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The BosWash Infrastructure Biome and Energy System Succession

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Abstract: The BosWash corridor is a megalopolis, or large urbanized region composed of interconnected transportation, infrastructure, physiography, and sociopolitical systems. Previous work has not considered the BosWash corridor as an integrated, holistic ecosystem. Building on the emerging field of infrastructure ecology, the region is conceptualized here as an infrastructure biome, and this concept is applied to the region's energy transition to a post-fossil fueled heating sector, in analogy to ecosystem succession. In this conception, infrastructure systems are analogous to focal species. A case study for an energy succession from an aging natural gas infrastructure to a carbon-free heating sector is presented, in order to demonstrate the utility of the infrastructure biome framework to address climate and energy challenges facing BosWash communities. Natural gas is a dominant energy source that emits carbon dioxide when burned and methane when leaked along the process chain; therefore, a transition to electricity is widely seen as necessary toward reducing greenhouse gas emissions. Utilizing an infrastructure biome framework for energy policy, a regional gas transition plan akin to the Regional Greenhouse Gas Initiative is generated to harmonize natural gas transition within the BosWash infrastructure biome and resolve conflict arising from a siloed approach to infrastructure management at individual city and state levels. This work generates and utilizes the novel infrastructure biome concept to prescribe a regional energy policy for an element of infrastructure that has not previously been explored at the regional scale—natural gas.

Keywords: infrastructure biome; infrastructure ecology; regional energy policy; natural gas; boswash corridor

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1. Introduction—The BosWash Corridor

The urban corridor from Boston, MA, USA to the Washington, DC, USA (BosWash) corridor has been of research interest for decades because it is a hub of urbanization, economic growth, and social and political importance. First named "BosWash" by Kahn and Weiner in 1967, BosWash is the largest, most populous, and oldest urbanized area in the United States (USA), home to more than 50 million people, including major cities such as Baltimore; Boston; New York City; Philadelphia; and Washington, DC [1]. The region is home to nearly 20% of the US population, while occupying only 2% of the country's landmass [2]. Originally coined a "Megalopolis" by Jean Gottmann in 1961, the corridor is a string of metropolitan centers, the "Main Street of America," recognized for "economic growth and political and social power supported by high levels of mobility and accessibility" [3–7].

Though extensive, the foundational work describing BosWash does not extend to conceptualizing the BosWash corridor as a holistic ecosystem, integrating the suite of coupled human-natural systems (CHANS) across the region [8]. This is an important gap in the study of the BosWash corridor. Utilizing a CHANS framework allows research into infrastructure relationships that are integral to the function and future sustainability of the region. This paper examines the BosWash region as an infrastructure biome, utilizing the language of ecology to describe relationships among co-located infrastructure to further understand CHANS at a regional level. This work builds upon the framework of infrastructure ecology, used previously for an analysis of urban infrastructure [9–11], and demonstrates the effectiveness of expanding the ecological analogies across an entire region. This paper conceptualizes and defines the BosWash corridor as an ecological biome, and applies the concept to the analysis of the energy transition of a key element in the infrastructure ecosystem, previously unexplored at the regional level—the natural gas distribution system.

1.1. The BosWash Infrastructure Biome

The BosWash corridor is conceptualized as an infrastructure biome for the first time using ecological analogies, interconnected by physical geography, biogeography, hydrology, transportation corridors, natural gas transmission and distribution lines, diverse populations, and a wide variety of land uses. A foundational principle of ecology is interconnectedness and interdependence among elements of ecosystems. Interconnectedness in ecological science describes the linkages that exist among ecosystem components, and explains why, when something changes in the ecosystem, downstream effects propagate to other parts of the system [12]. Ecosystems can be described as interdependent, meaning that organisms within an ecosystem depend upon one another for their individual success and overall ecosystem function [13].

These ecological principles can be applied to both the natural and built infrastructure and sociopolitical systems across the BosWash infrastructure biome (Figure 1). Natural infrastructure systems across the corridor include the extensive water network, ecotones, and cultivated lands that contribute to a diversity of land cover types across the region. Traditional land designations across the BosWash corridor described regional similarities in land-surface form, soils, climate, vegetation, and fauna [14]. The BosWash region is home to interconnected waterways, including Mass Bay, Chesapeake Bay, and major rivers such as the Connecticut, Hudson, Delaware, and Susquehanna rivers [15]. Waterways and watersheds are inherently interconnected, as changes to water quality or flow rates in one area can have consequences downstream, including but not limited to combined sewage water overflow events, contamination limiting drinking water supplies, or development projects altering the natural pattern of riverways and causing changes to biodiversity [16–18].

