Data Source: Esri, Garmin, FAO, NOAA, USGS, EPA



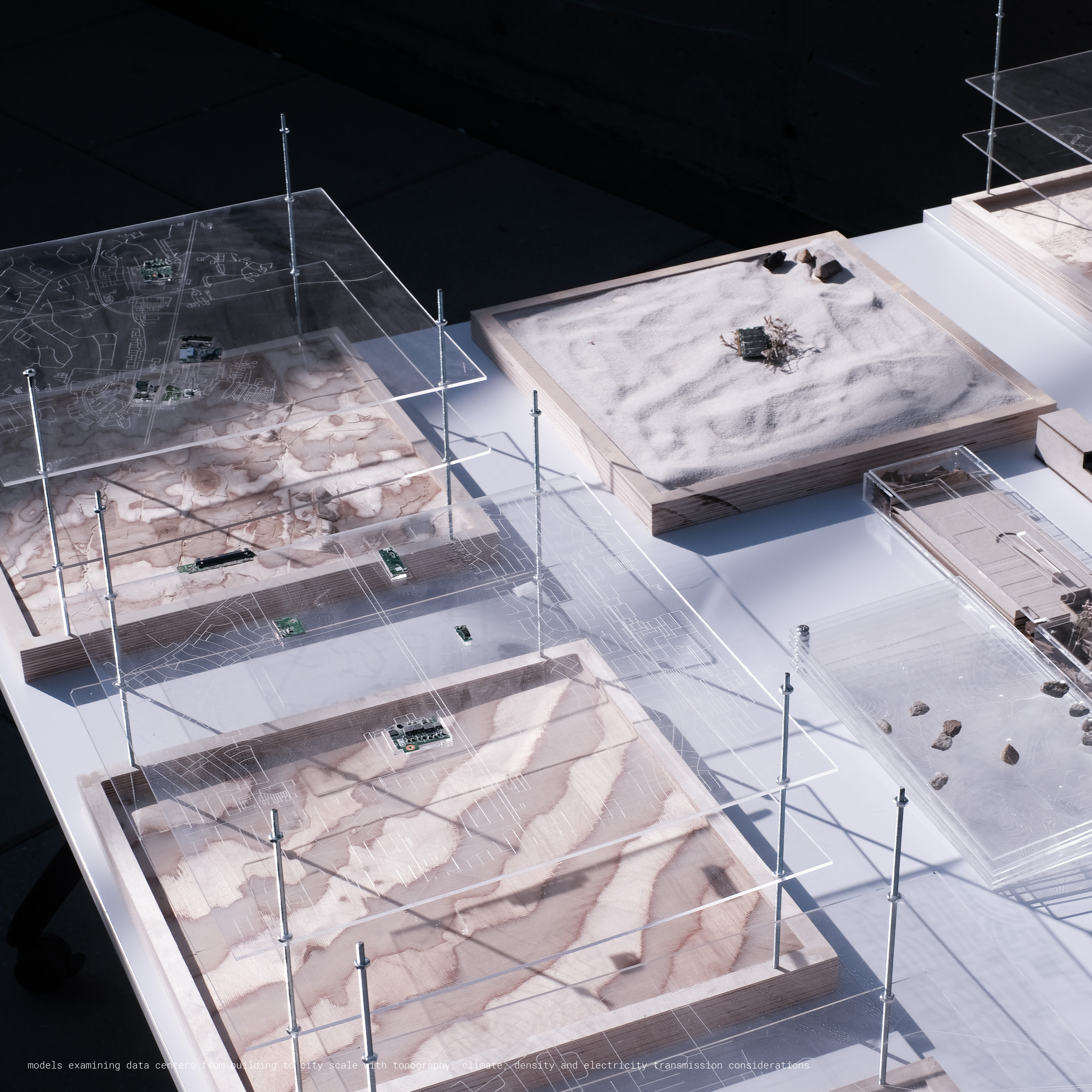
Projected Temperature in May (2070-2099) 38.0°C 1.5 °C
Data Source: Esri Earth Observations, Global Historical Climate Network - Daily v. 3.24.,HadUK Grid, Met Office

The United Nations Department of Economic and Social Affairs' Sustainable Development Goal 9, which is "build resilient infrastructure, promote sustainable industrialization and foster innovation" explicitly defined the direction of infrastructure development.

Target 9.4:

By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.

investigative models of site made with found electronic waste to represent data centers



models examining data centers from building to city scale with topography, climate, density and electricity transmission considerations

This thesis argues that infrastructure needs 1) to become multifunctional structures and 2) planning and design for its life after being decommissioned. The proposition considers a spectrum of spatial and temporal dimensions – mini to mega size, pre-, peri- and post-operations. It proposes potential functions that are synergistic with a data center during and after its active lifespan, given its spatial conditions and operational properties such as machine-oriented architecture, building footprint, power requirements, and waste heat production. Building on the position of data center as a node in its existing infrastructure, this thesis posits polymathic data centers at multi-scalar iterations that can perform functions beyond computing. Examples illustrated include power grid balancing, district heating, hydrological, and/or ecological resilience nodes that are design strategies to prompt further exploration. At the same time, the thesis also urges planning for the site's life after the decommissioning of the data center. For instance, if a data center is retired, how does it not become a post-industrial void or brownfield? It imagines the structure serving other functions, such as a grid balancing node in the renewable energy network and/or an ecological resiliency node as a horticultural reserve for climate adaptation. By elaborating and visualizing potential post-decommission scenarios, this thesis provides direction and inspiration to incite more speculation about the futures of infrastructural planning and landscapes.

The literature review is divided into two sections that examine data centers and infrastructure. The first section identifies a gap in the comprehension of data centers between the related industries and government. In the process of closing this gap, it emphasizes that the complexity of data centers requires system-based thinking beyond spatial dimensions. The second section will examine the theories of infrastructure and internet infrastructure to set up the framework for assessing the data center sites of study later.

This section reviews the existing literature about data centers to understand, reorganize and reinterpret them in terms of physical properties, scale, and typologies for planners and designers. It also interrogates the poor commensurability between disciplines that understand data centers differently. The data center industry conceives data centers in terms of systems operations[15] and the fields of planning, design and real estate evaluate data centers in terms of space[16]. This divergence reveals a gap between seeing data centers as infrastructure and real estate asset. It establishes that the intangibility of the core purpose of data centers – digital communications – entails that it is a typology of infrastructure that cannot be perceived as a real estate asset as easily as other types of infrastructure. To do so, this section will examine the unique features of data centers that call for additional considerations and reconsiderations as infrastructure and asset property.

First, we dissect what data centers are. Most definitions of data centers, including those by industry associations, classify data centers in terms of efficiency and performance. The indicators are power capacity in watts, latency in milliseconds, and power usage efficiency which is a ratio.

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[15] "What Is a Data Center?"

[16] "Data Center REITs | Information on Investing & More | Nareit," accessed April 2, 2023, https://www.reit.com/what-reit/reit-sectors/data-center-reits.

Operations

Data Center Industry

Power Capacity and Consumption
Measured in watts, often in kW (1,000 watts) or mW (1,000,000 watts). This indicates 1) how much power capacity the data center has access to and 2) how much power the server rack consumes as a proxy for compute capacity. Higher is faster and more computing capacity, which needs more cooling.

Power Usage Effectiveness (PUE).

PUE measures the efficiency of power usage in data center designs. PUE shows the ratio of power used to run the computer infrastructure vs overall power usage (for cooling etc.) total facility power/IT equipment energy = PUE. Closer to 1 is more efficient if the data center is monofunctional.

Latency
Measured in milliseconds (ms). Latency is the delay between a user's action and a web application's response to that action, often referred to in networking terms as the total round trip time it takes for a data packet to travel.

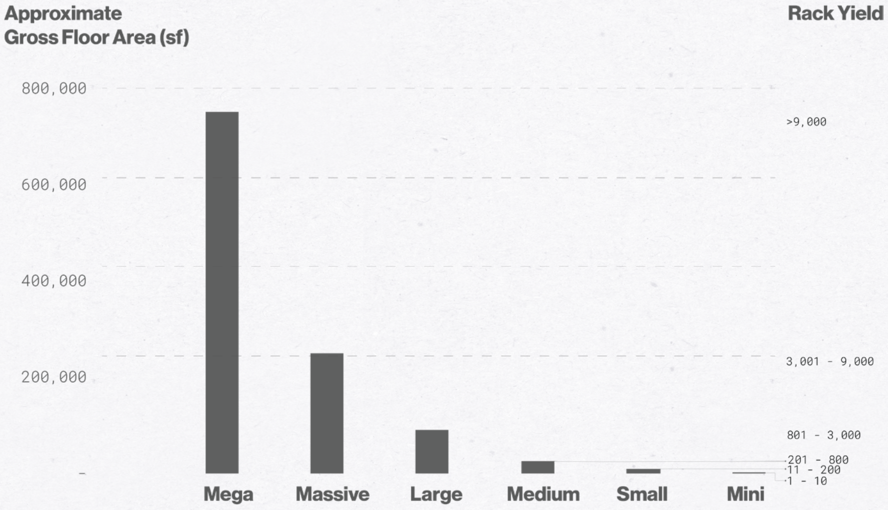
U, or RU:
A unit of space in a rack, equal to 1.75" in height to hold servers.

Server
Ordinary servers are 3U tall. A 42U rack will hold 42 1U servers, 21 2U servers and 14 3U servers. The more servers it can hold, the higher the density, the more powerful the computing.

Rack
Shelf for servers. Standard 42U racks racks are approximately 24in. w x 78in. h x 40in. d (2ft. w x 6.5ft. h x 3.3ft. d) Each rack is assumed to be 16-25 square feet to allow aisle and perimeter space around the server room.

Rack yield
The number of servers that can fit within a compute space. Compute space is the area containing server racks and related IT equipment in a data center. It is typically 30-35% of the data center's gross floor area.

language barrier



Spatial Implicatiions

Planners, Designers, Developers, Neighbors

Pure-play Data Center – By Storage Capacity

Cabinet Capacity

Cabinet capacity is the total number of cabinets that are available at a data center, i.e., the total cabinet capacity at which the data center operates. Clients can combine and use multiple adjacent cabinets within a data center, based on their requirements.

Utilization Rate (%)

Utilization rate indicates the ratio of utilized cabinets in service. It showcases the percentage of cabinet capacity utilized.

Billed cabinets

Billed cabinets are the total number of cabinets that are used by clients.

Average Monthly Revenue Per Cabinet

Average monthly revenue per cabinet indicates revenue generated by a data center from each cabinet. It is calculated as total revenue divided by the average number of cabinets occupied.

Pure-play Data Center – By Power Consumption

Capacity In Service

Capacity in service is the total power capacity available at a data center to operate the facility, i.e., electricity consumption, specifically kilowatts (kW) and megawatts (MW).

Utilized Capacity

Utilized capacity is the total of all capacity sold in MW for utilization where the service has commenced.

Utilization Rate (%)

Utilization rate indicates the ratio of utilized capacity to capacity in service. It showcases the percentage of capacity utilized.

Contracted Capacity

Contracted capacity is the capacity for which clients are required to pay reservation fees.

Average Monthly Revenue per MW

Average monthly revenue per MW indicates revenue generated by a data center from each unit of megawatt (MW). Average monthly revenue per MW is calculated as total revenue divided by the average utilized capacity (MW).

Qualified Data Center REITs

Portfolio Occupancy Rate / Utilization (%)

Portfolio occupancy rate measures the occupancy rate or the percentage area of a REIT’s property that has been leased. It is calculated as leased space divided by total leasable area. The portfolio occupancy rate is a measure of success that a REIT has had in attracting tenants and leasing the space it owns. The higher the occupancy rate for a REIT over time (compared to its peers), the better.

Total Square Feet (K) / Area in Service

Total square feet (K) is the total amount of floor space available for rent to retail tenants.

Square Feet of Expiring Lease (K)

Square feet to expiring lease (K) is the number of square feet of lease which is expiring in a period.

Expiring Rent Per Square Feet

Expiring rent per square foot is the rent per square foot at the time of expiration of the lease.

Average Cost of Debt (%)

Average cost of debt (%) is a measure of the average interest rate paid to fund a retail business. It is calculated as interest expense paid divided by average debt (secured and unsecured loans and revolving credit facilities)

Size Metric	Rack Yield	Compute Space (sf)	Approximate Gross Floor Area (sf)
Mega	>9,000	>225,000	750,000
Massive	3,001 - 9,000	75,001 - 225,000	250,000
Large	801 - 3,000	20,001 - 75,000	90,000
Medium	201 - 800	5,001 - 20,000	25,000
Small	11 - 200	251 - 5,000	8,000
Mini	1 - 10	1 - 250	400

Data Center by Tiers

Tier	Description	Uptime	Downtime per year
I - Basic Capacity	Data centers provide dedicated site infrastructure to support IT beyond an office setting, including a dedicated space for IT systems, an uninterruptible power supply, dedicated cooling equipment that does not shut down at the end of normal office hours, and an engine generator to protect IT functions from extended power outages.	99.671%	28.8 Hours
II - Redundant Capacity	Data centers include redundant critical power and cooling components to provide select maintenance opportunities and an increased margin of safety against IT process disruptions that would result from site infrastructure equipment failures.	99.749%	22 Hours
III - Concurrently Maintainable	Data centers have no shutdowns for equipment replacement and maintenance. A redundant delivery path for power and cooling is added to the redundant critical components of Tier II so that each component needed to support the IT processing environment can be shut down and maintained without impactingthe IT operation.	99.982%	1.6 Hours
IV - Fault Tolerance	Site infrastructure builds on Tier III, adding the concept of Fault Tolerance to the site infrastructure topology. Fault Tolerance means that when individual equipment failures or distribution path interruptions occur, the effects of the events are stopped short of the IT operations	99.995%	26.3 Minutes

Data Source: Chamber of Commerce Technology Engagement Center 2017

Yet their spatial properties are rarely explained. In the screenshot of a web search, most results focus on the certification level, also known as “Tier”, or single or multi-tenant business model than the scale of a data center. The Data Center Institute provided classification in 2017 shown below.

Generally, this classification can still be applied today. However, these figures are meaningless to planners and designers because one cannot easily infer the spatial significance of 10kW. The differences in metrics inhibit communication and collaboration[17] between data center professionals, planners, designers, and developers to build better performing and sustainable data centers.

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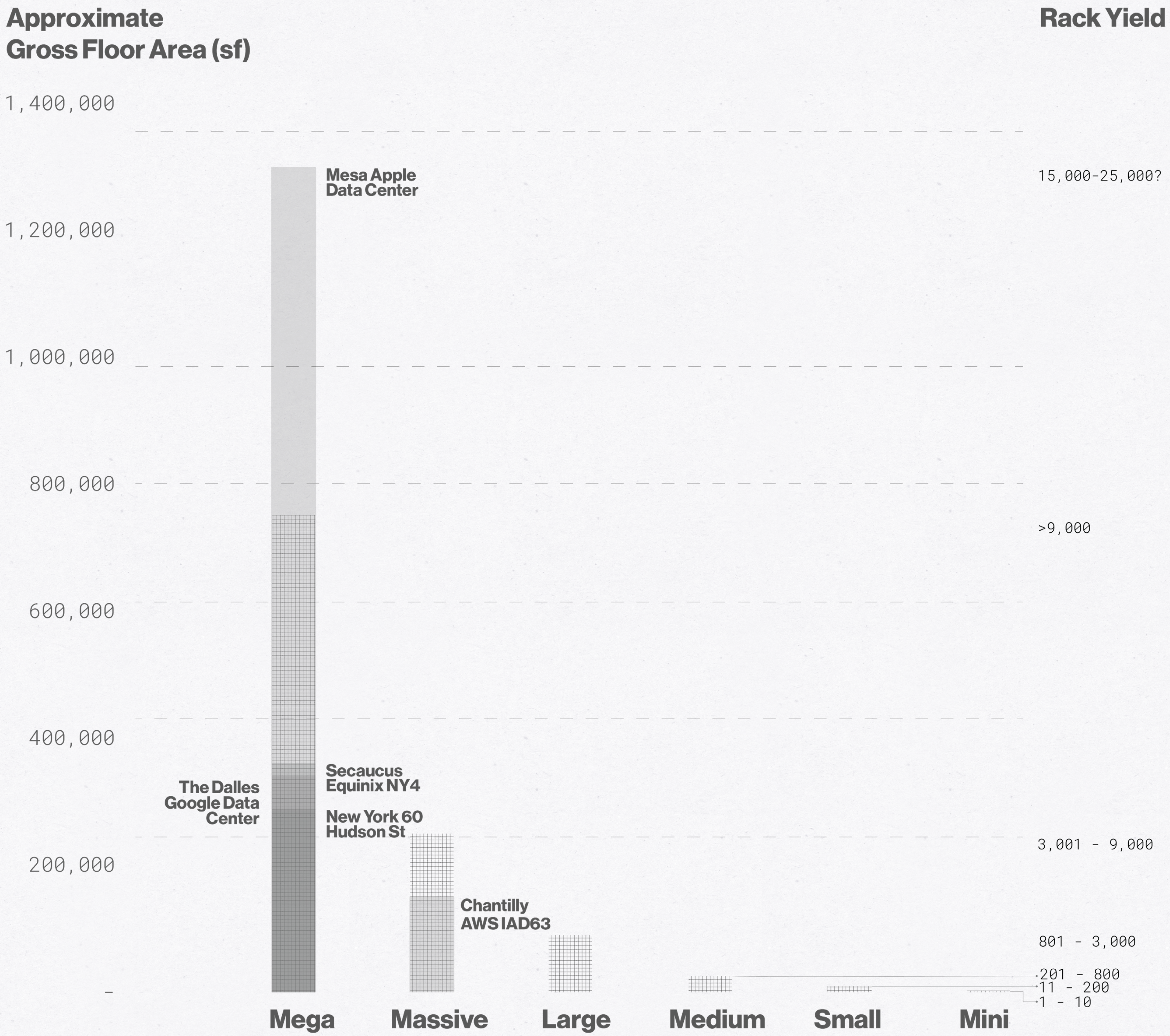
[17] Hirst, “Scientific Jargon, Good and Bad.”


Approximate Gross Floor Area (sf)
Rack Yield
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
–
Mesa Apple Data Center
Secaucus Equinix NY4
The Dalles Google Data Center
New York 60 Hudson St
Chantilly AWS IAD63
15,000-25,000?
>9,000
3,001 - 9,000
801 - 3,000
201 - 800
11 - 200
1 - 10
Mega
Massive
Large
Medium
Small
Mini

It is also noteworthy that extreme or higher density and mega data centers have been increasing as the industry grows. The Data Center Institute noted the increase of rack density and compute space in from 2007 to 2017[18]. In essence, there is no comprehensive classification of data centers that includes gross floor area and compute space, such as its function can be applied for technology professionals, who understand the kind of data centers that is suitable or needed at a site, and for planners and designers who can evaluate the spatial, social, economic, and environmental implications of a kind of data center on said site. More critically, a comprehensive classification needs periodic updates as the equipment technologies are also innovating at a competitive pace.

A more critical discussion is the current perception by investors, developers, owners, and operators that data centers are real estate assets rather than infrastructural units with social, economic, environmental, and political implications. Through existing literature and a series of interviews with industry professionals, it is observed that data centers specifically cannot be evaluated in conventional real estate terms as such a perception would not only result in complications that impact their communities and environments, but also inhibit technological development in the industry as well. In the longer term, once technological development prevails, it would change the spatial requirements of data centers, and without due planning, we may be left with another generation of post-industrial landscapes that are socially, economically, and environmentally expensive to recorrect[19] [20].

Remedial Option	**Cost per acre-foot**
Consolidation and covering contaminated soil on-site (i.e., under roads and structures)	$1,000 – $2,000
Cap contaminated soil with clean soil	$7,000 – $12,000
Blending with clean soil from on-site	$1,000 – $2,000
Blending with clean soil from off-site	$8,000 – $15,000
Excavation and removal of contaminated soil	$32,000 –$ 80,000
Proven and innovative soil treatment technologies	$50,000– $100,000

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[18] Pham, "Data Centers."

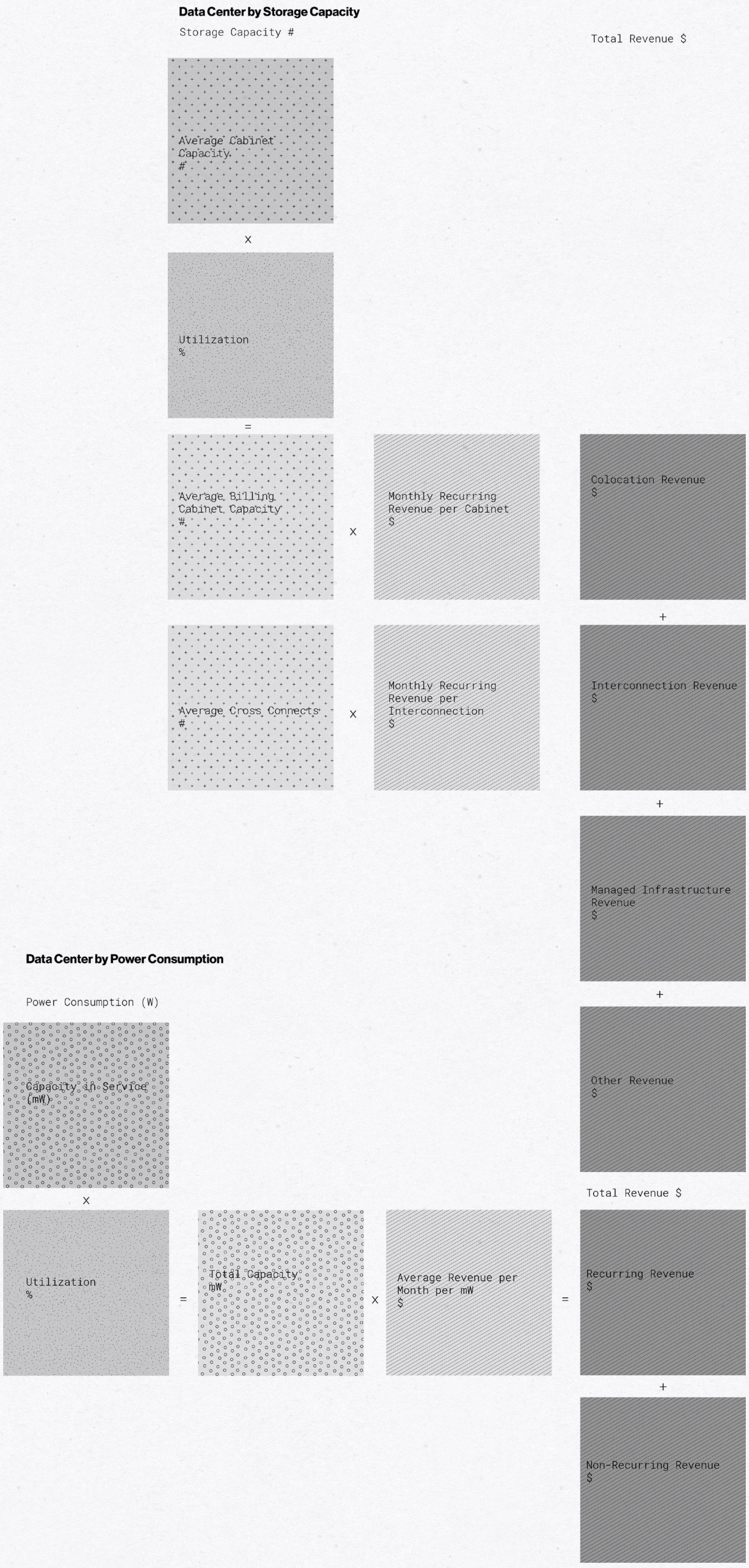
[19] US EPA, "Understanding Brownfields."

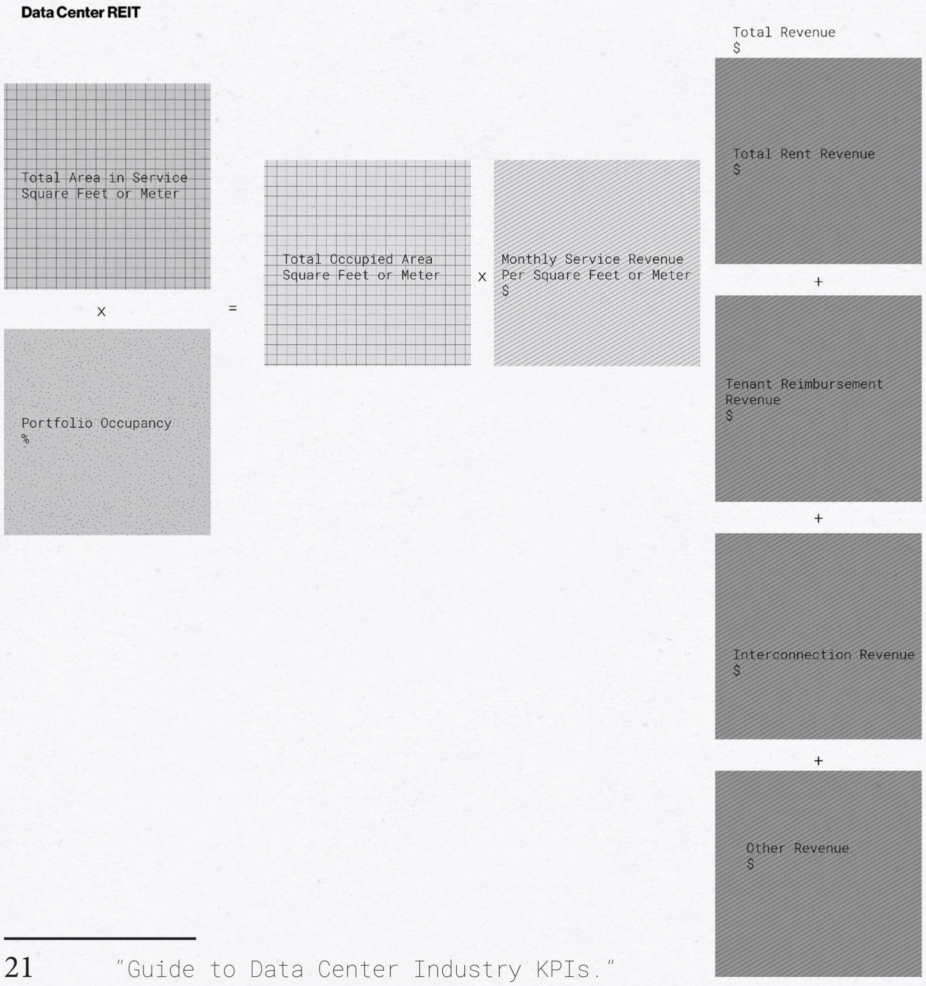
[20] Grandoni, "After Decades, Some of America's Most Toxic Sites Will Finally Get Cleaned up."

In terms of business operations, data centers can be classified based on the needs of businesses. Common types include[21]:

1. Enterprise data centers: owned and operated by companies in-house.
2. Colocation data centers: lease individual servers, racks/cabinets, bandwidth, other equipment, and space to companies/tenants on the lease.
3. Managed data centers: offer servers or cabinets for rent and provide management services, including maintenance, system upgrades, and restoring services, among others
4. Cloud data centers provide third-party cloud services to set up virtual data centers on the cloud. This concept is similar to colocation data centers but is off-premises and hosted by a cloud service provider.

From a data center ownership perspective, the main categories are pure-play data centers and data center REIT (Real Estate Investment Trust). The revenue models can be based on power consumption or compute capacity and is visualized below:





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[21] "Guide to Data Center Industry KPIs."

While data center REITs are motivated by the price per square foot to maximize their profits[22], data centers as infrastructure should be focused on maximizing thier operational performance, which is concerned with increasing density[23]. This creates tension between the technological and real estate development of data centers. In order to attain denser data centers, more advanced cooling systems and better-performing servers need to be in place. This requires higher capital expenditure to install or replace existing cooling systems, servers, and other equipment. Meanwhile, data center owners with business models that obtain income from leased area in service do not immediately benefit from the higher density because the area occupied does not increase. This is reflected in today's data center market in which "high-density" refers to data centers that accommodate servers that compute 10kW or higher in one server when densities as high as 100kW per rack are possible with existing data center technologies[24] [25] such as that of Nautilus Data Technologies[26]. In interviewing with an engineer of their team, it was highlighted that the data center market was not ready for density per rack of 100kW as higher performing servers are more expensive, technological unfamiliarity and occupying less square footage were not favorable to data centers owners, such as data center REITs, whose revenues are generally tied to floor area leased and cannot increase the price per square foot lease immediately due to business considerations. This difference in key metrics inhibits the development of efficient data centers that can support advancements in technology, such as machine-learning, artificial intelligence, data science, digital media, and communications[27]. Responding to Goal 9[28], it calls for an alignment of metrics to assess data centers between the different actors within the industry itself for more efficient *innovation*. Existing government policies and incentives such as land use and tax credits may induce this alignment by tying technology and sustainability metrics such as density, energy, and water efficiencies to the policy. Given the necessity of data centers in ICT infrastructure and their impact on our world, efficiency in performance and land use should be prioritized. The following section discusses the infrastructural status of data centers and proceeds to the complications of their presence in our built environment today in the section after.

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22 Wood, "Australia Data Center Market Investment Analysis Report 2022-2027."
23 Isberto, "What Is Data Center Density and Why Is It Important?"
24 "100 KW UPS Power Module Launch."
25 "Clustered Systems Cools 100kW in Single Rack."
26 "Nautilus Data Technologies - Water-Cooled Data Centers."
27 "2022 Global Data Center Market Comparison."
28 "Goal 9 | Department of Economic and Social Affairs," 9.

perspective of a data center amidst grass field

The notion that data centers are infrastructural members is not novel. It falls in the purview of communications and information infrastructure, which are present in academic discourse, policy and manifest in practice as the use of the internet is increasingly integrated into our physical world such as digital banking, e-commerce, e-learning, e-mail, instant messaging, virtual meetings, remote working, and more. This section contains a literature review about 1) the theories of infrastructure, 2) internet infrastructure, and 3) the relationship between infrastructure and real estate to locate the role of data centers within this edifice.

Embedded in the dictionary definitions of infrastructure stated in the introduction earlier is the notion of a system of relations. To borrow Gregory Bateson's premise in *Steps to an Ecology of Mi*nd, "What can be studied is always a relationship or an infinite regress of relationships. Never a "thing."[29] Infrastructure is the constructed ecology that supports the human condition. The material manifestation of this ecology is "physical things: pipelines, roads, wiring, cables, military installations, computer equipment, buildings…[which are] organized into physical networks (think Internet servers or sewer systems) but often include immaterial elements (wireless signals). They require a lot of capital."[30] The physical buildings and high value of data centers, such as Meta's USD 1 billion facility of 1.25 million square feet in Prineville, Oregon[31] correspond to this definition. These structures are process "over 2.5 quintillion bytes of data [that is] being created every single day."[32] The unprecedented magnitude and integration of their influence in the quotidian is evocative of the sublime posited by Immanuel Kant, who elucidates our inability to comprehend the infinite in his Critique of Judgment[33].

> the mere ability even to think [the infinite] as a *whole* indicates a faculty of mind transcending every standard of the senses…

Literary scholar Jina B. Kim interprets this for infrastructure as "an overpowering awareness of our enmeshment, via infrastructure, in a webbed systemic infinity.[34]" The territories of the built presence and service coverage of data centers are astounding. Yet, more awestriking of data centers that differentiates them from other types of infrastructure is its comprehensive integration into the layers of our daily socioeconomic functions and the theoretical immortality of digital memory.

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[29] Bateson, *Steps to an Ecology of Mind*.

[30] Wilson, "The Infrastructure of Intimacy."

[31] "Data Centers."

[32] "Data Center Storage, Capacity Planning and Requirements."

[33] Kant, *The Philosophy of Kant*.

[34] Kim, "Toward an Infrastructural Sublime."

Despite its massive and distributed presence, infrastructure is generally invisible and absent from everyday thought. Only when there is a failure does it come to mind. This assumed functionality was observed by Martin Heidegger in *Being and Time*[35] as a trait of human perception of the world. Heidegger puts forth a worldview that is about "totality of involvements." As a 20th-century philosopher attributed to phenomenology and existentialism, Heidegger sees the world in "totality of involvements" – an interrelated system of relations. His postulations apply to internet infrastructure quite aptly.

> Equipment can genuinely show itself only in dealings cut to its own measure (hammering with a hammer, for example); but in such dealings an entity of this kind is not grasped thematically as an occurring Thing, nor is the equipment-structure known as such even in the using. The hammering does not simply have knowledge about [urn] the hammer's character as equipment, but it has appropriated this equipment in a way which could not possibly be more suitable.

Similar to Heidegger's hammer, the use of the internet does not simply have knowledge about the server's character as equipment, but it has appropriated this equipment. The being of the equipment exists in referential totality as humans focus on the operation of equipment rather than the physical equipment itself.

> [G]enerally speaking, human beings do not focus on a tool or a piece of equipment but on the work in which they have become engaged.[36]

To the common person, the post-phenomenological notion of infrastructure is only disrupted during malfunction.

> When somebody uses a tool or piece of equipment, a referential structure comes about in which the object produced, the material out of which it is made, the future user, and the environment in which it has a place are related to each other. But that this is so, according to Heidegger, generally appears only when a handy or ready to hand tool or piece of equipment breaks down. When this happens, the tool suddenly demands attention for itself. The reliable dealings we are used to having with the tool are ruptured, and instead of withdrawing from our attention the tool suddenly forces itself upon us. Someone sits at a word processor focused on the text at hand and all of a sudden the computer freezes. The trustworthy world that developed around the computer – the open book, the keyboard, the screen, the cup of coffee; in short, the entire mutually referring network that Heidegger calls a world – is abruptly destroyed. The computer changes from being one of the handy or ready-to-hand that shape this world to what Heidegger calls something vorhanden: 'objectively present' in the newer translation, or 'present-at-hand' in the older. Its transparency is transformed into opacity… The relation with the world around the computer that took place 'through' it is disturbed. Only when it starts up again and everything works without a hitch is the world that was destroyed again restored.[37]

The internet has replaced telecommunications as the medium for exchange and has increasingly been integrated into other functions of contemporary life. To further inspect the infrastructural qualities of data centers, this analysis turns to Susan Leigh Star, who defines the following nine properties of infrastructure in her seminal text *The Ethnography of Infrastructure*[38] : 1) Embeddedness, 2) Transparency, 3) Reach or scope, 4) Learned as part of membership, 5) Links with conventions of practice, 6) Embodiment of standards, 7) Built on an installed base, 8) Becomes visible upon breakdown, and 9) Is fixed in modular increments, not all at once or globally. Star's discussions clarify the metrics to assess the infrastructure-ness of something and confirm it in data centers, as demarked in the following annotations.

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[35] Polt, *Heidegger's Being and Time*.

[36] Graham and Thrift, "Out of Order."

[37] Verbeek and Crease, *What Things Do*.

[38] STAR, "The Ethnography of Infrastructure."

Embeddedness. Infrastructure is **sunk into and inside of other structures, social arrangements, and technologies**. People do not necessarily distinguish the several coordinated aspects of infrastructure. In the Worm study, our respondents did not usually distinguish programs or subcomponents of the software they were simply "in" it.

Transparency. Infrastructure is transparent to use, in the sense that it does not have to be reinvented each time or assembled for each task, but **invisibly supports those tasks**. For our respondents, the task of using ftp to download the system was new and thus difficult; for a computer scientist, this is an easy, routine task. Thus, the step of using ftp made the system less than transparent for the biologists, and thus much less usable.