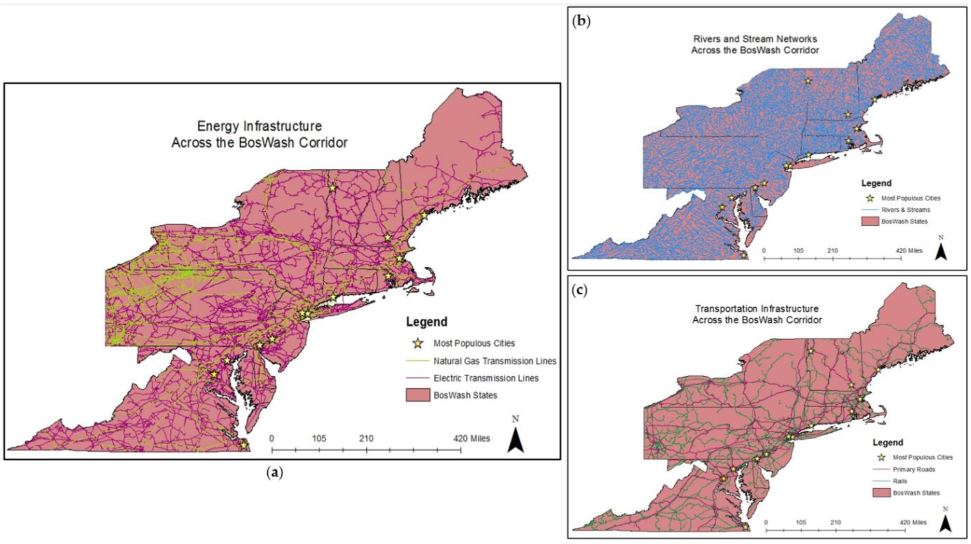

Figure 1. Maps of the BosWash region highlighting networks of various infrastructure systems. (**a**) Energy infrastructure networks of the BosWash corridor including major natural gas transmission lines [19] and electric transmission lines [20]. (**b**) Rivers and streams across the BosWash corridor [21]. (**c**) Map of the major roadways [22] and railroad networks [23] connecting states and urban areas across the BosWash corridor. These systems of infrastructure demonstrate the interconnectedness of the region and the complexity of infrastructure networks that connect beyond jurisdictions.

Natural infrastructure systems across the BosWash corridor serve as examples for the usefulness of ecological language for examining infrastructure systems across the region, as shared benefits and threats surpass jurisdictional boundaries and responsibilities [7].

Interconnected, co-located, and interdependent energy infrastructure networks further build the analogy of the infrastructure biome across the BosWash corridor, as exemplified by the complexity of energy pipelines and transmission lines throughout the region (Figure 1a). Grid outages in one state can spill over into other states across the region, such as the Great Northeast Blackout of 1965, causing power outages across CT, MA, NH, NJ, NY, PA, RI, and VT [24]. Gas transmission line outages in one city or state can impact the energy supply across the entire region. One recent example of this was the Colonial Gasoline Pipeline Outage in 2021 that occurred because of a ransomware attack and resulted in the shutdown of 5500 miles of pipeline. Although this outage occurred in only a small portion of BosWash (DC, MA, PA, NJ, and NY) it had economic impacts throughout the corridor [25]. Beyond geographical spillover effects, distinct infrastructure systems are functionally interdependent. For example, Superstorm Sandy demonstrated how the gasoline supply chain was disrupted because of electric grid failures, which shut down electric-driven gasoline pumps, causing spikes in the cost and availability of gas [26]. Additional research has explored the benefit of the challenges that are associated with natural gas usage for electricity generation and home heating [27,28]. In New England, for example, the regional transmission organization is challenged in winter months to provide enough natural gas to residential heating customers, while maintaining electricity production demand [29]. This imbalance can lead to an energy-security risk, resulting in the use of coal, oil, or nuclear to meet demand or ordering load shedding.

Originally built for rail and expanded to roadways, the transportation infrastructure physically connects the region (Figure 1c) [3]. A collapse in the transportation network of the BosWash region would have tremendous consequences for economic, social, and political functioning across the region [30]. The northeast is home to the most users of public transportation and intercity railways in the US, in part because of the concentration of jobs and housing opportunities, but also because of the availability of transportation networks that connect the region [15]. The co-located transportation infrastructure network plays a critical role in the infrastructure biome by connecting municipalities and states across rigid political borders.

The physically interconnected transportation infrastructure elements have inspired regional initiatives to work collaboratively to develop regional transportation policy and lower transportation carbon emissions. The Eastern Transportation Coalition is a partnership of 200 agencies across 17 states and Washington, DC that have joined together to enhance modes of transportation along the east coast [31]. The recently disbanded Transportation Climate Initiative (TCI) was a regional collaboration between 13 states that aimed to build a clean energy economy, reduce emissions from transportation across the region, and promote the research of clean fuels and transportation options [32]. The interconnectedness of the region's transportation infrastructure has resulted in the creation of communities that are integrated beyond state or city lines [7].

Both the built and the natural infrastructure systems connect the states and cities/towns of the region beyond jurisdictional boundaries, demonstrating the importance for infrastructure management and policy to extend beyond jurisdictional boundaries. Previous research has shown the effectiveness of coordinating infrastructure management among a variety of stakeholders and the ineffectiveness of a siloed approach [10,33,34]. Siloed infrastructure management, or the separate management of interconnected infrastructure systems across political boundaries, can hinder collaboration and ultimately slow sustainable progress by challenging the success and implementation of large-scale infrastructure projects, such as a transition away from natural gas. The infrastructure biome analogy considers the CHANS infrastructure systems and the interacting elements as more than the sum of its parts, allowing us to understand spatial and functional interdependencies among infrastructure elements which we might otherwise not recognize if we treat the bio-, economic-, political- and infrastructure ecologies in mutual isolation.

1.2. Political Ecology of the Infrastructure Biome

The infrastructure biome analogy extends beyond the built and natural infrastructure features and should be considered in the political ecosystem that is embedded in the BosWash corridor. Political formal jurisdictional boundaries often fail to reflect the spatial extent or dynamic relationships within a region [2,3], and challenges that are faced by stakeholders are often not localized to one municipality or state but instead are a common occurrence across the region [15]. The framework of political ecology examines the nature–society interface, examining how political and economic structures are integrated in ecological changes [35]. Political ecology is a useful framework for understanding the relationships between nature and society and is helpful in analyzing the politics of these relationships for the pursuit of environmental health and sustainability [36].

Political ecology is useful when political circumstances extend beyond traditional jurisdictional boundaries, and researchers in the field have found benefit in examining political ecology at the regional scale [36–39]. A region is a spatial unit with neighborhood effects and political outcomes. Within regional political ecosystems there are often informal politics and institutions across the scale that influence the region and reflect shared neighborhood experience and interests. Therefore, political discussions can be more meaningfully understood in the regional context because of the shared political interests and spatially unique challenges that are faced among stakeholders [37]. In the political ecology's foundational work, the term region is central [38,39] because of the regions' commonalities stemming from shared histories, cultures, environments, and institutions [36]. To address the environmental and social challenges that are associated with aging natural gas infrastructure throughout BosWash, political initiatives and ecologies need to be considered as elements of infrastructure that cross borders to enable regional collaboration [38].