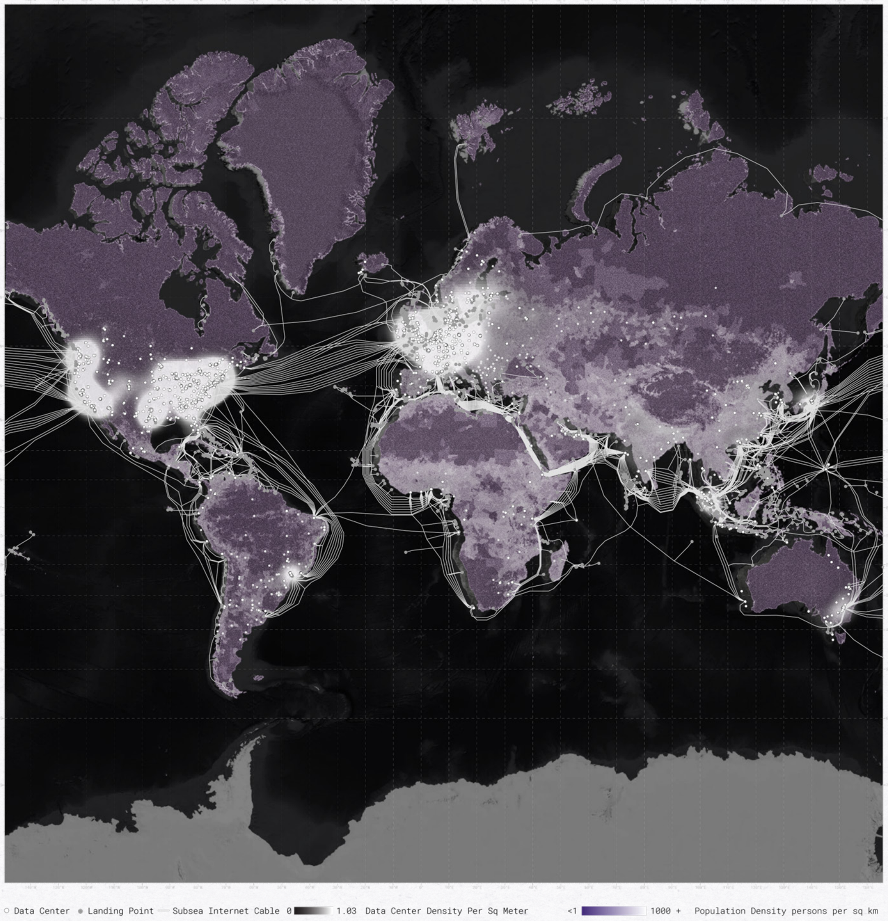
Reach or scope. This may be either **spatial or temporal-infrastructure has reach beyond a single event or one-site practice**. One of the first things we did in system development was scan in the quarterly newsletter of the biologists so that one of the long-term rhythms of the community could be emulated online.

Learned as part of membership. The **taken-for-grantedness** of artifacts and organizational arrangements is a sine qua non of membership in a community of practice (Bowker & Star, in press; Lave & Wenger, 1991). Strangers and outsiders encounter infrastructure as a target object to be learned about. New participants acquire a naturalized familiarity with its objects, as they become members. Although many of the objects of biology were strange to us as ethnographers, and to the computer scientists, and we made a special effort to overcome this strangeness, it was easy to overlook other things that we had already naturalized, such as information retrieval practices over networked systems.

Links with conventions of practice. Infrastructure both **shapes and is shaped by the conventions of a community of practice** (e.g., the ways that cycles of day-night work are affected by and affect electrical power rates and needs). Generations of typists have learned the QWERTY keyboard; its limitations are inherited by the computer keyboard and thence by the design of today's computer furniture (Becker, 1982). The practices of reporting quarterly via the newsletter could not be changed in the biologists' system-when we suggested continual update, it was soundly rejected as interfering with important conventions of practice.

Embodiment of standards. Modified by scope and often by conflicting conventions, **infrastructure takes on transparency by plugging into other infrastructures and tools in a standardized fashion**. Our system embodied many standards used in the biological and academic community such as the names and maps for genetic strains, and photographs of relevant parts of the organism. But other standards escaped us at first, such as the use of specific programs for producing photographs on the Macintosh.

Built on an installed base. Infrastructure does not grow de novo; **it wrestles with the inertia of the installed base and inherits strengths and limitations from that base.** Optical fibers run along old railroad lines; new systems are designed for backward compatibility, and failing to account for these constraints may be fatal or distorting to new development processes (Han seth & Monteiro, 1996). We partially availed ourselves of this in activities such as scanning in the newsletter and providing a searchable archive; but our failure to understand the extent of the Macintosh entrenchment in the community proved expensive.



Data Source: Baxtel, CIESIN, Columbia University, Earth Institute, EIA, Esri, NASA SEDAC, Telegeography, USGS

Becomes visible upon breakdown. The normally invisible quality of **working infrastructure becomes visible when it breaks: the server is down,** the bridge washes out, there is a power blackout. Even when there are back-up mechanisms or procedures, their existence further highlights the now-visible infrastructure. One of the flags for our understanding of the importance of infrastructure came with field visits to check the system usability. Respondents would say prior to the visit that they were using the system with no problems-during the site visit, they were unable even to tell us where the system was on their local machines. This breakdown became the basis for a much more detailed understanding of the relational nature of infrastructure.

Is fixed in modular increments, not all at once or globally. Because infrastructure is big, layered, and complex, and because it means different things locally, it is never changed from above. **Changes take time and negotiation, and adjustment with other aspects of the systems are involved**.! Nobody is really in charge of infrastructure. When in the field, we would attempt to get systems up and running for respondents, and our attempts were often stymied by the myriad of ways in which lab computing was inveigled in local campus or hospital computing efforts, and in legacy systems. There simply was no magic wand to be waved over the development effort.

It is recognized that data centers, along with other internet-related structures, have been referred to as infrastructure across various disciplines including but not limited to urban planning, politics, civil engineering, mechanical engineering, computer science, geography, media and communications, landscape architecture, economics, literature, and art. The complexity of this subject often sparks interdisciplinary exchanges and collaboration, experienced firsthand by the research for this thesis and elsewhere.

A policy brief, “Data-center infrastructure and energy gentrification: perspectives from Sweden” by Frans Libertson, Julia Velkovab, and Jenny Palm[39] of the International Institute for Industrial Environmental Economics and Department of Thematic Studies of Lund University in Sweden reviewed data centers in relation to energy, economics, communications, and technology. In the creative fields, Andrew Blum[40], Evan Roth[41] and Ingrid Burrington[42] explored the physical structures of the internet through writing, installation art and digital media to reveal and provoke critical thinking and awareness around the hardware of the internet.

Government policy recognizes internet connectivity and security as information and communications infrastructure and values it highly with substantial capital investment. For example, broadband and cybersecurity are included in the Infrastructure Investment and Jobs Act[43], also known as the Bipartisan Infrastructure Bill. The Act dedicates USD 65 billion to broadband and USD 1.3 billion to cybersecurity. The key focus on equity of connectivity recognizes that “high quality internet service is necessary for Americans to do their jobs, to participate equally in school learning, health care, and to stay connected.” as embodied by Title III - Digital Equity Act of 2021 and Title IV Broadband Affordability.

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[39] Libertson, Velkova, and Palm, “Data-Center Infrastructure and Energy Gentrification.”

[40] Blum, *Tubes*.

[41] “Evan Roth.”

[42] Ingrid Burrington, *Networks of New York*.

[43] “Guidebook to the Bipartisan Infrastructure Law | Build.Gov.”

DIVISION F--BROADBAND

TITLE I--BROADBAND GRANTS FOR STATES, DISTRICT OF COLUMBIA, PUERTO RICO, AND TERRITORIES

This title establishes measures to promote broadband deployment in unserved and underserved areas through specified projects (e.g., connecting libraries and other community anchor institutions, collecting data and conducting broadband mapping, and installing internet infrastructure).

Specifically, the title establishes the Broadband Equity, Access, and Deployment Program to award grants to carry out the purposes of this title. Further, it requires broadband providers to deliver information to the Federal Communications Commission (FCC) to facilitate the creation and maintenance of broadband maps.

The FCC must establish an online mapping tool to provide a geographic footprint of each federally funded broadband infrastructure deployment project.

TITLE II--TRIBAL CONNECTIVITY TECHNICAL AMENDMENTS

This title modifies the Tribal Broadband Connectivity Program, through which the National Telecommunications and Information Administration (NTIA) makes grants to expand access to and adoption of broadband service on tribal land for remote learning, telework, or telehealth resources.

Specifically, the title extends the deadline for a grant recipient to (1) commit grant funds to a specific use, and (2) expend the grant funds. The title also authorizes a grant recipient to use grant funds to cover up to 2.5% of the total project cost for planning, feasibility, and sustainability studies.

If Congress appropriates additional funds for these grants after the enactment of this bill, the NTIA (1) may use a portion of the funds to fully fund grants that were not fully funded initially, and (2) shall allocate any remaining funds through subsequent funding rounds.

TITLE III--DIGITAL EQUITY ACT OF 2021

Digital Equity Act of 2021

This title requires the NTIA to establish grant programs for promoting digital equity, supporting digital inclusion activities, and building capacity for state-led efforts to increase adoption of broadband by their residents.

Specifically, the title establishes the State Digital Equity Capacity Grant Program to make distributions to states based on their populations, demographics, and availability and adoption of broadband. The title also establishes the Digital Equity Competitive Grant Program for supporting efforts to achieve digital equity, promote digital inclusion, and stimulate adoption of broadband.

TITLE IV--ENABLING MIDDLE MILE BROADBAND INFRASTRUCTURE

This title requires the NTIA to make grants to eligible entities for the construction, improvement, or acquisition of middle mile infrastructure (i.e., the midsection of the infrastructure required to enable internet connectivity for end users but which does not connect directly to an end-user location). Entities eligible to receive such grants include states, tribal governments, telecommunications companies, various nonprofit entities, and economic development authorities.

TITLE V--BROADBAND AFFORDABILITY

This title revises and makes permanent the Affordable Connectivity Benefit Program (formerly, the Emergency Broadband Benefit Program) established to reimburse broadband providers for costs associated with discounting broadband service for certain households during the COVID-19 emergency period.

Participating providers must allow recipient households to apply the affordable connectivity benefit to any of its internet service offerings and may not require the households to submit to a credit check in order to apply the benefit. Such providers must also carry out public awareness campaigns in service areas to highlight the existence of the program and the value and benefits of broadband.

The FCC must promulgate regulations to require the display of broadband consumer labels to disclose to consumers specified information regarding broadband internet plans, including information regarding whether the offered price is an introductory rate.

Further, the FCC must adopt final rules to facilitate equal access to broadband, which must include (1) preventing digital discrimination of access based on factors such as income level, race, or religion; and (2) identifying necessary steps for the FCC to eliminate such discrimination.

The Government Accountability Office (GAO) must evaluate and report on the process used by the FCC for establishing, reviewing, and updating the upload and download speed thresholds for broadband service.

TITLE VI--TELECOMMUNICATIONS INDUSTRY WORKFORCE

Telecommunications Skilled Workforce Act

This title establishes measures to address the workforce needs of the telecommunications industry.

Specifically, the title requires the FCC to establish an interagency working group to develop recommendations for addressing these workforce needs, including the safety of that workforce.

The FCC must also establish and issue guidance for states on matters related to workforce needs and safety of the telecommunications industry, including how a state workforce development board can (1) utilize federal resources available to meet relevant workforce needs; (2) promote and improve recruitment in the Telecommunications Industry Registered Apprenticeship Program and other qualified industry-led workforce development programs; and (3) ensure the safety of tower climbers and other members of the telecommunications workforce.

The GAO must submit to Congress a report that estimates the number of skilled telecommunications workers that will be required to build and maintain (1) broadband infrastructure in rural areas, and (2) the infrastructure needed to support 5G wireless technology.

DIVISION G--OTHER AUTHORIZATIONS

TITLE VI--CYBERSECURITY

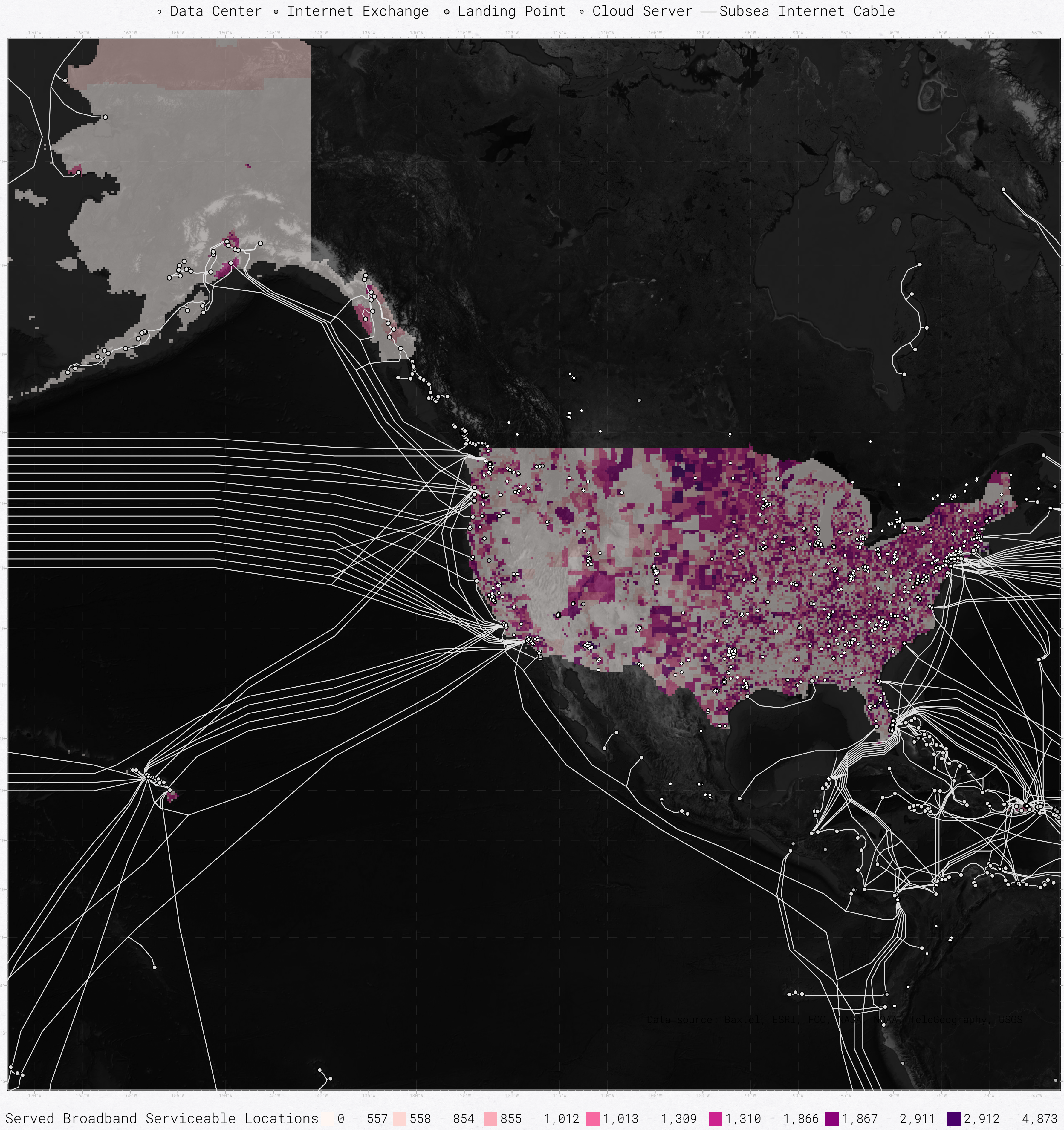
Cyber Response and Recovery Act

This title authorizes the Department of Homeland Security (DHS) to declare a significant incident in the event of a breach of a public or private network and establishes a Cyber Response and Recovery Fund.

Specifically, DHS may make the declaration upon determining that a specific significant incident has occurred or is likely to occur imminently and that otherwise available resources, other than the fund, are likely insufficient to respond to or mitigate the incident effectively.

Upon a declaration, the Cybersecurity and Infrastructure Security Agency must coordinate the response activities of (1) each federal agency; (2) local governments, law enforcement agencies, and other responding entities; and (3) federal, state, local, and tribal emergency management and response agencies.

The fund shall be available for the coordination of such activities and for response and recovery support.



Data source: Baxtel, ESRI, FCC, NASA, NOAA, TeleGeography, USGS

One may question the integrity of data centers as infrastructure as they are largely privately owned and operated. Globally, data centers that provide service directly to citizens are mostly held by private companies. The world's 10 largest providers and operators including Amazon Web Services (AWS), Microsoft Azure, Google Cloud, Meta Platforms, Equinix, Digital Realty, NTT Global Data Centers, CyrusOne, GDS Holdings, and KDDI's Telehouse[44] are private or publicly traded corporations. Governments may contract these companies for service. Meanwhile, government-owned data centers exist but typically serve the government only. In other words, they do not provide information and communication services such as data computing and storage to the public. However, infrastructure can be privately-owned and operated, as exemplified by water and utility companies across the world.

The World Bank reported that 17% of investments in infrastructure were private. In the United States, private utilities served 72% of US electricity customers in 2017[45].

Notably, the ownership does not change the infrastructural status of an entity if it is necessary for one "to do their jobs, to participate equally in school learning, health care, and to stay connected."[46]

However, despite its apparent infrastructural status with necessity, substantial resource consumption, territorial presence, and operational confidentiality, the commodification of data centers has precipitated confusion and complications in the built environment. A deeper question to consider is how to plan and design them within the framework of infrastructure responsibly. This reveals the underlying motivations of this thesis – encountering this new breed of infrastructure, how do we plan and design infrastructure today? The emergence of data centers as a new typology of infrastructure is an opportunity to use as a proxy to change the infrastructure planning and design. The new paradigm asks for multifunctionality and post-decommission adaptation in infrastructure.

In light of infrastructure's high economic, environmental and social costs, this thesis argues that we should not have mono-functional infrastructure. The main paradigm of infrastructure today sees each unit as a contributor which produces waste. Yet, a more comprehensive or holistic perspective can reveal symbiotic and synergistic potential across different types of infrastructure and non-infrastructure programs. For instance, the waste heat from the Facebook data center[47] in Odense, Denmark is redistributed through a district heating system to provide heating for neighboring buildings. Here, the data center also acts as a utility center providing heat to a part of the city. Multifunctionality asks more of existing concepts of a sustainable data center which largely focuses on using clean energy. It calls for the integrating alternative functions such as heating and, as proposed in the later section of this thesis – energy grid balancing, groundwater recharging, and ecology hosting.

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[44] Zhang, "Top 250 Data Center Companies in the World as of 2023."

[45] "Investor-Owned Utilities Served 72% of U.S. Electricity Customers in 2017."

[46] Rep. DeFazio, "H.R.3684 - 117th Congress (2021-2022)."

[47] Alley, "Facebook Plugs Its Danish Data Center into Odense District Heating System."

At the same time, the post-commission adaptation requires planning at pre-construction for the site after the infrastructural facility retires. The post-industrial landscapes today, which include defunct infrastructure sites such as decommissioned railroad facilities and power plants of the previous century, are often abandoned voids[48] or brownfields[49]. This cannot be the fate of new infrastructures constructed today.

While abandoned voids may contribute to urban culture, identity, and freedoms[50], they mostly do so temporarily. Ultimately, they are retrofitted or redeveloped for an updated function. If the site is contaminated due to prior activity, it requires land remediation[51] before it can become safe and eligible for human occupation or agricultural purposes. Depending on the type of contamination, costs of remediation range from $1,000 to $100,000 per acre foot[52].

Remedial Option	**Average**	**Mesa, AZ** Apple Data Center	**The Dalles, OR** Google Data Center	**Chantilly, VA** AWS IAD63	**Secaucus, NJ** Equinix NY4	**New York, NY** 60 Hudson St
Consolidation and covering contaminated soil on-site (i.e., under roads and structures)	$ 1,500	$ 44,766	$ 9,936	$ 5,165	$ 11,672	$ 12,397
Cap contaminated soil with clean soil	$ 9,500	$ 283,517	$ 62,926	$ 32,713	$ 73,925	$ 78,512
Blending with clean soil from on-site	$ 1,500	$ 44,766	$ 9,936	$ 5,165	$ 11,672	$ 12,397
Blending with clean soil from off-site	$11,500	$ 343,205	$ 76,173	$ 39,601	$ 89,489	$ 95,041
Excavation and removal of contaminated soil	$54,000	$ 1,611,570	$ 357,682	$ 185,950	$ 420,207	$ 446,281
Proven and innovative soil treatment technologies	$75,000	$ 2,238,292	$ 496,780	$ 258,264	$ 583,621	$ 619,835

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[48] Lopez-Pineiro, *A Glossary of Urban Voids*.

[49] US EPA, "Understanding Brownfields."

[50] Lopez-Pineiro, *A Glossary of Urban Voids*.

[51] "Cleaning Up Brownfield Sites."

[52] "NJDEP - HPCTF Final Report - V. Costs and Economic Impacts."

The concern for data centers is becoming an abandoned, polluted void after its decommissioning. As the size of data centers are on a broad spectrum, the extent of their impact as a defunct site will also be proportionally challenging. An edge data center, typically 250 square feet or smaller, may be easier to repurpose. On the other hand, a hyperscale data center would take more planning and design to retrofit or incur higher carbon costs to demolish. It is also likely to be in a rural or industrial area that, if collectively did not plan and design with their post-decommission futures before, would leave a abandoned void in the terrain.

Additionally, data centers also contribute to pollution in terms of electronic waste[53]. The life cycle of computing equipment is approximately five years. These electronic products are retired and shipped to developing countries for processing or disposal[54]. Unique to data centers, its territories of life in commission (by supporting internet connectivity) and post-decommission (with offshore electronic waste disposal) are global despite local presences as buildings. The complexity of data centers and the trend of globalization and digitalization foreshadow the multi-faceted nature of future infrastructures. This prophecy demands creative, experimental, and far-sighted speculations of infrastructures and the attempts to do so through data centers as the infrastructural subject are elaborated and imagined in the next section.

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[53] Ensmenger, "The Environmental History of Computing."

[54] Lepawsky and Mcnabb, "Mapping International Flows of Electronic Waste."

model of data centers in Lower Manhattan


cartographic models of five sites

In the analysis of existing data centers, five sites are examined based on their site characteristics of environment, energy, land use, density, and economy. They also range from 100,000 to 1,300,000 square feet in floor area. The maps do not include the smaller edge data centers as their locations are generally private and "closer to the end-user."[55] An exploration on their influence on modular design of data centers will be made in the next section on design strategies.

The sites analyzed are examined based on the following characteristics: environment, energy, land use, density, and economy. Each site hosts one or several data centers that range from 100,000 to 2.5 million square feet. This series of investigations reveals 1) reasons for the location of data center, 2) complications in terms of the concurrent synergies and tensions between data centers and the continuum of contexts they inhabit.

In summary, the reasons identified for a data center location are 1) Connectivity, 2) Power, 3) Natural Disasters, 4) Policy incentives, 5) Demand. Consequences, on the other hand, include environmental, social, and economic impacts that are not unilaterally negative. Instead, they are beneficial and damaging at the same time.

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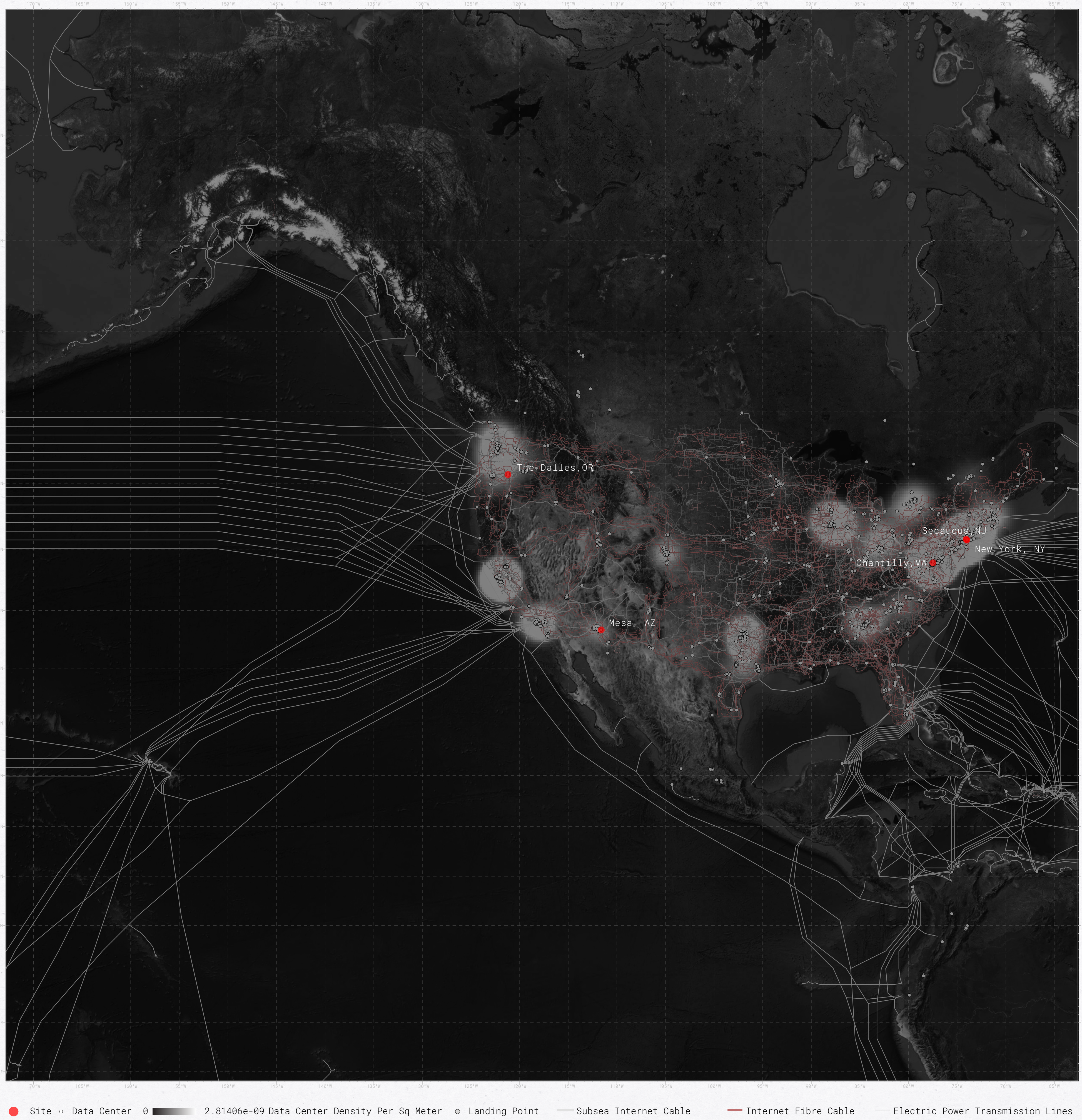
[55] Zhang, "What Is an Edge Data Center?"



Data Source: Baxtel, EIA, Esri, NASA, Telegeography, USGS

Mesa, AZ

Mesa, Arizona first caught attention when reports of its water crisis criticized data centers for their consumption[56]. Despite only 3 data centers in the city, each occupies a sizable footprint, most notably the Apple Data Center with 1.3 million square feet[57]. Additionally, Meta's 2.5 million square feet center is underway in construction[58].

There is strong institutional and political support for the development of data centers in Arizona. Mesa envisions the Elliot Road Technology Corridor[59] where data centers including, Apple and Meta's will find themselves in the company of other technology enterprises. Its proximity to The University of Arizona fortifies its geographic advantages to develop its technology industry[60].

Politically, Arizona is supportive of developing its data center and technology industry. The State exempts qualifying data centers from sales tax on equipment[61]. It first enacted tax incentives for data centers in 2013 and extended them through H.B. 2649 Computer data centers; tax incentives[62] for 10 years in 2021.

The Dalles, OR

The Dalles demonstrates the social and economic complexity of data center presence in a small city. Relatively rainier than Mesa, The Dalles encounters the same challenge of excessive water consumption by the city's Google Data Center. After water use records were finally released after a lawsuit settlement, it was revealed that Google's data centers consumed 29% of the city's total water consumption. The water in the Columbia River cannot be used or disposed into the river as it is under federal jurisdiction. Witnessing the drawdown of the Colorado Basin which supplies Mesa's water, the restriction is appropriate.

The Dalles first welcomed the Google Data Center in 2005 with tax breaks "worth at least $260 million since then."[63] The strong policy support is reciprocated by the company becoming a key contributor to the local economy. Google employs 200 employees and generated more than $5 million in local tax in 2021 after its property tax exemptions expired. The company has planned two more data centers[64] along the Columbia River that "will bring up to $125 million in estimated new property taxes and fees."

Another upside that ties the data center to local water is a commitment by Google to contribute $28.5 million for upgrading the city's water infrastructure and cessation of some water rights "in exchange for an increased supply of municipal water."[65] Here, The Dalles exemplifies a compensatory approach that resonates with the resource – municipal water - that the project would exhaust in its negotiation with Google for permission to build a data center.

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[56] "Data Centers Consume Millions of Gallons of Arizona Water Daily."

[57] Altavana, "Inside the Fortress: Apple's 1.3 Million-Square-Foot Mesa Data Center."

[58] Swinhoe, "Meta Expanding Mesa, Arizona Data Center Campus with Three New Buildings."

[59] "Elliot Road Technology Corridor® | City of Mesa."

[60] "UA and Microsoft Create Cloud Infrastructure Partnership to Train Tomorrow's Leaders."

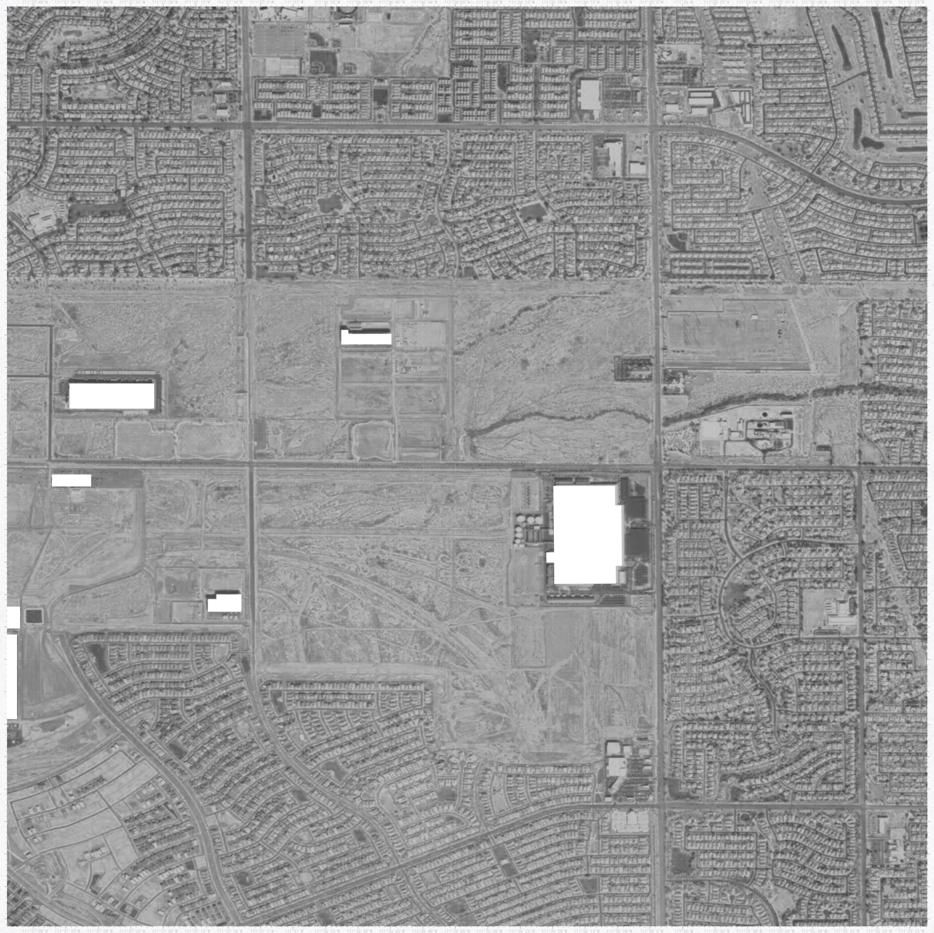
[61] "42-6004 - Exemption from Municipal Tax; Definitions."

[62] "Arizona State Data Center Sales Tax Incentives."

[63] Oregonian/OregonLive, "Google's Water Use Is Soaring in The Dalles, Records Show, with Two More Data Centers to Come."

[64] "Google Makes Move to Break Ground on New Data Center in TD — Columbia Community Connection News Mid-Columbia Region."

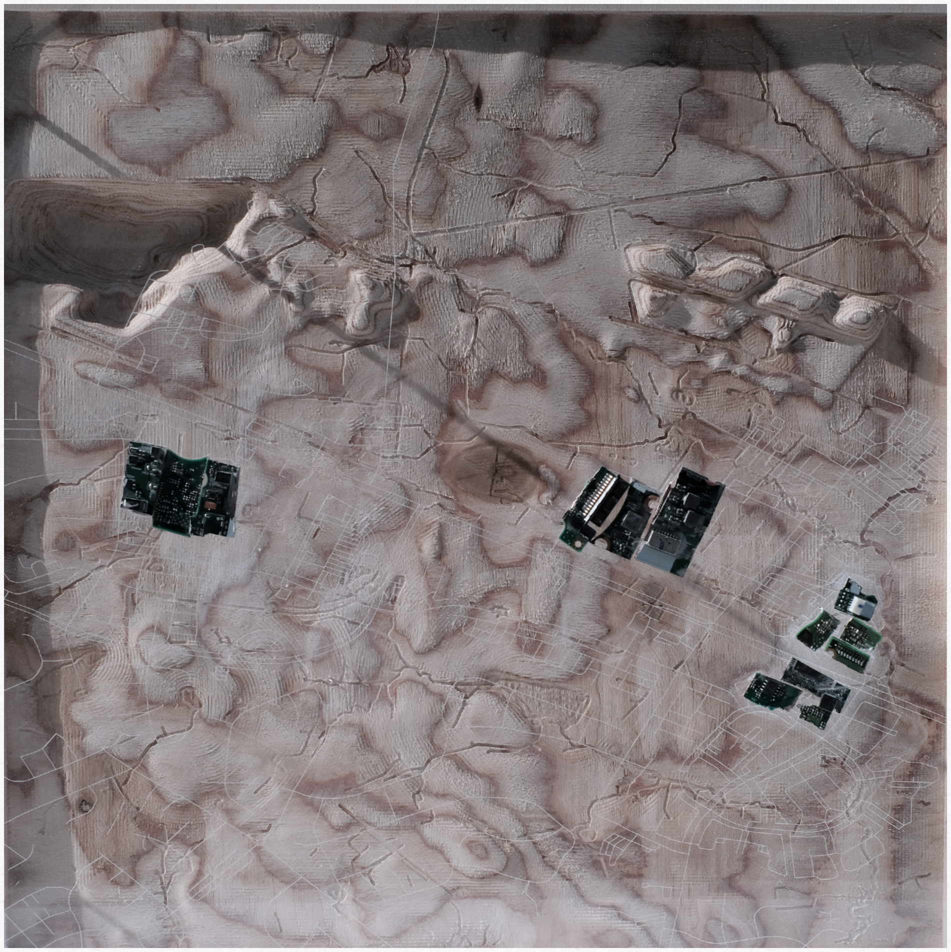
[65] Oregonian/OregonLive, "Google's Water Use Is Soaring in The Dalles, Records Show, with Two More Data Centers to Come."