The Infrastructure Biome construct and concept, as developed above, serves as a systems framework for the analysis of the regional natural gas infrastructure system. As in natural ecosystems, an infrastructure biome can be viewed through an autecological or synecological lens [40,41]. In this paper, we study the power of the infrastructure biome construct by examining an individual species (natural gas infrastructure) and the importance of considering the impact of an energy transition across the BosWash community.

1.3. The Natural Gas Case Study

Natural gas became widespread in the 1970s, framed as a "bridge" fuel in the energy transition from coal to renewables, but it has grown to become a primary source of heat and electricity for many states and cities across the US [42]. The BosWash corridor is no exception, being responsible for more than 18% of the total natural gas consumption in the US in 2020 [43]. Natural gas is a fossil fuel that emits carbon dioxide (CO_2) and methane (CH_4) along its supply chain, from sourcing, to distribution, and end-use [44,45]. In addition to the greenhouse gas (GHG) emissions that are associated with its life cycle, aging natural gas infrastructure poses added threats to the environment and the health of the public [46].

As natural gas distribution infrastructure ages, cracks develop and leaks release uncombusted natural gas, composed primarily of CH_4, into the atmosphere. The corrosion of steel pipes and mechanical failures (joint leaks) of cast iron mains are the two most common causes of leaks. Cracks are repaired upon discovery or as soon as reasonably possible. Atmospheric CH_4 is a potent GHG and is considered by the Intergovernmental Panel on Climate Change (IPCC) to be the second most important GHG after CO_2, and the oil and natural gas systems in the US are estimated to account for 31% of anthropogenic CH_4 emissions [47,48]. A recent study found that CH_4 emissions from the natural gas system may be significantly underestimated, and that the climate impacts of leaking natural gas infrastructure are potentially more impactful than previously estimated [49]. Leaking infrastructure has also been reported to cause damage to street trees. When leaked CH_4 travels through the soil in a tree pit, it displaces oxygen by volume and limits tree growth or causes tree death [50–52]. In addition to the environmental impacts of aging natural gas infrastructure, emerging research suggests that natural gas energy poses a significant threat to the health of the public. In homes with poor ventilation and gas-powered stoves, inhabitants were exposed to dangerous levels of combustion byproducts (primarily nitrogen dioxide, NO_2) at concentrations that exceeded the 1-h national standard for NO_2 in just a few minutes [53].

Natural gas energy in the BosWash corridor is prevalent with more than 213,000 miles of distribution pipelines in the region [54], and aging gas infrastructure is a growing threat across the corridor. A recent study in Washington, DC; Baltimore; Philadelphia; New York City; Providence; and Boston found that CH_4 emissions from fugitive natural gas losses were nearly twice the total of the US EPA inventory [55]. Extensive scientific evidence demonstrates the intensity of climate change effects in urban centers [56,57] and the inequitable distribution of climate change impacts that are dependent on socioeconomic factors within cities [58,59]. Emissions from natural gas distribution infrastructure follow this trend. Research examining the prevalence of natural gas leaks in urban areas and quantifying the CH_4 emissions from leaking natural gas distribution infrastructure have shown "that urban CH_4 emissions are significant and the frequency and location of leaks ... in [urban areas] supports the inference that natural gas is a large contributor of excess urban CH_4 " [55]. A recent study in MA demonstrated that natural gas leaks are an issue of environmental justice, being more concentrated and more slowly repaired in neighborhoods of marginalized populations [60].

States and cities across the BosWash region have robust climate action plans (CAP) that mandate GHG emission targets that cannot be met unless aging natural gas infrastructure is addressed. A broad policy framework of "electrify everything" has emerged in recent years [61–63]; however, there has been little research carried out on what a managed, strategic electrification implementation plan looks like across spatial scale. If building electrification occurred randomly in space across a gas infrastructure network by building owners defecting from gas service, this could produce a gas utility "death spiral", in which a declining number of customers is required to maintain the same aging distribution infrastructure [64,65]. Conversely, strategic electrification could involve a managed retraction of a gas network based on a systematic consideration of factors such as the spatial pattern of leak prone pipelines, and/or city, state or regional policy and financing incentives.

Previous regional collaborations across the BosWash corridor for managing infrastructure and GHG emissions, such as the Regional Greenhouse Gas Initiative (RGGI) or the recently disbanded Transportation Climate Initiative (TCI), have demonstrated various levels of success, but to date, there has been no collaborative regional policy for addressing natural gas infrastructure. Sustainable energy transitions are powered by a variety of regional actors with different aims/interests, which culminates in the development of a regional energy initiative that is specific to the needs of those that are involved [66], making this approach logical for dealing with aging natural gas infrastructure in the BosWash infrastructure biome. As stated by Beiler et al., "a corridor can be viewed as a holistic system in which resiliency is achieved at a regional level" [3]. Further utilizing the infrastructure biome metaphor, one can think of this grand challenge of regional energy transition as an ecosystem undergoing succession.

To prescribe the importance of a regional collaborative policy for addressing aging natural gas infrastructure across the BosWash region, the physical state of the region's natural gas infrastructure was analyzed for aged and leak-prone gas distribution pipelines. The natural gas infrastructure system is further contextualized in the socio-political ecosystem of the BosWash region with an analysis of population density and state/city climate action plans across the region, in order to ensure a just transition away from natural gas, especially for densely populated and/or environmental justice communities. Culminating from this infrastructure biome analysis are policy recommendations for a regional energy-transition policy that could benefit the BosWash corridor and alleviate conflict from a siloed approach to aging infrastructure and energy succession. This work describes a novel infrastructure biome and demonstrates the utility of this concept through the application to regional policy addressing aging natural gas infrastructure.