Data Source: Baxtel, City of Mesa, USGS

Data Source: Baxtel, Esri, METI/NASA, Microsoft, Oregon State Parks, State of Oregon GEO, WA State Parks GIS,USGS

Data Source: Baxtel, County of Loudoun, County of Prince William, Fairfax County, VA, EPA, Esri, NPS, USGS, US Census Bureau, USDA



Cartographic Model of Chantilly, VA
Discarded circuit boards as data centers superimposed on topography

Chantilly, VA

As a suburban city within Fairfax County in Northern Virginia, the site in Chantilly was selected because of its proximity to neighboring technological hubs Loudoun County[66] and Prince William County[67]. Fairfax on its own, also hosts a growing data center market[68]. The analysis will expand to neighboring counties due to the territorial extent of data centers. The region now has 275 data centers that "stands over 2,600 megawatts of commissioned power." [69] and houses "more than 20% (100) of all known hyperscale data centers worldwide."

A critical factor in its emergence as a "Tech Hub" is its proximity to government agencies which required reliant communications infrastructure. The region is home the first large public network access point (NAP) and internet exchange point (IXP) built in 1990s known as MAE-East located in Washington, D.C. The MAE-East also established locations in Vienna, Reason and Ashburn. Over 50% of the world's internet traffic passed through it by 1997 and today, it is estimated that 70% of the world's internet traffic moves through it daily.

Additionally, with reference to the entire 113,000 miles[70] of US fiber-optic network[71] and the subsea internet cable, Northern Virginia has geographic advantages as a communications infrastructure center. More dark fiber is underway as the industry develops in Northern Virginia. Meanwhile, the presence of data centers improved local fiscal health. Fairfax County foresees paying off debt for its Route 28 highway widening projects through the increase in assessment values of surrounding parcels[72].

However, the location has its drawbacks. Residents have been affected by their machine neighbors whose ventilation systems continues to operate at noticeable noise level. Carlos Yanes lives about 600 feet from a data center and has been forced to sleep in the basement with white noise machines to "in hopes of drowning out the sound of the data center fans. Last year, in hopes of fixing the problem, the couple spent about $17,000 on soundproof windows. But that made it worse, Yanes said, creating a vibrating droning noise inside the house."[73]

His story reveals a critical problem in planning that asks why the local regulation has not updated its land use policies. Local noise ordinances exempt air conditioners at night, which are substantial structures in data centers. IT equipment typically takes up 30-35% of floor space, and cooling is required 24/7. Although Loudoun County, Virginia passed a new guideline in September 2022 which limits where data centers can be located and includes standards for environmental sustainability and proximity to residential areas[74], noise is still unaddressed. Considering the historical and extensive presence of data centers in Northern Virginia, it is paramount that a technically solvable[75] issue like noise from existing data centers should be regulated and resolved.

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[66] "Data Center Alley."

[67] "PW Digital Gateway."

[68] Zhang, "Virginia Data Centers."

[69] Zhang.

[70] Kuzoian, "Animated Map Reveals the 113,000 Miles of Cable That Power America's Internet."

[71] Durairajan et al., "InterTubes."

[72] "Change in Data Center Values Has Implications for Fairfax County Route 28 Taxpayers | FFXnow," 2.

[73] Olivo, "Northern Va. Is the Heart of the Internet. Not Everyone Is Happy about That."

[74] Miller, "Loudoun County Passes New Rules to Limit Data Center Growth."

[75] Soluna, "Designing A Quiet Data Center."

Secaucus, NJ

Secaucus is an industrial city unfamiliar with the warehouse typology which its data centers occupy. The town has 1.71 data centers per square mile, while Chantilly has 0.83 and New York City has 0.12.

However, the role that it plays is not for itself. Instead, data centers in Secaucus predominantly serve the computing needs of New York City as a "business continuity site"[76]. This reiterates the non-locality of data centers in terms of the purpose of their functions. The upshot appeals for a system-based thinking that can recognize the true territories in spatial and functional dimensions.

More importantly, as a significant economic contributor, Secaucus's New York-serving data center industry wields too much influence over the city. Threats to exit the State should a proposed financial transaction tax[77] be imposed would leave the city with post-industrial voids and damage the local economy.

New York, NY

New York as a site demonstrates data centers in the urban core. The financial industry is a key reason for the data center presence in the expensive real estate of New York. As the global financial capital and home to the New York Stock Exchange and NASDAQ, New York has high demand for fast and reliable communications infrastructure. It inherited windowless telephone buildings which now accommodate data centers. The forms of Manhattan's data centers vary from their counterparts in other cities considerably.

Like Arizona, New York exempts data centers from sales tax on computing equipment. It is notable that data center companies can negotiate for tax incentives with the government[78].

Data centers in New York have not drawn much criticism from their communities. This is likely due to their architectural and operational discretion. The city has modulated the introduction of data centers so far. The existing high-value real estate and building density also impose cost and spatial constraints on new data centers.

On the other hand, New York presents a flood risk for data centers. The waterfront which surrounds the Financial District is set too close. Data centers here, including those in 33 Whitehall and 75 Broad Street, have experienced flooding from extreme weather events. Hurricane Sandy left data centers in the financial districts to bring their own fuel up the stairs to maintain operations by hand.[79] Even 111 8th Avenue up on 15th Street, a key hub for global internet traffic, experienced "outages for some [data center] tenants"[80] despite having 90,000 gallons of fuel stored in the same building[81]. Such risks should not be contemplated by the private sector alone. Given the criticality of internet infrastructures, it is important for cities to take an active role in locating data centers in planning as well.

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[76] "H5 Data Centers - New Jersey Data Center."

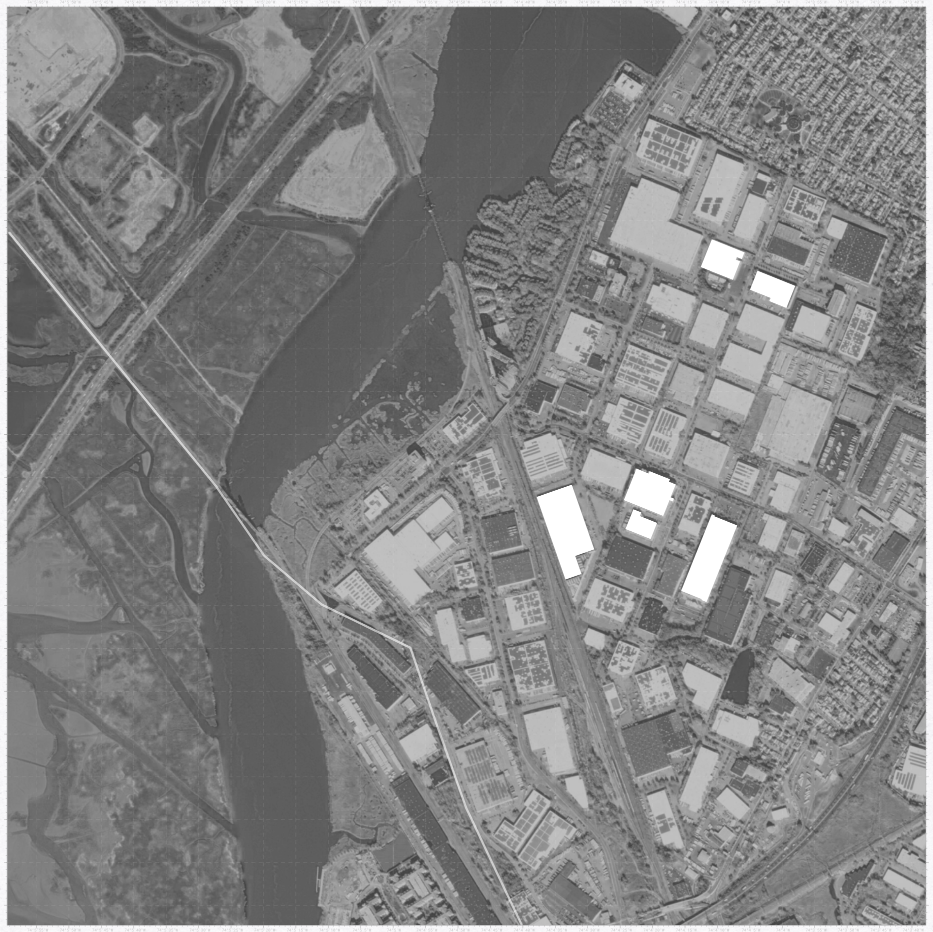
[77] "Leaving NJ Data Centers for Chicago No Easy Tax Fix for Nasdaq, NYSE."

[78] "New York Data Center Sees Tax Incentives."

[79] Brodkin, "How One NYC Data Center Survived Hurricane Sandy."

[80] McNevin, "Hurricane Sandy Takes out Manhattan Data Centers."

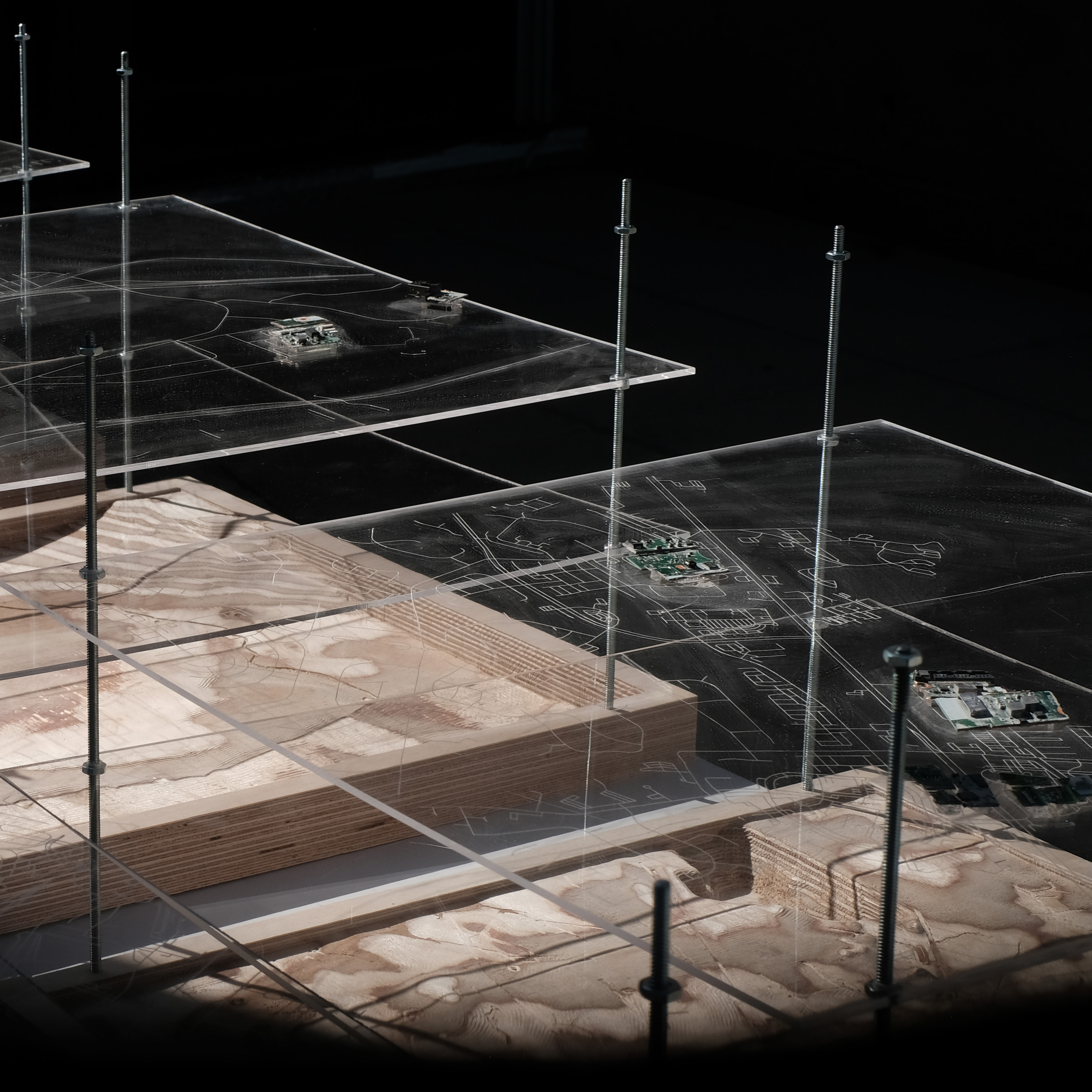
[81] Thibodeau, "Storm Forces Internet Hubs to Run on Generator Power."



Data Source: Baxtel, New York State, Maxar, Microsoft, State of New Jersey

Data Source: Baxtel, New York State, Maxar, Microsoft

site investigation models: data centers, electricity transmission lines, topography



This section elaborates on the design strategies for data centers that embody the principles of multifunctionality and planning for post-decommission futures of an infrastructural unit. The proposals anchor data centers as nodes for power grid balancing, hydrology, district heating and ecological resiliency. Additionally, it imagines a typology of data centers that are architecturally elastic by constructing and assembling to the existing modular rhythm of equipment.

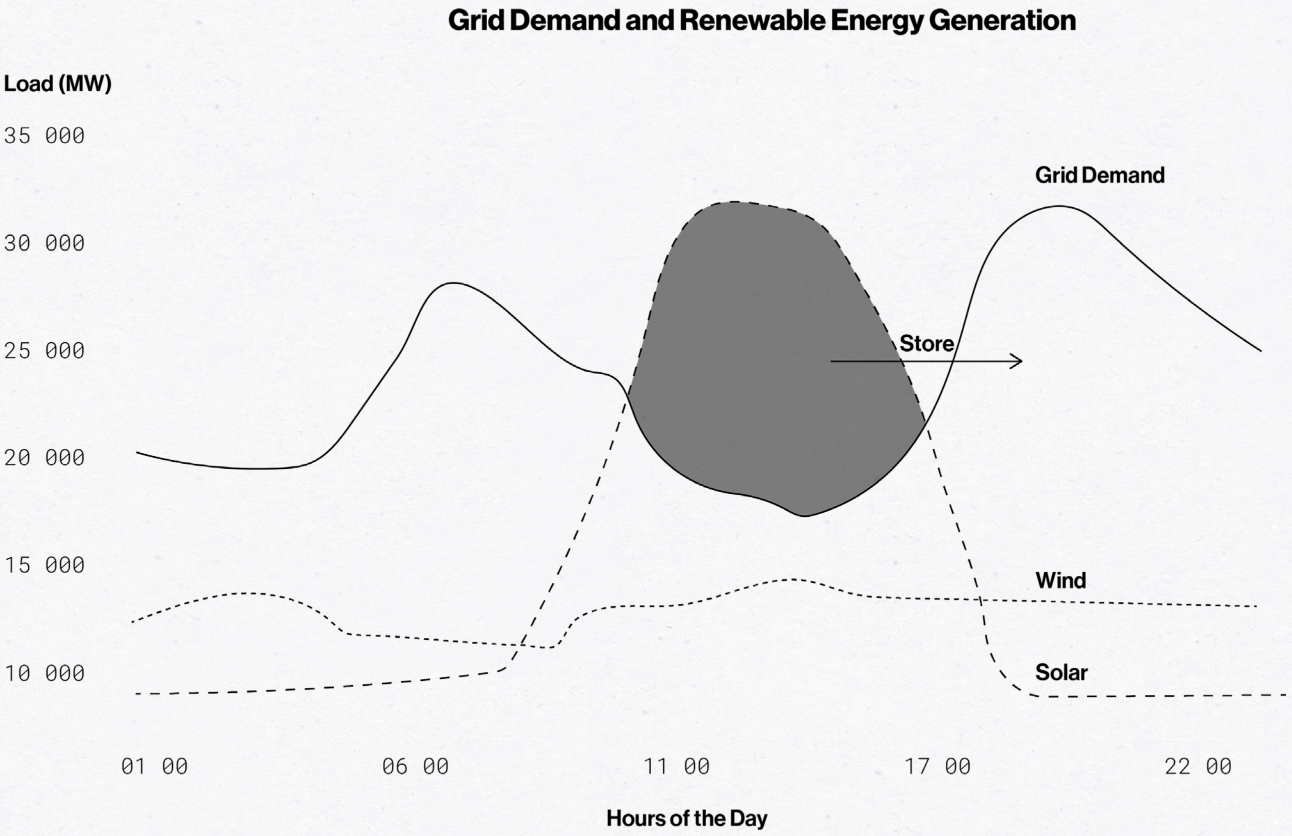
aerial perspective of data centers in wind farm

Power grid balancing

The power grid balancing function aligns data centers with the transition to an intermittent energy production paradigm of renewable energy infrastructure. Two of the greatest limitations of renewable energy today are its discontinuous energy generation and the costs of excess energy storage. This is what transactive energy management[82], seeks to resolve. Defined as "A system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter." Transactive energy management is a framework developed to ensure a balance of electricity load (demand) and generation (supply) for the power grid can deliver "a steady supply of electricity to consumers."[83]

As an excess supply problem, we cannot control the underlying variable of renewable energy. Current measures rely on turning off renewable energy power plants to maintain grid equilibrium. Data centers as power grid balancing nodes incorporate the function of batteries to store energy generated that exceeds the load on the grid reducing energy wastage by capturing that excess power supply. In doing so, a data center as infrastructure no longer remains only an energy consumer but a utility unit that resolves imbalances of the grid.

The transition into renewable energy sources shifts the paradigm of stable, controlled, and on-demand energy production to one that is sporadic or intervallic. The existing technology and infrastructure of energy does not accommodate that, and efforts to adapt it for the new "transactive energy" model are determined but still nascent.



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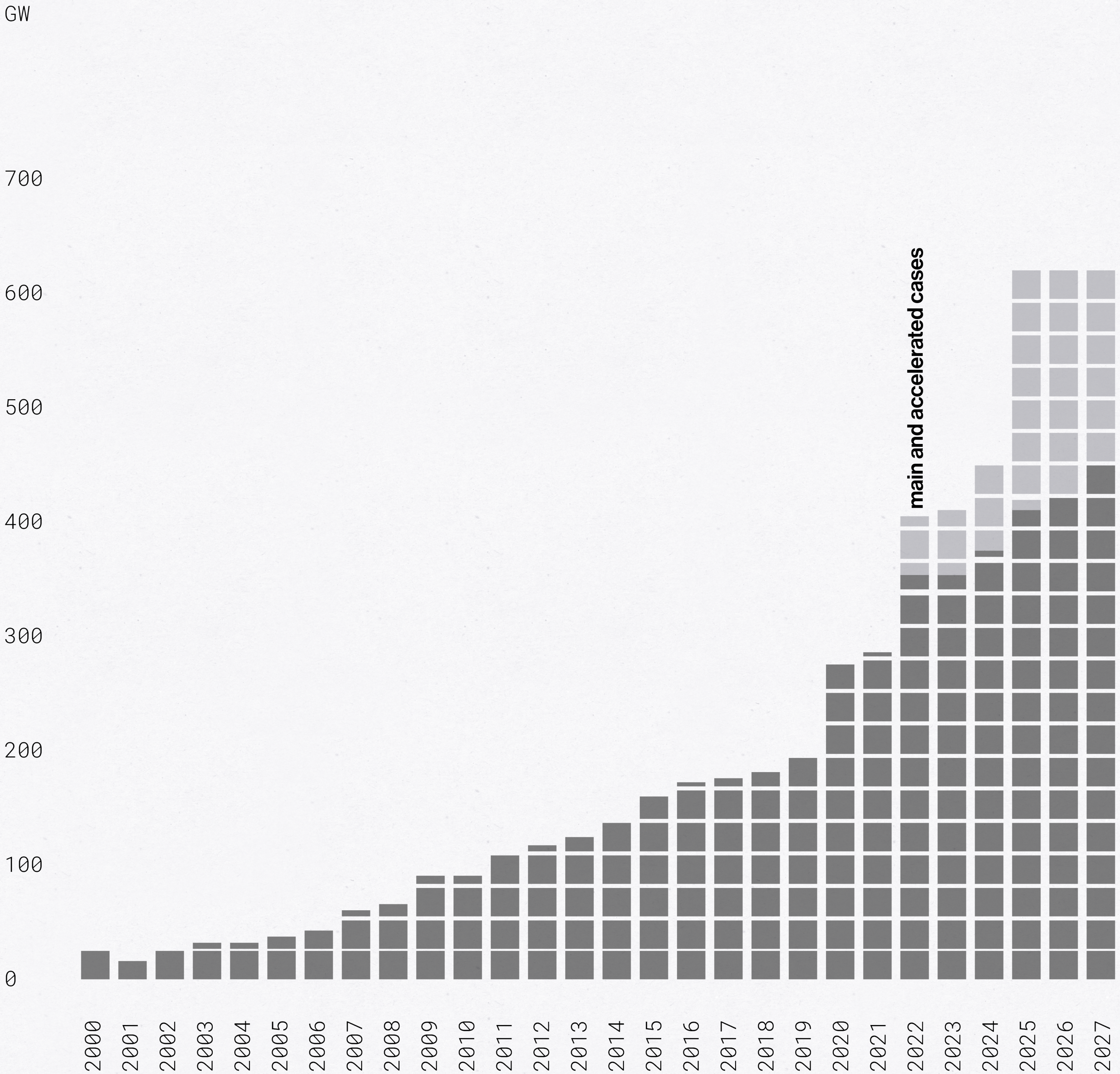
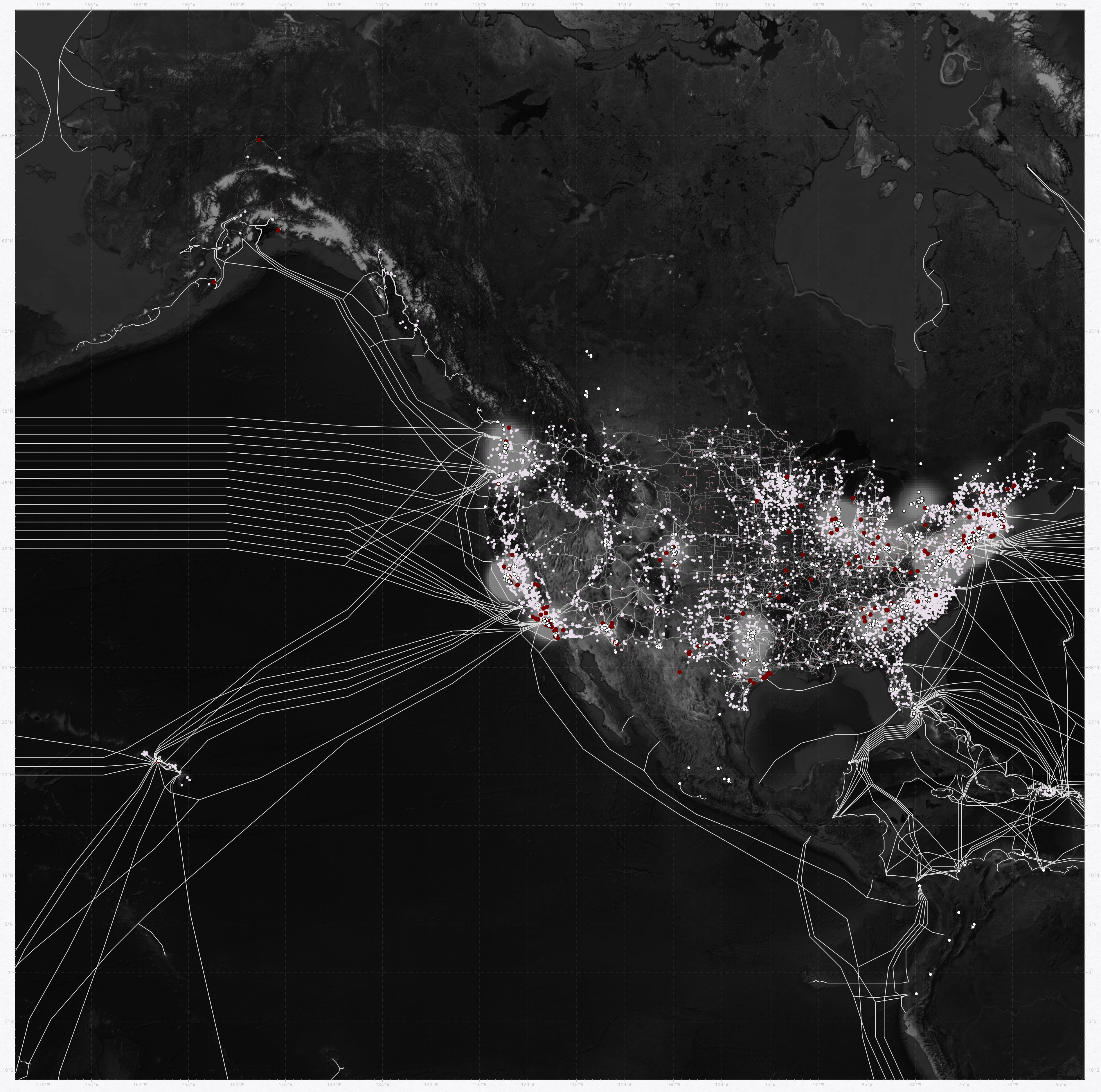
[82] "Transactive Energy."

[83] "Electricity Generation, Capacity, and Sales in the United States - U.S. Energy Information Administration (EIA)."

World Renewable Energy Total Capacity Net Additions, Main and Accelerated Cases



Data Source: IEA

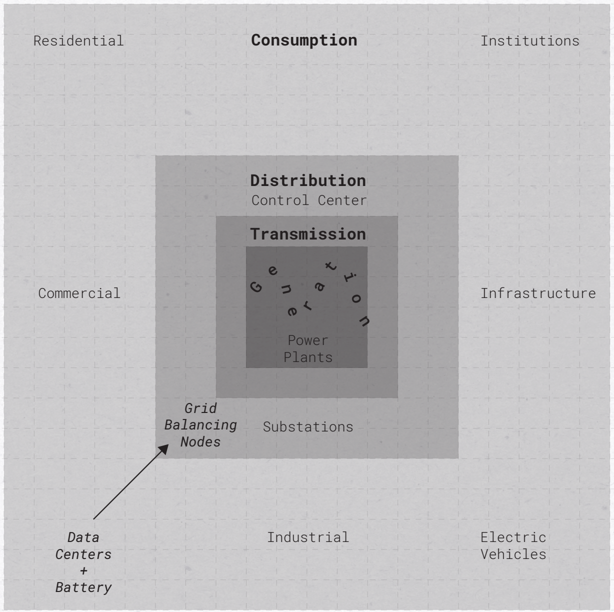


○ Data Center ● Power Storage Battery ● Renewable Energy Plant 0 ▬ 2.814e-09 Data Center Density Per Sq Meter ○ Landing Point ▬ Subsea Internet Cable — Electric Power Transmission Lines

Data Source: Baxtel, EIA, Esri, NASA, Telegeography, USGS

insect resting on investigative model of energy consumption, data center and renewable energy plants intersections

diagrammatic model of data center (disposed circuit board part) and battery (wood) in a tundra setting



This strategy addresses the storage issue by imagining a data center with a battery that is connected to renewable energy generators such as a solar, wind or hydro plant. This combination optimizes the machine-centric architecture by placing batteries on the same premises as servers. As a data center also needs backup power generators in case of any power disruption events, batteries in fact, support the backup power requirement of data centers. The potential for data centers as a core battery user is already recognized by battery makers[84]. Swedish battery maker Vattenfall projected annual energy cost savings of 30,000 to 80,000 euros (USD 35,000 to 92,000) for an industrial power consumer to install batteries onsite. Additionally, the data center can consume previously stored energy during peak load to relief the carbon intensity of the power grid. It reduces the need to turn on peaking power plants[85], which are often problematic natural gas plants[86], avoiding the carbon emissions during peak load.

The idea of replacing peaking power plants with batteries is already being contemplated. The New York Power Authority had put out a Request for Proposals "to replace its small power, or 'peaker' plants with bulk-scale battery storage projects" in April 2022[87]. In Ventura County, California, a new battery storage facility of "142 Tesla large-scale lithium-ion batteries" replaced the original plan for a fossil fuel peaking power plant[88] after the community opposed the latter[89]. This also reflects the local awareness and push for non-polluting infrastructure.

The complementary geographies of energy infrastructure and data centers suggest promise for this strategy. For instance, data centers in California that are also power grid balancing nodes can store energy generated during noon when the energy load of the Golden State cannot consume the energy that is generated. Maine grid balancing data centers can store the excess energy generated during sudden strong winds.

Architecturally, this inter-infrastructural strategy locates machines with machines in a facility with servers and batteries. In microeconomic terms, integrating the function of energy storage repositions the data center from an electricity consumer to a generator[90]. This gives data centers access to wholesale electricity prices, which may be negative during excess electricity generation[91], and gain financial upsides[92].

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[84] "Vattenfall Sees Data Centers as Expanding Battery Market."

[85] "Peak Load Power Plants."

[86] "Environmental Impacts of Natural Gas | Union of Concerned Scientists."

[87] International, "NYPA Seeks to Replace Gas Peaker Plants with Battery Storage."

[88] "142 Tesla Megapacks Replace Fossil Fuel-Powered Peaker Plant in California, Shows Company Video."

[89] Lambert, "142 Tesla Megapacks Power on to Create Giant New Battery, Replacing Gas Peaker Plant in California."

[90] "Electricity Generation, Capacity, and Sales in the United States - U.S. Energy Information Administration (EIA)."

[91] "The Causes and Effects of Negative Power Prices."

[92] "VCharge in Pennsylvania."

Hydrology

This concept utilizes of greywater in data centers and combining it with compatible hydrological uses. Given the existing dominance and growing trend of water-cooling technologies[101] as the preferred cooling method for data centers, this strategy speculates the reuse of wastewater from data centers. It tackles data centers that use water-cooling technologies. The research on water use in data centers reveals constant efforts to innovate equipment that operate in higher temperatures and cooling technologies that are more efficient and do not produce contaminants that cannot be recycled or reused or require substantial treatment to do so[102]. With this trend in mind, this strategy postulates two tactical ideas as examples that utilize the heated greywater output of data centers.

The first combines the current infrastructural framework of civil engineering that utilizes artificial groundwater recharge[103] to replenish water in aquifers that feed the municipality. Since data centers consume high volumes of water for cooling purposes, the water output is heated greywater, which may be filtered naturally or artificially and injected back into the subsurface aquifers to rebalance underground hydrology.

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93 Beaty, Quirk, and Morrison, "Liquid-Cooling Trends In Data Centers."

94 "Nautilus Data Technologies - Water-Cooled Data Centers."

95 "Artificial Groundwater Recharge | U.S. Geological Survey."

section perspective of data centers with artificial groundwater recharge

Second, it considers hydrological infrastructure in coastal regions – desalination plants. Desalination is the process of removing mineral salts from saline water, such as seawater, for human consumption and agricultural purposes[104]. Several methods including evaporating saline water and collecting condensation from its water vapor or reverse osmosis which pushes saline water through a semi-permeable membrane that only allows smaller water molecules to pass through. For the evaporation method, saline water needs to be heated prior to desalination. The scheme assimilates a data center with a desalination plant and preheats untreated saline water by using it to cool the data center first before transferring it to the desalination part of the premises. This removes the need of consuming water from other sources and reduces the amount of energy required to heat the saline water to the required temperature before desalination by lowering the temperature difference between the untreated saline water and the temperature it needs to be for desalination process. There is also a cooling effect from the evaporation method in desalination that may be recaptured by the data center for cooling, optimizing the synergies of the two infrastructural units.

Fundamentally, this strategy seeks to turn the water use challenges in data centers into opportunities to create a new typology of infrastructure rooted in system-based thinking, internally symbiotic, and multifunctional.

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96 "Desalination | U.S. Geological Survey."

perspective of data center in desalination plant

perspective of data center with rainwater basins in the architecture

perspective of data center with waste heat-warmed pool on terrace

Heat redistribution

The waste heat of data centers is explored due to it being another common by-product of equipment operations. There are precedents of this strategy at various scales. Recently, a machine-learning and AI start-up in London partnered with a local leisure center to redistribute the waste heat from its "washing machine-size data center" for heating their pool[93]. This utility cost-saving idea is timely with rising energy prices. The small data center heats the pool at 30 degrees Celsius 60 percent of the time with an existing technology adapted and refined in the past five years.

Alternative uses for the low temperature waste heat include the provision of street heating during winter along the streets close to the data center in higher population density areas. At a larger scale, Sweden's Thule data center has been lauded for its district heating and cooling system which inspired others to consider[94]. The Floridsdorf Hospital in Vienna receives heat recovered from the Interxion data center across the street through a district heating system[95]. This tactic requires a heating and cooling infrastructure that extends beyond the site at a district scale. Thule was able to do this by connecting to existing district heating and cooling system in Stockholm. The Austrian government funded the 3.5 million euro (USD 3.7 million) insulated pipe to connect the data center to the hospital less than 80 meters (262 feet) away. In areas without such infrastructure, such as most American cities and towns, there would be substantial costs to create or modify the utility network and market structure.

However, the benefits of district heating make a strong case for them. They bring cost savings and lower carbon emissions with more efficiency and will likely increase as we move towards a Net Zero Scenario. Meanwhile, as the number of data centers, regardless of size, is set to increase[96] and energy generation becomes intermittent[97], this strategy is worth examination and investment to recover waste heat in a structure that constantly produces it.

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97 Kleinman, "Tiny Data Centre Used to Heat Public Swimming Pool - BBC News."

98 "Bahnhof Data Centre Thule - Öppen Fjärrvärme."

99 Judge, "Vienna Hospital to Get Waste Heat from Interxion Data Center."

100 "2022 Global Data Center Market Comparison."

101 Fares, "Renewable Energy Intermittency Explained."

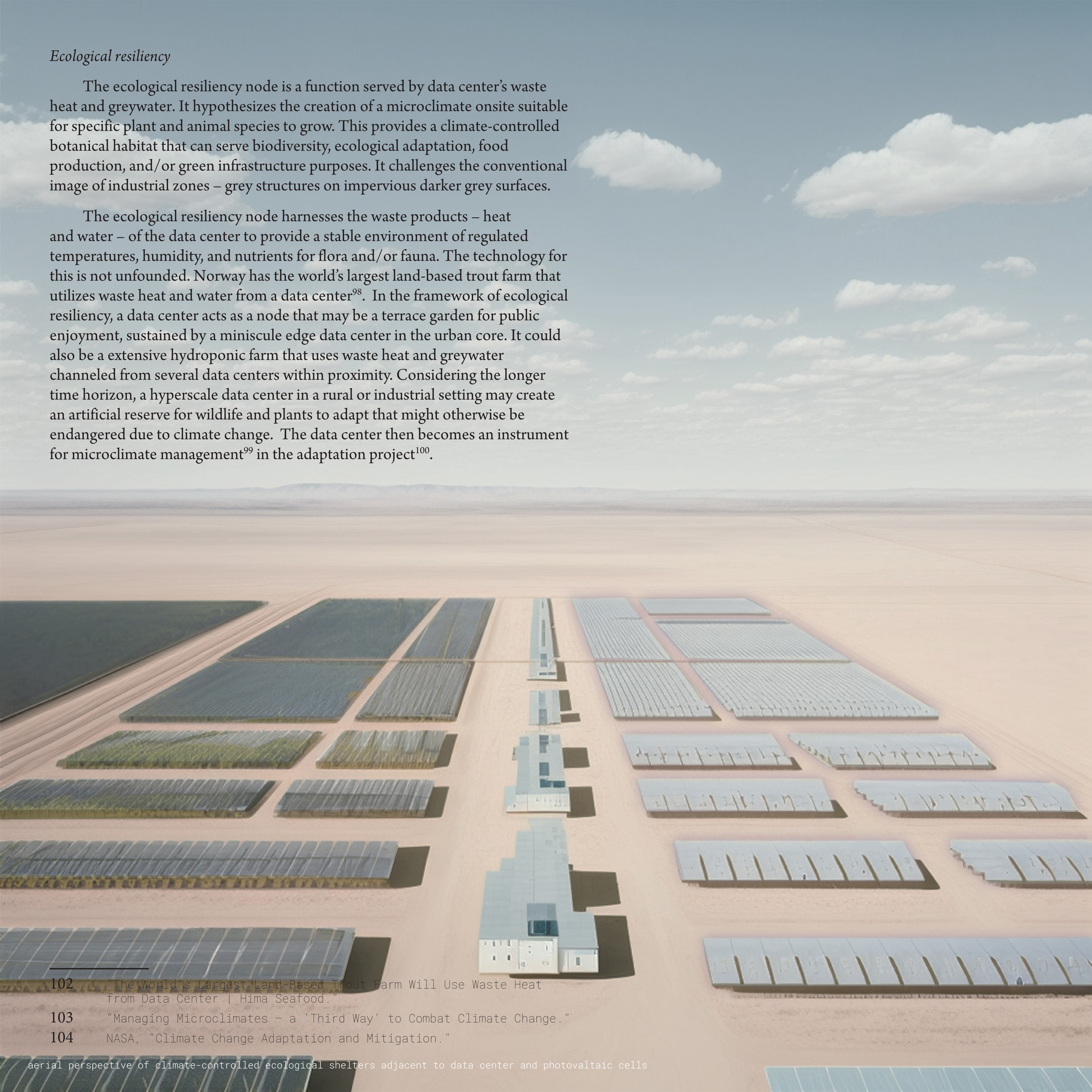
visualization of waste heat emitted from data center in city

perspective of data center with micro-climate for plants

Ecological resiliency

The ecological resiliency node is a function served by data center's waste heat and greywater. It hypothesizes the creation of a microclimate onsite suitable for specific plant and animal species to grow. This provides a climate-controlled botanical habitat that can serve biodiversity, ecological adaptation, food production, and/or green infrastructure purposes. It challenges the conventional image of industrial zones – grey structures on impervious darker grey surfaces.