2. Materials and Methods

To develop a regional natural gas transition policy for the BosWash corridor, a three-part methodology was used to:

1. Develop baseline data of the physical state of the natural gas infrastructure;
2. Analyze urban demographics that are associated with natural gas utilities;
3. Contextualize energy transition within the various state/city CAP targets.

The physical state of the natural gas distribution infrastructure was captured by categorizing leak-prone infrastructure and quantifying natural gas leaks. Pipeline data were collected from the US Pipeline and Hazardous Materials Safety Administration (PHMSA) and natural gas consumption reports from the US Energy Information Administration (EIA) were compiled for each of the 12 states and Washington, DC. Regional county-level census data were collected to estimate the relationship between natural gas leaks, leak-prone infrastructure, and population density across the corridor. Lastly, the CAPs from each of the states and the largest cities were analyzed to understand the policies to reduce GHG emissions and electrify heating where applicable. Together, the physical, social, and political analyses were compiled to create recommendations for a regional natural gas energy-transition policy.

2.1. Area of Study

For this study, the BosWash corridor is defined as 12 states and 13 major cities. States include ME, NH, VT, MA, CT, RI, NY, NJ, PA, DE, MD, VA, and major cities are identified as the most populous city in each state, based on US Census Annual Estimates for 2020, and Washington, DC (Figure 2, Table 1) [67].

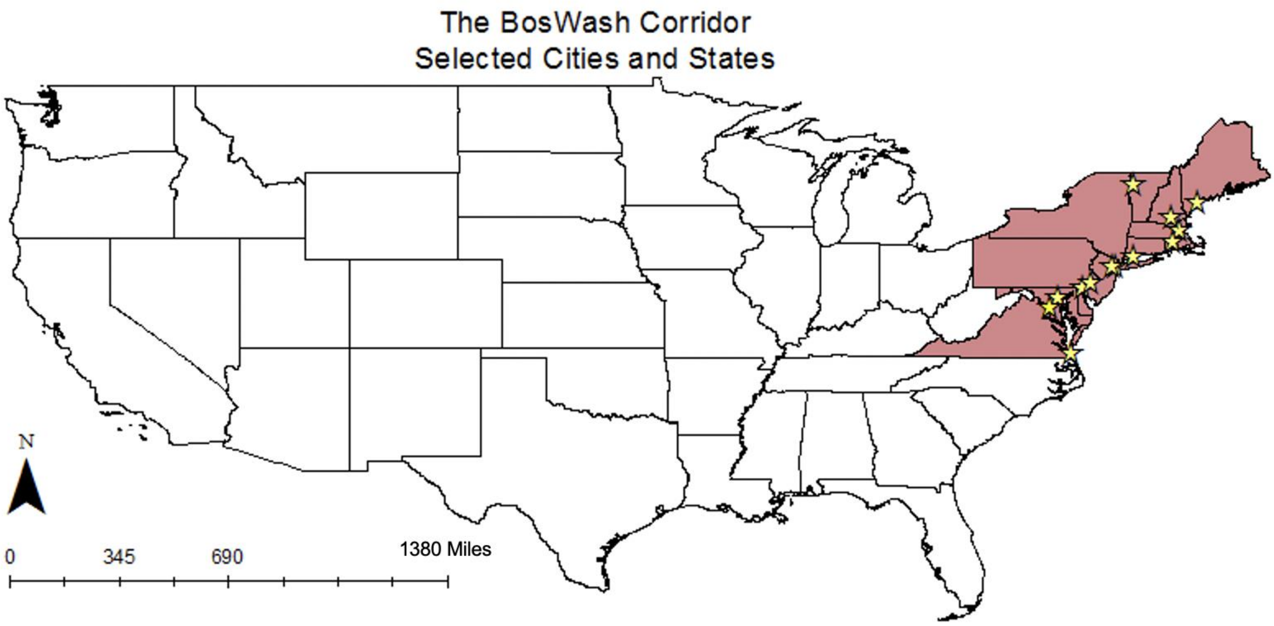

Figure 2. Selected states and major cities considered in the BosWash corridor. Selected states highlighted in red and selected cities noted by yellow stars.

Table 1. The 12 states and 13 major cities in this study. For this study, the BosWash corridor was defined as 12 states from Maine to Virginia and each of the most populous cities in each state, and Washington, DC were included for analysis.

State, USA	Most Populous City
ME	Portland, ME
NH	Manchester, NH
VT	Burlington, VT
MA	Boston, MA
RI	Providence, RI
CT	Bridgeport, CT
NY	New York City, NY
NJ	Newark, NJ
PA	Philadelphia, PA
MD	Baltimore, MD
DE	Wilmington, DE
VA	Virginia Beach, VA
–	Washington, DC

2.2. Physical State of Pipeline Infrastructure

To analyze the physical state of the natural gas infrastructure across the BosWash corridor, 2020 data that were published by PHMSA and the EIA were compiled for each state. The PHMSA data were reported by individual utility companies, reporting characteristics of the gas infrastructure within their respective service territory. The states in which each utility service was located were used to compile state reports, using data from each of the utilities within the 12 states. From the PHMSA reports, data summarizing the total mileage of distribution pipe per state, the materials of gas pipelines, the diameter of pipelines, and the number of gas leaks in the system were collected. Leak-prone pipes were defined as miles of pipe that were made of cast/wrought iron or bare steel, materials that were more prone to leakage after years spent buried underground [68,69]. Cast/wrought iron pipes were chosen because they were susceptible to failures at the joint locations and leaks from earth movement, such as frost heave or digging, and from graphitization. Bare steel pipes lack an outer protective coating, making them vulnerable to corrosion [70].