The ecological resiliency node harnesses the waste products – heat and water – of the data center to provide a stable environment of regulated temperatures, humidity, and nutrients for flora and/or fauna. The technology for this is not unfounded. Norway has the world's largest land-based trout farm that utilizes waste heat and water from a data center[98]. In the framework of ecological resiliency, a data center acts as a node that may be a terrace garden for public enjoyment, sustained by a miniscule edge data center in the urban core. It could also be a extensive hydroponic farm that uses waste heat and greywater channeled from several data centers within proximity. Considering the longer time horizon, a hyperscale data center in a rural or industrial setting may create an artificial reserve for wildlife and plants to adapt that might otherwise be endangered due to climate change. The data center then becomes an instrument for microclimate management[99] in the adaptation project[100].



aerial perspective of climate-controlled ecological shelters adjacent to data center and photovaltaic cells

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102 "The World's Largest Land-Based Trout Farm Will Use Waste Heat from Data Center | Hima Seafood."

103 "Managing Microclimates – a 'Third Way' to Combat Climate Change."

104 NASA, "Climate Change Adaptation and Mitigation."

Modularity

The strategy to integrate modularity into the architecture of data centers is a radical hypothesis that envisions each data center as a spatially elastic structure that can disassemble into smaller individual mini data centers or assemble and propagate in size to become larger mega data centers. This existing modularity within the data center inspires this hypothesis. Multiple servers amalgamate into a rack of servers, and racks of servers combine to form aisles and aisles array to form data halls. The modules can be deployed to various sites – from mountains to cities, to naval and air fleets and scale according to required computing capacities.

This modularity allows for more possibilities after the data center has been decommissioned as its configuration may also be rearranged to suit its next life. The concept strives to inspire and provoke architectural innovations in the typology of data centers to spatially capitalize on the modularity of machines that reside inside. From a planning perspective, a system's modularity provides versatility, efficiency and responsiveness. Modular construction may have limitations such as monotonous aesthetic that might be concerning for other building types like housing. However, it is compatible for data centers whose occupants – machines – do not care for phenomenology or beauty very much. In fact, modularity increases efficiency and allows for easier repair and maintenance since parts can also be easily switched out.

perspectives (left and right) and collage (middle) of modular data centers in micro, meso, and macro configurations (left to right)

New Criteria

This section contains program-driven recommendations that focus existing policies on data centers and electronic waste. It suggests that 1) government policies and incentives for data centers should include technology and sustainability metrics, and 2) data centers should be positioned as leaders in the effort to build a more efficient and responsible system of electronic waste management.

Government policies and incentives to attract data centers to their cities should include technology and sustainability metrics such as density, power usage efficiency, and carbon emissions in qualifying data center projects for such programs. These considerations for some municipalities, including the aforementioned Loudoun County[105]., are already underway. However, even in the pioneering example of Loudoun, a social sustainability metric to indicate the impact on noise pollution, which is a voiced complaint[106], is absent in the current guidelines. More importantly, they should also be periodically updated as the industry and its demand are developing[107]. Existing policies for data centers are generally tax incentives such as exemption from sales tax for the purchase of equipment or property tax breaks[108]. Cities are attracted by data centers for the economic growth, property value appreciation and subsequent tax revenue[109] that they bring, as explained in the example of Fairfax County[110] earlier.

Critiques of this emphasize that the incentives that data center companies enjoy far exceed what they pay and contribute economically. In a 2021 report by Forbes[111]., it was emphasized that 15 data center projects launched since 2015, an average of $1 million of tax abatement was awarded per job created.

> The combined $10 billion in value of the projects, which created approximately 837 permanent jobs, was offset by at least $811 million in tax abatements, penciling out to almost $1 million for every permanent job created.

In a review of 32 tax incentives by The Montrose Group, the criteria for data center projects are assessed based on the dollar value on capital investment, building size, and timeframe. For instance, Minnesota companies "that build data or network operation centers of at least 25,000 square feet and invest at least $30 million within 48 months may qualify for a sales tax exemptions for up to 20 years on computers and servers; cooling and energy equipment; energy use; software; and pay no personal property tax" While the sales tax exemption on equipment and software may spur technological development, exempting energy use from sales tax does not motivate companies to look for energy-efficient solutions particularly when the electricity rate is already cheaper at 12% lower than the national average[112].

This thesis does not discourage the growth of data centers, but it calls for a considerate growth, which optimizes its benefits and mitigates its adverse effects. Policymakers can close this gap by incorporating social, environmental, and technological metrics in the formulation and revisions of incentives to support the data center industries in their respective jurisdictions.

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[105] Fluet, "Data Center Evolution."

[106] Olivo, "Northern Va. Is the Heart of the Internet. Not Everyone Is Happy about That."

[107] McPherson, "How Data Centers Are Paving the Way for Economic Growth."

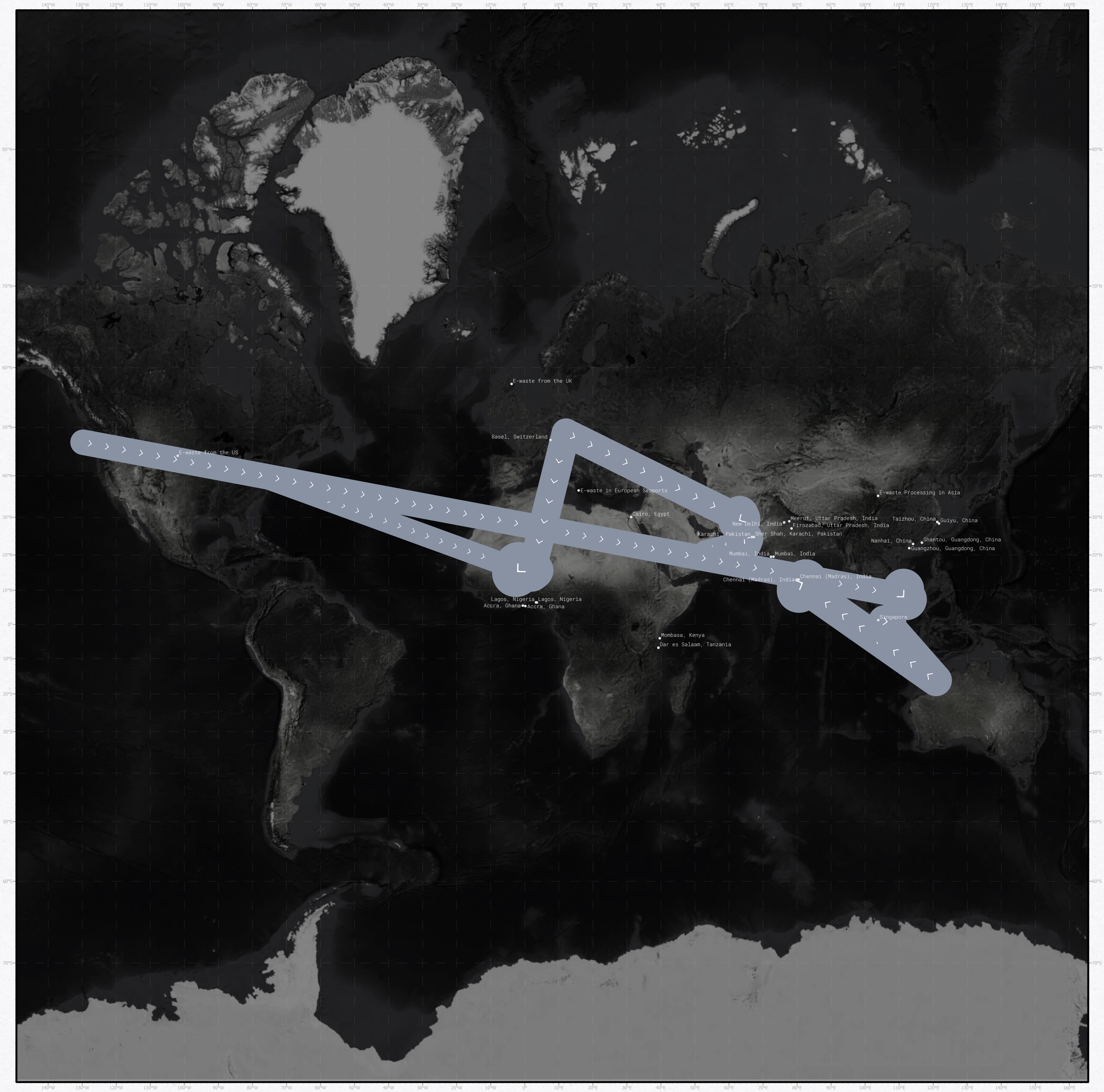
[108] Oregonian/OregonLive, "Data Centers' Small-Town Tax Breaks Bring Silicon Valley to Rural America."

[109] Pham, "Data Centers."

[110] "Change in Data Center Values Has Implications for Fairfax County Route 28 Taxpayers | FFXnow."

[111] Jeans, "Data In The Dark."

[112] "Electricity Cost in Minnesota."



● E-Waste Process Points (Port of Entry) ›› E Waste Movement (Thickness = Quantity) Data source: Esri, FAO, Google, NOAA, USGS

Sharing Expertise

In the final analysis, this discussion turns to the physical output of data centers – electronic waste. Electronic waste is a global problem increasingly aggravated by the proliferating digitalization of our world.

> A record 53.6 million metric tonnes (Mt) of electronic waste was generated worldwide in 2019, up 21 percent in just five years, according to the UN's Global E-waste Monitor 2020[113], released today.
>
> The new report also predicts that global e-waste (discarded products with a battery or electrical plug) will reach 74 Mt by 2030 — almost a doubling of e-waste tonnage in just 16 years. This makes e-waste the world's fastest-growing domestic waste stream, fueled mainly by higher consumption rates of electric and electronic equipment, short life-cycles, and few options for repair.
>
> …
>
> For perspective, last year's e-waste weighed substantially more than all the adults in Europe, or as much as 350 cruise ships the size of the Queen Mary 2, enough to form a line 125 km long.[114].

Meanwhile, less than 20 percent of electronic waste generated each year is recycled[115].

While data centers are high carbon emitters[116] due to their embedded carbon and resource-intensive operations, they can also contribute positively to managing electronic waste. This is because they are highly economic and efficient in the maintenance and repair of electronic equipment given the business nature of their organizations[117]. Unlike retail consumers, who may be persuaded by marketing and replace their devices more often than required, data centers would be cost-conscious to maximize profit. Their expertise in equipment management at a corporate scale can contribute to the formalization of electronic waste management infrastructure – a system that is still nascent.

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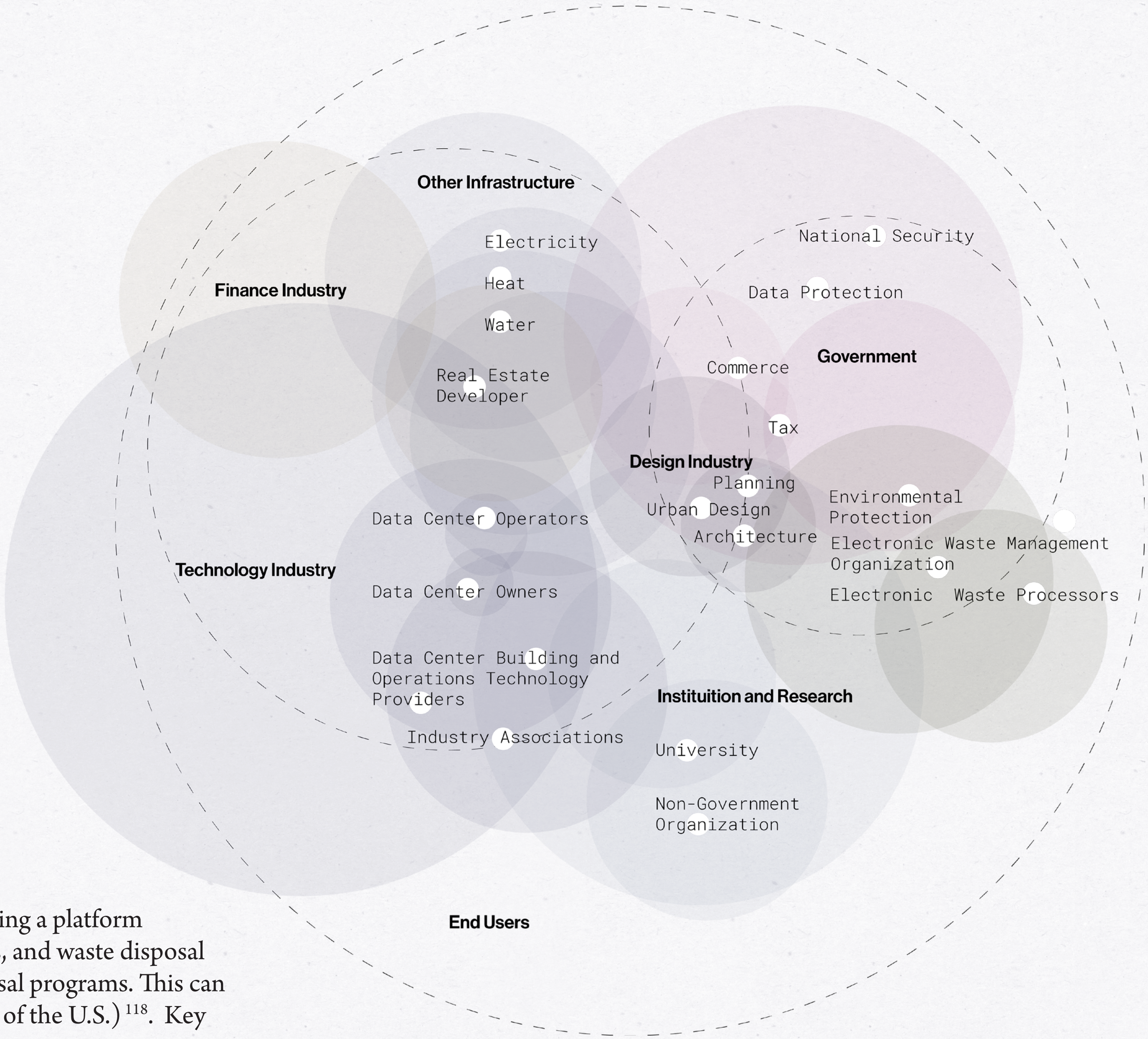
[113] Forti et al., *The Global E-Waste Monitor 2020*.

[114] "Global E-Waste Surging."

[115] "UN Report."

[116] Ensmenger, "The Environmental History of Computing."ABSTRACT:, From Charles Babbage's Difference Engine (a product of an increasingly global British maritime empire

[117] McCall, "Data Centers & E-Waste."



inter-field and intra-infrastructure platform relations diagram

A potential direction on this topic is formalizing a platform engaging data center operators, electronics makers, and waste disposal organizations with sophisticated electronics disposal programs. This can be R2 certified (in the US) or ISO 14001 (outside of the U.S.) [118]. Key principles for this initiative are:

1. Promote repair over recycle
2. Ensure destruction of data before upcycling or recycling

The production of electronic waste is not limited to data centers. However, data center companies, which comprise tech giants such as Amazon, Google, and Microsoft, have resources and existing aggressive sustainability goals and initiatives that include addressing electronic waste[119]. Microsoft Circular Centers, for instance, achieved 85% reuse and 17% recycle of critical parts[120]. This thesis identifies an opportunity for data centers as leading equipment specialists to collaborate with government and international agencies and contribute to the development of electronic waste management.