In addition to defining leak-prone pipes based on material, miles of pipelines that were installed prior to 1970 in each state were collected. Pipelines that were installed prior to 1970 were installed before broad pipeline regulations took effect, making them more susceptible to failure due to potential defects during manufacturing [70]. To further understand pipeline leakage and vulnerability at the state level, volumes of lost and unaccounted-for (LAUF) gas were collected from the EIA. Volumes of LAUF gas were calculated using the volume of gas that was lost to leaks, damage, accidents, migration, and/or blow-down, and volumes of unaccounted-for gas were calculated as a percentage of the total gas that was consumed by each state [71].

2.3. Social Vulnerability across the Region

To estimate the impacts of aging and leak-prone natural gas infrastructure on climate-vulnerable urban communities, 2018 county-level population totals were used from the Center for Disease Control and the Agency for Toxic Substances and Disease Registry [72]. Counties of high population, which included the most populous cities in each of the 12 states and Washington DC, were used to compare the concentration of leak-prone pipelines, aged pipelines, and natural gas leaks and population concentrations within urbanized counties and the rest of the state.

The service territory for each gas utility in BosWash was considered. Service territory was identified by state from the 2020 PHMSA reports. County-level service territory was identified from individual utility websites. To estimate the physical state of the infrastructure within the major cities that were identified for this analysis, utility companies servicing the county within which the most populous city was located, or counties immediately surrounding, were chosen. These utilities were chosen over wider service territories because the limited-service territories that were localized to the major cities gave a more accurate estimation of the infrastructure within each of the major cities. It is important to acknowledge that pipeline characteristics can change between and within counties that are serviced by the same utility, and the location of leak-prone natural gas pipelines was not publicly available at the time of research. Challenges that were associated with the wide breadth of service territory for each utility resulted in a small sample of densely populated counties for analysis. The mis-matched spatial scale of pipeline data and population data required some assumptions to be made regarding the location of vulnerable pipelines within county limits. The authors acknowledge intracity variation that is not captured in this analysis due to the aggregated county-level spatial scale of the reported natural gas pipeline data.

2.4. State and City Climate Action Plans

The most recently published CAP for each of the 12 states and the most populous cities in each state, including Washington, DC were used to identify the GHG emission reduction goals and commitment dates. The commitment dates and percent-reduction goals were pro-rated to compare state/city plans across the region. A variety of target percentages and target dates made comparison among the states/cities challenging. Pro-rating allowed the authors to estimate progress along a similar timescale by tracking progress among states/cities along a common timescale. In addition to individual action plans, research for state and city conflict over natural gas ban ordinances was completed. Web searches for the political history of gas ban ordinances for each state and a uniform state building code were reported. The policy and regulatory environment across the BosWash corridor reveal some conflict between state and city governments, in the passing or consideration of preemption laws—statutes that limit a municipality's ability to prohibit natural gas hookups or require electrification in new construction or renovation projects [73]. In some cases, exemplified by MA, states did not have a passed or pending gas ban preemption law but existing state building and/or gas codes prevented the passing of municipal gas ordinances [74]. For all states without a formal preemption law, the state building codes were searched to determine whether a municipal gas law could be disapproved by a uniform state building code.

3. Results & Discussion

3.1. The Physical Context—Natural Gas Infrastructure

The physical gas infrastructure in BosWash is aging and vulnerable to failure. A regional report of the severity of leak-prone and aging infrastructure for the BosWash region has not previously been created and the prevalence of gas leaks and leak-prone infrastructure demonstrates a strong requisite for a regional natural gas transition policy. Leak-prone pipes were defined first by material, made from bare steel or cast iron [75–77]. Then, pipelines that were installed prior to 1970 were considered to be leak-prone because of the policy and regulation changes that have happened over the past decades to improve pipeline manufacturing [70]. As depicted in Table 2, more than 13% of the total pipelines in the region are made of leak-prone materials and 30% were installed prior to 1970.

The number of gas leaks data reported in Table 2 are Grade 2 leaks that were scheduled for repair at the end of the reporting period for 2020 and should be considered an underestimation of the severity of leakage across the pipeline network. Utilities grade leaks based on repair priority: grade 1 leaks are slated for immediate repair because of the danger and risk of explosions; grade 2 leaks are leaks that are currently non-hazardous but could become dangerous over time and are slated to be repaired within the next 6 months; grade 3 leaks are recorded but are defined as non-hazardous and not in need of repair [78]. Few states in the region report the location of all natural gas leaks. MA passed state legislation requiring the address of reported gas leaks, regardless of grade, to be made publicly available. In MA, total leaks in the state exceed 23,000 leaks, while PHMSA datasets report only a subset of 8900 for the state [79].

Table 2. Natural gas distribution pipeline statistics for each of the 12 states and Washington, DC in the BosWash corridor. Data reported from PHMSA in 2020 [69]. For each state, the total number of pipeline miles and the total number of Grade 2 leaks scheduled for repair is reported. A total of 2020 reports of LAUF are displayed for each state as a percent of total consumption [71]. A negative value means that supply is less than disposition. Leak-prone pipelines are defined as distribution pipelines made of bare steel or cast/wrought iron and are reported as total miles and percent of state's total miles [70]. Total miles of pipeline in each state installed prior to 1970 is reported both as total miles and percent of state's total miles. Each descriptive statistic and leak-prone classification is totaled for the BosWash corridor. Data are rounded to the nearest whole mile. States and utility information is sorted by the number of miles of pipeline in each state, with NY having the most, and VT having the least.

State	State Pipelines (miles)	Total # of Grade 2 Leaks	LAUF (% of Total Consumption)	Leak-Prone Pipe (miles)	Leak-Prone Pipe (% of Total Miles)	Pipelines Constructed Prior to 1970 (miles)	Pipelines Constructed Prior to 1970 (% of Total Miles)
NY, USA	49,602	10,761	0.7	7577	15.3	18,093	36.5
PA, USA	48,651	10,567	3.9	8,286	17.0	15,594	32.1
NJ, USA	35,604	3871	0.8	3824	10.7	9932	27.9
VA, USA	22,133	2544	2.2	590	2.7	3790	17.1
MA, USA	21,800	8983	−3.2	3934	18.0	7596	34.8
MD, USA	15,266	4595	4.6	1239	8.1	4770	31.2
CT, USA	8355	1212	1.8	1289	15.4	2841	34.0
DE, USA	3295	246	4.3	59	1.8	626	19.0
RI, USA	3204	743	1.5	855	26.6	1017	31.8
NH, USA	2006	22	0.3	49	2.4	325	16.2
ME, USA	1382	122	0.4	25	1.8	154	11.1
VT, USA	868	13	−0.9	0	0	72	8.3
Washington DC, USA	1221	867	2.1	430	35.2	690	56.5
BosWash Corridor	213,387	44,747		28,157	13.2	65,499	30.7

The prevalence of leak-prone gas infrastructure across the BosWash region provides motivation for regional policy to address the environmental and public health/safety threats from the near 30,000 miles of leak-prone infrastructure across the region. Unfortunately, the lack of policy requiring data transparency discourages a full understanding of the amount of gas leakage and CH_4 emissions across the region. In MA, leak reporting is comprehensive, compared to other states across BosWash, allowing for an estimated concentration of CH_4 emissions to be calculated. For 2021, this was an estimated 6734 metric tons of CH_4, equivalent to 5.79×10^6 metric tons of CO_2 [71,78] Further research into the size and frequency of natural gas leaks would provide useful insights for stakeholders that are interested in improved CH_4 climate accounting and leak hazard assessment. In Boston, MA, roughly half of the CH_4 emissions from gas leaks could be attributed to only 7% of the leaks [45]. Identifying leaks, such as these large emitters, as environmentally significant leaks can help cities and towns to prioritize gas-leak repair for the greatest CH_4 emission reduction [80] and help to identify gas leaks causing significant damage to street trees [45,51]. Across the region, improved data availability and a re-structuring of leak grading to incorporate significant CH_4 emitters is imperative for generating a baseline of regional CH_4 emissions and improving the safety of the public. Improved natural gas leak reporting also gives cities and states the opportunity to include a more accurate estimation of the impact of CH4 emissions in GHG inventorying initiatives [60,81,82].

3.2. Regional Social Vulnerability

The BosWash corridor is the prime example of a megalopolis because of its concentration of urban populations (Figure 3); therefore, addressing the impacts of aging natural gas infrastructure in densely populated areas is crucial for creating a regional energy-transition policy.

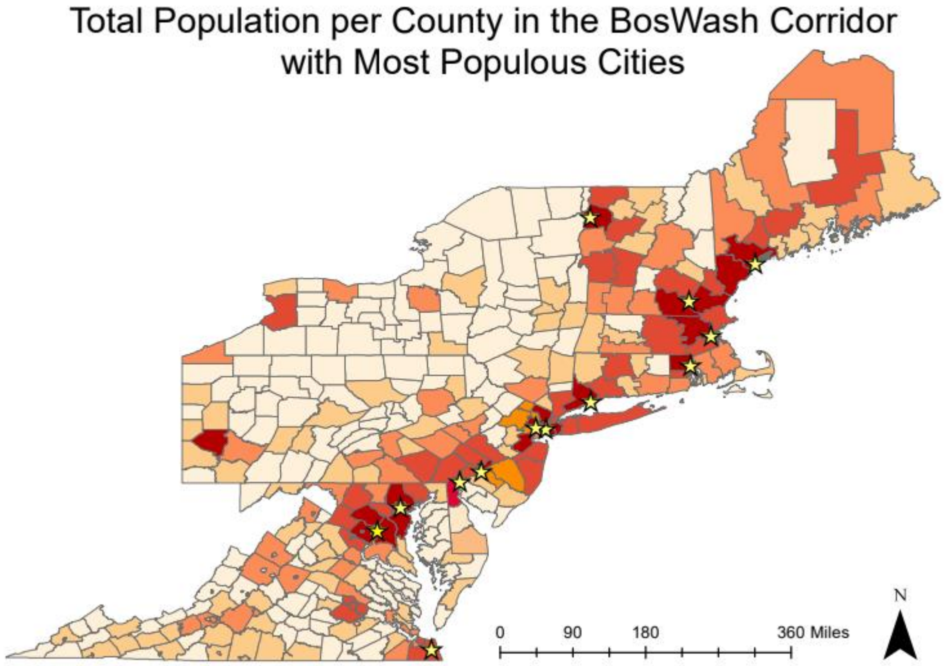

Figure 3. Population density by county across the 12 states in the BosWash corridor. Within each state, population densities are broken into 5 classes using natural break (Jenks), which maximizes the difference between classes. Populations vary dramatically across counties within the BosWash corridor so natural breaks for each state were chosen to demonstrate regional population trends. Yellow stars identify the location of the most populous cities within each state and Washington, DC [72]. Areas of dense population across the region are highlighted and define the cities chosen for analysis. Cities chosen for analysis are marked with a yellow star.

In the 2020 PHMSA dataset, pipeline characteristics (miles, material, diameter, etc.) are reported by individual utility companies [69]. To estimate the impact of leak-prone infrastructure on densely populated urban areas (Figure 3), a spatial analysis of the leak-prone pipelines at the utility scale was completed. Due to a lack of spatial data and cohesion between population density and the service territory of the natural gas utility companies, only two utility companies were considered for this analysis. It is important to note that within the service territory of a utility company, there is fuel-source variability that is not captured by these data. Within a county, residents/businesses may not have natural gas, meaning no distribution infrastructure is present in certain areas. Additionally, some utilities service multiple counties and currently, the location of specific pipelines is not accessible because of data availability and stated security concerns.