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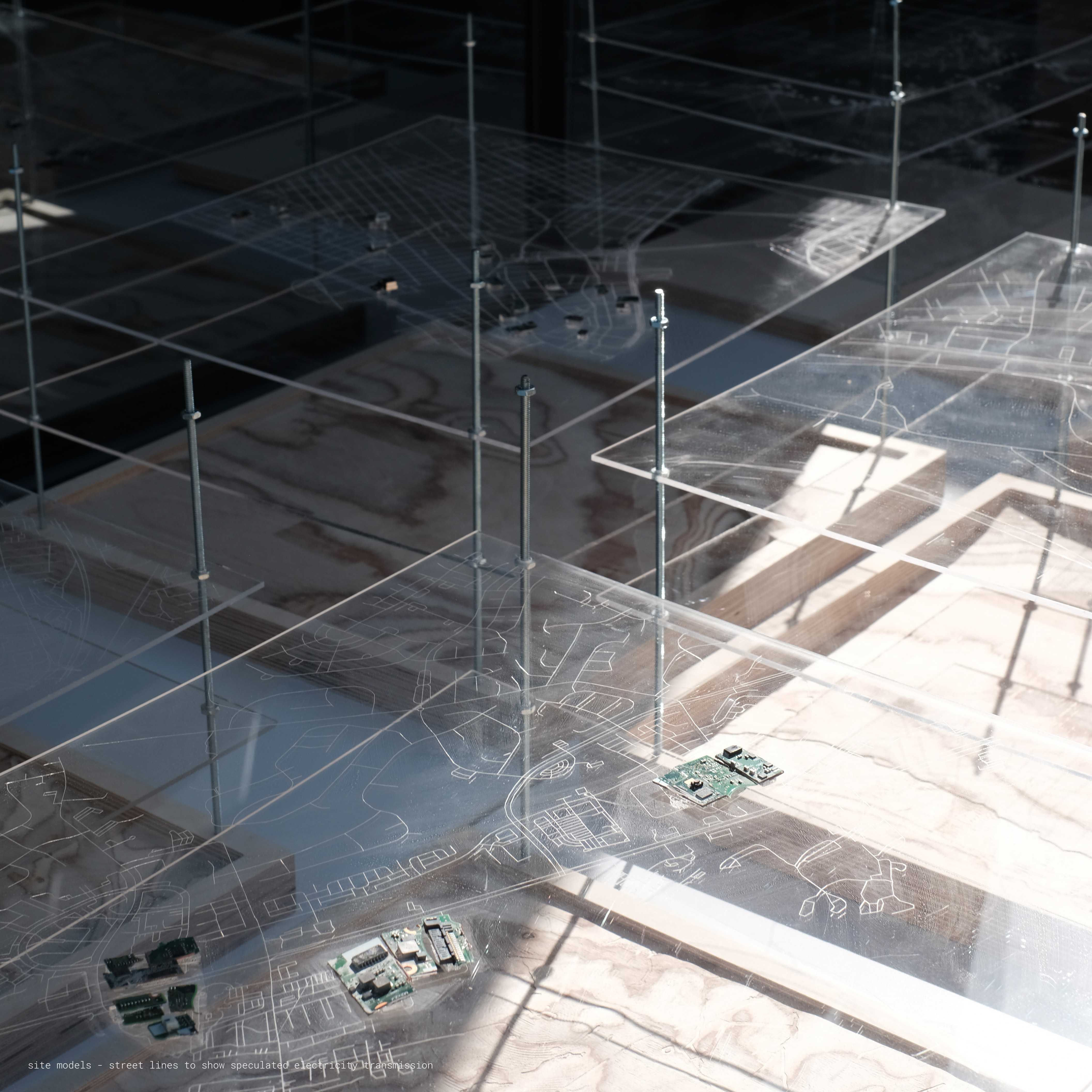
[118] "R2 and ISO | Charitable Computer Recycling & Reuse."

[119] Editorial, "Data Center Management And The Circular Economy."

[120] "Learn How Microsoft Circular Centers Are Scaling Cloud Supply Chain Sustainability."



site models - street lines to show speculated electricity transmission

> By the middle of the century… [infrastructure] had already acquired its bad reputation as a jargon word[121]

It is noteworthy that this thesis does not intend nor serve to prescribe directives for technical research or solutions. Its core purpose is to invite more questioning and reconsiderations of how we can think about infrastructure through the exercise of annotating the complexities of new infrastructure today and hypothesizing some, and calling for more, possible futures of them.

Returning to Heidegger, I turn to his later work *The Question Concerning Technology*[122] which Michael Wheeler eloquently explained[123],

> The primary phenomenon to be understood is not technology as a collection of instruments, but rather technology as a clearing that establishes a deeply instrumental and, as Heidegger sees it, grotesque understanding of the world in general. Of course, if technological revealing were a largely restricted phenomenon, characteristic of isolated individuals or groups, then Heidegger's analysis of it would be of limited interest. The sting in the tale, however, is that, according to Heidegger, technological revealing is not a peripheral aspect of Being. Rather, it *defines our modern way of living*, at least in the West.

As a unit of technology and serving technology today, data centers are instrumental in facilitating the omnipresent internet of things in our lives. However, they should not exist as necessary evils or Locally Unwanted Land Use (LULU)[124]. This calls back the discussion on infrastructure, a traditional LULU that necessitates reconsideration at this point of our civilization, and change is not unfamiliar to infrastructure[125].

> revision in scientific thought… has been occurring in many fields, from physics to biology.[126]

The nature and construction of infrastructure engages multi-disciplinary sciences that include social, technological, economic, geographical, and environmental. Data centers as the subject of study have demonstrated this through the international and cosmic[127] [128] networks of its connectivity operations while presenting territorial complications of its resource consumption and waste pollution. What has not been discussed, which it asks of future thinkers and actors, are the metaphysical considerations of our relationship to technology. For instance, for how long does information need to be stored? What value do we place on the work that machines can and cannot do for us? Do we need ethics for machine labor? What is the new economic paradigm if human capital is no longer an input? These potential complications precipitate grave social and economic empirical consequences if not planned or navigated sensitively and responsibly.

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[121] Ayto, *Movers and Shakers*.

[122] Heidegger, "The Question Concerning Technology."

[123] Wheeler, "Martin Heidegger."

[124] hlr, "To License a LULU."

[125] CARSE, "Keyword."the keyword infrastructure and its non-English variants\n(infraestructura, infrastruktura, infrastruktur, imprastraktura, infrastruttura

[126] Bateson, *Steps to an Ecology of Mind*.

[127] "Space Is the Final Frontier for Data Centers."

[128] Morrison, "Data Centres in Space Will Boost Satellite Computing Power and Storage."

Underlying this thesis are motivations to optimize data centers and future iterations of infrastructure in the larger project to promote "public health, safety, comfort, convenience, and general welfare."[129] This endeavor has 1) elaborated data centers, infrastructure, and the relation of the two, 2) identified the multi-dimensional implications of the built form of data centers beyond real estate and the intangible function they serve, and 3) postulated *some* present and future alternatives of their typology that are multifunctional and designed for adaptation post-decommissioning. It also presented two directions for policy consideration. At heart, this work seeks to be useful and enthuse new thinking for planners, designers, data center professionals, real estate developers, and community members to navigate the development of infrastructure in the integrated physical and meta landscapes of our world.

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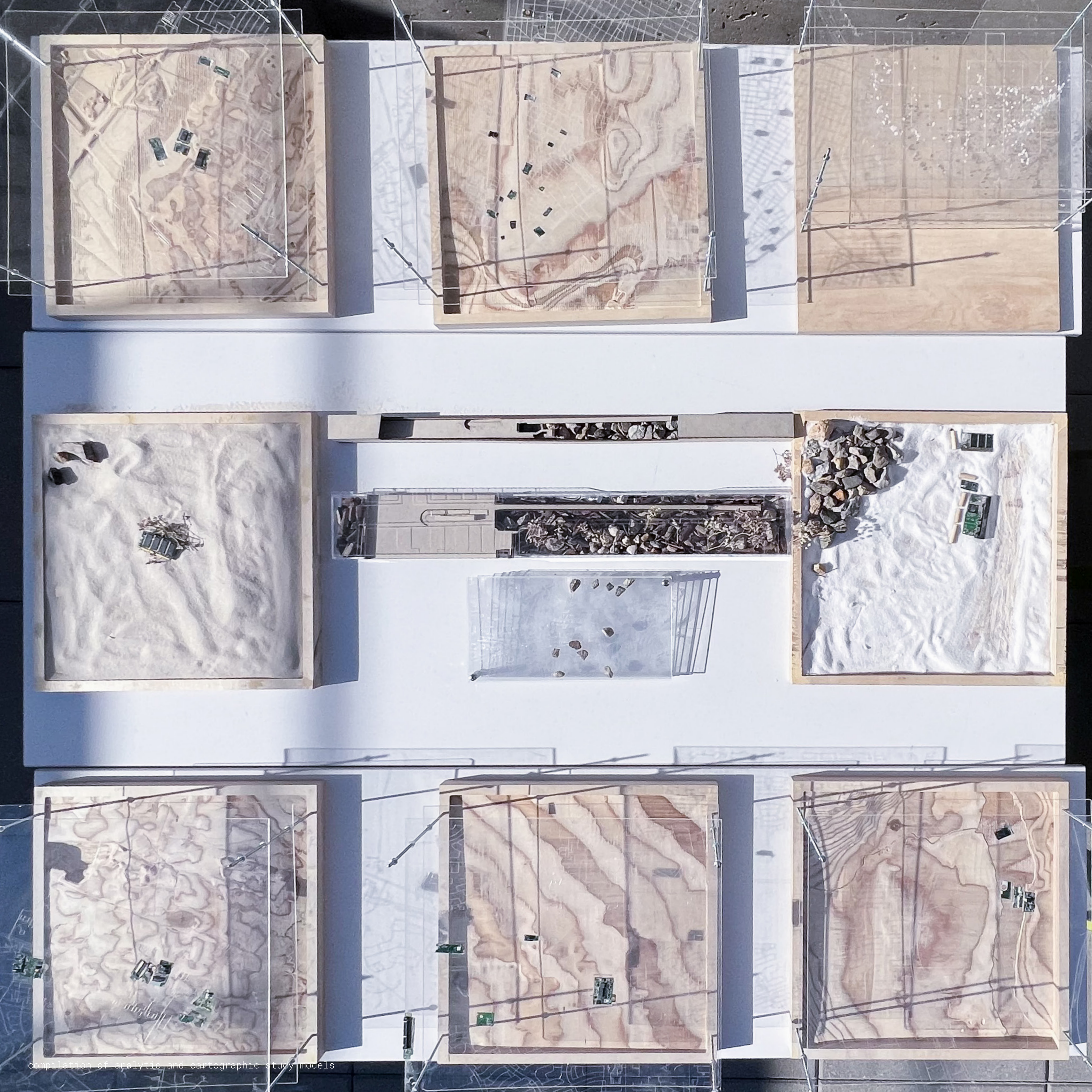
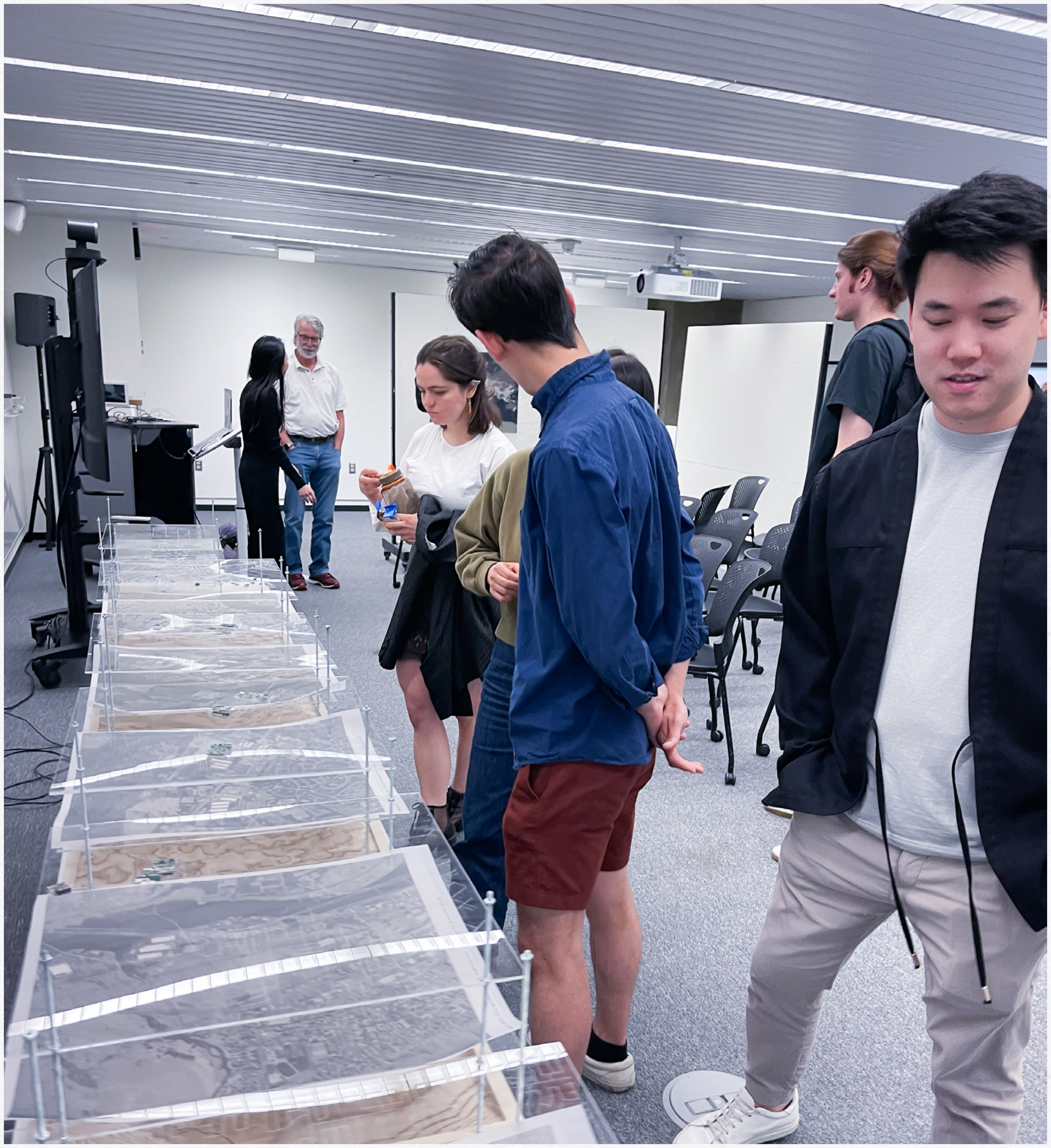
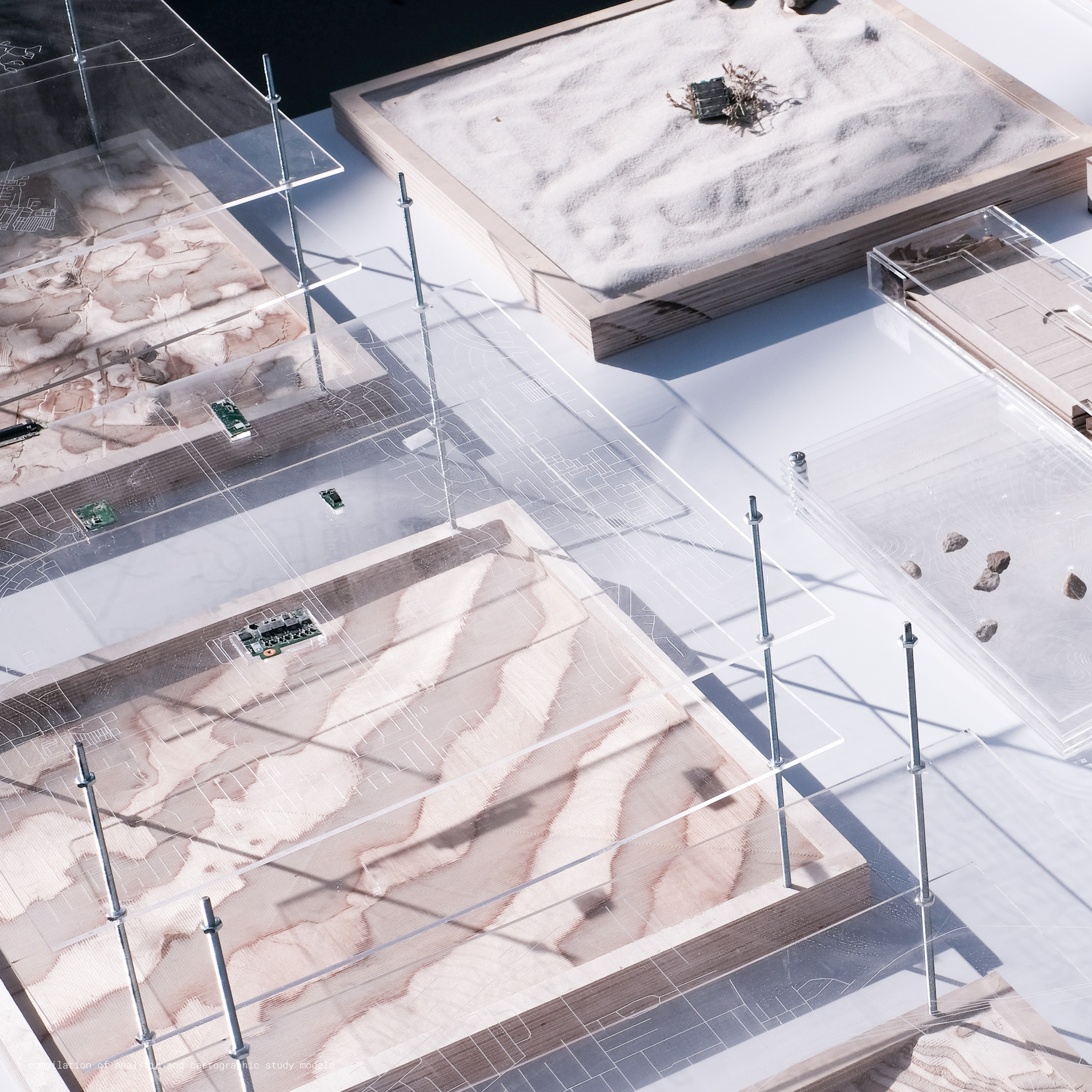


compilation of analytic and cartographic study models

thesis presentation at GSD on May 10, 2023
photos by Meng Qi Xu





compilation of analytic and cartographic study models

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