By examining the service territory for each of the utility companies servicing the most populous cities in the BosWash corridor, the utility companies servicing the most populous cities and the immediately surrounding counties were identified. The utility companies servicing New York City and Philadelphia were chosen because the service territory is isolated to the most populous cities, and/or the immediately surrounding counties. Philadelphia Gas Works (PGW) is the only utility company that is isolated to the boundary of the City of Philadelphia [83]. Although PGW only manages 6.2% of the distribution network across the state of PA, 42% of the gas infrastructure in Philadelphia is classified as leak-prone, posing significant public safety and environmental consequences for the most populous city in PA [69]. Consolidated Edison, the utility company servicing New York City and Westchester County, is not isolated to the boundary of the city but services areas of the state where the population density is highest [84]. The distribution pipelines that are owned by Consolidated Edison in these densely populated counties are more than 35% leak-prone [69].

Although data on the location of natural gas pipelines are limited, some utility companies and cities have worked to make the location of natural gas leaks publicly available to educate the public about the hazards that are associated with aging natural gas infrastructure. One such example is a non-profit research group, The Home Energy Efficiency Team (HEET), in Cambridge, MA. The location of reported gas leaks is made publicly available at the end of every year and HEET uses these reports to create maps of reported gas leaks across the state of MA [78].

Estimating the location of leak-prone infrastructure and gas leaks across the BosWash corridor has important policy implications because natural gas can pose environmental and public health/safety threats in dense, climate-vulnerable, urban areas. Given the data availability in MA, the relationship between the location of gas leaks and environmental justice communities was previously studied, with the results showing that marginalized populations were disproportionately exposed to natural gas leaks [60].

The study has implications for the importance of prioritizing leak repair and leak-prone pipeline replacement for densely populated areas. This type of analysis is possible in MA because of the state policy that requires utilities to submit leak reports that include the reported location of all gas leaks within the service territory of a utility [80]. The issue of gas leaks extends beyond the boundaries of MA and should be considered in other states/municipalities [60].

3.3. Policy Context across the BosWash Corridor

The BosWash corridor is a region that has prided itself on "strong leadership and commitment to energy efficiency and clean energy issues" [32]. Climate initiatives promoting collaboration across the megalopolis include the recently disbanded TCI and existing RGGI to address transportation sustainability and GHG emissions, respectively. Climate action goals and targets across states and cities in the corridor demonstrate shared interests and challenges of addressing aging infrastructure and promoting clean energy implementation across the region. While older transportation and infrastructure systems contributed to and fueled the original development and success of the region, these systems are now in need of replacement [15].

As explored in previous sections, the interconnectedness and dependencies that exist within the natural gas infrastructure system in the BosWash corridor mean that successful transition can only be achieved if it is approached holistically. Coordinated regional policy is required to implement projects of large-scale energy transition in such an interdependent biome. To develop a regional policy for a just transition away from natural gas across the BosWash corridor, the shared interests among actors in the region must be understood.

The emerging need for policy collaboration among states and cities is exemplified in the region's concerns with climate change and the shared interest in lowering GHG emissions. The effects of GHG emissions and climate change cross jurisdictional boundaries; therefore, "care and protection require more than the piecemeal efforts of individual metro areas or even states. It demands concerted, coordinated action across a range of relevant issues and a multitude of jurisdictions" [15]. Tables 3 and 4 present timelines outlining the GHG emission reduction targets for each state and city and the benchmark goals that they aim to reach in the coming years. Table 3 presents the % of leak-prone natural gas infrastructure in each state, establishing a sense of urgency and approximating the need for addressing aging natural gas infrastructure to attain GHG emission reduction goals.

Table 3. For each of the 12 states across the BosWash corridor, the % of leak-prone natural gas infrastructure in the state is presented from 2020 PHMSA datasets [69]. The GHG emission reduction goals and the year by which these targets will be achieved are outlined and benchmark goals are pro-rated to compare progress requirements across states from 2025 to 2050 [85–96]. Many of the states have a target emission reduction deadline in 2050, defining the upper bound for pro-rating progress. Included are the baseline emission values for each state for which to base the percentage reduction.

State	% Leak-Prone Infrastructure	2025 Progress to Reach GHG Emission Reduction Target	2030 Progress to Reach GHG Emission Reduction Target	2040 Progress to Reach GHG Emission Reduction Target	2045 Progress to Reach GHG Emission Reduction Target	2050 Progress to Reach GHG Emission Reduction Target
ME, USA	1.8	13.3%	26.6%	53.3%	66.6%	**TARGET** 80% (1990 baseline)
NH, USA	2.4	13.3%	26.6%	53.3%	66.6%	**TARGET** 80% (1990 baseline)
VT, USA	0	13.3%	26.6%	53.3%	66.6%	**TARGET** 80% (1990 baseline)
MA, USA	18.0	16.65%	33.3%	66.6%	83.25%	**TARGET** Net-zero GHG
RI, USA	26.6	13.3%	26.6%	53.3%	66.6%	**TARGET** 80% (1990 baseline)
CT, USA	15.4	22.5%	**TARGET** 45% (2001 baseline)	–	–	–
NY, USA	15.3	35%	**TARGET** 70% (1990 baseline)–drafted	–	–	–
NJ, USA	10.7	13.3%	26.6%	53.3%	66.6%	**TARGET** 80% (2006 baseline)
PA, USA	17.0	13.3%	26.6%	53.3%	66.6%	**TARGET** 80% (2005 baseline)
DE, USA	1.8	**TARGET**–28% (2005 baseline)	**–**	–	–	–
MD, USA	8.1	25%	**TARGET**–50% (2006 baseline)	–	–	–
VA, USA	2.7	20%	40%	80%	**TARGET** Net-zero GHG	

By interpolating a timeline to compare the GHG emission reduction goals among the 12 states, we can see the incremental achievements that states should achieve are similar. Most of the states have similar end target goals and dates, and therefore need to make significant progress together in the coming decades. RI, MA, and PA have the highest percentage of leak-prone natural gas infrastructure in the region, presenting a significant source of CH_4 emissions that needs to be addressed to achieve their goal of an 80–100% reduction in GHG emissions by 2050. Attaining the GHG emission reduction targets that are outlined in Table 3 would have impressive impacts on improving the region's climate preparedness and resiliency; however, it is important to note the challenges that are associated with reaching GHG emission reduction goals. Although sometimes legally binding, with the turnover of elected leaders and tumultuous fuel markets, energy-transition goals can change or become obsolete [97].

The dynamics of climate policy across the state boundaries of the BosWash corridor are complex. NY and DE are two of the only states in the region with plans/policies that actively limit natural gas usage at the state level. NY Governor Hochul recently supported what would be the first statewide requirement for all new construction to use zero-emission sources for heat, while DE is focused on retro-fitting existing buildings to be all-electric and require 90% of new construction to be electric by 2050 [98]. Some states in the region, NY, NJ, MA, DE, ME, and VT are considering reducing the use of natural gas energy in favor of geothermal heat pump technology or geothermal micro districts [99–105].

Additional challenges that are associated with achieving GHG emission reduction goals are those that are faced by some cities in the BosWash corridor, resulting from the political dynamic between state and local governments. In some cases, the ability of cities or towns to pass an ordinance reducing natural gas reliance is restricted due to either a natural gas ban preemption law or uniform state building codes. Within the BosWash corridor, the presence of natural gas preemption laws varies. Some states have more specific and targeted preemption laws that have been passed or considered in direct response to the spike in national municipal interest in restricting natural gas hook-ups in new construction. Other states in the region have existing uniform building codes or other state laws that were put in place years ago to regulate energy or building standards and municipalities do not have the ability to alter their local energy policies. NH has passed and PA is considering a preemption law [106,107].

Across the US, as of July 2021, 54 municipalities have successfully passed ordinances limiting natural gas in new construction buildings [108]. In response to the gas-ban movement, some states have passed preemption laws, restricting the ability of municipalities to pass such an ordinance. As of January 2022, preemption laws have been passed in 20 states and preemption laws are being considered in two more [108]. However, not all gas-ban preemption laws are as intentional as laws that are passed in some states. In MA, the Town of Brookline attempted to pass a by-law that would have limited the ability of new construction homes and buildings to join the natural gas network, but the by-law was disapproved by the Attorney General of MA because the by-law conflicted with existing laws of the Commonwealth of Massachusetts. In brief summary, the AGO cited three ways in which the Brookline by-law conflicted with state laws, including (1) preemption by the State Building Code, which establishes statewide building standards; (2) preemption by the Gas Code because the by-law created a new reason for the denial of a gas permit; (3) preemption by General Law c. 168, which gives the Mass Department of Public Utilities regulation over the sale and distribution of natural gas across the state. MA did not pass a gas-ban preemption law but instead, when a municipality attempted a natural gas ban, the Attorney General cited conflict with existing state law [74].

Presented in Table 4 are the GHG emission reduction targets for each of the 12 most populous cities in each state, and Washington, DC. Like the state GHG emission reduction targets, timelines were interpolated to compare progress requirements among cities with varying target dates. Due to a lack of refined data availability, the percent of leak-prone infrastructure within each city was not included.

Table 4. For each of the 13 cities across the BosWash corridor, GHG emission reduction goals and the year by which these targets will be achieved are outlined and benchmark goals are pro-rated to compare progress requirements for each city from 2020 to 2050 [109–121]. Many of the cities have a target emission reduction deadline in 2050, defining the upper bound for pro-rating progress. Included are the baseline emission values for each city for which to base the percentage reduction.

City	2020 Progress to Reach GHG Emission Reduction Target	2025 Progress to Reach GHG Emission Reduction Target	2030 Progress to Reach GHG Emission Reduction Target	2040 Progress to Reach GHG Emission Reduction Target	2050 Progress to Reach GHG Emission Reduction Target
Portland, ME, USA	20%	30%	40%	60%	**TARGET** 80% (2017 baseline)
Manchester, NH, USA	–	–	–	–	–
Burlington, VT, USA	5%	**TARGET** 10% (2010 baseline)	–	–	–
Boston, MA, USA	25%	37.5%	50%	75%	**TARGET** Carbon neutral
Providence, RI, USA	25%	37.5%	50%	75%	**TARGET** Carbon neutral
Bridgeport, CT, USA	**TARGET** 10% (1990 baseline)	–	–	–	–
New York City, NY, USA	25%	37.5%	50%	75%	**TARGET** Carbon neutral
Newark, NJ, USA	20%	**TARGET** 26–28% (2006 baseline)	–	–	–
Philadelphia, PA, USA	20%	30%	40%	60%	**TARGET** 80% (2006 baseline)
Wilmington, DE, USA	13.3%	19.96%	26.6%	**TARGET** 40% (2008 baseline)	–
Baltimore, MD, USA	15%	**TARGET** 30% (2007 baseline)	**TARGET** 60% (2007 baseline)	**TARGET** 100% (2007 baseline)	–
Virginia Beach, VA, USA	–	–	–	–	–
Washington DC, USA			26.6%	53.3%	**TARGET** 80% (2006 baseline)

CAPs at the local/state scale typically focus on a reduction in GHG emissions from local emitters, primarily the building and residential energy sectors. However, the 12 states and 13 cities approach the achievement of this goal in a wide variety of ways, especially when approaching the role of natural gas energy. The most populous cities in ME, VT, RI, and PA are actively exploring policy and regulatory options to limit the use of natural gas energy in new construction builds or large renovation projects to lower overall gas reliance and prevent stranded assets [109,111,113,117]. NYC has successfully passed an ordinance to ban natural gas hookups in new single-family homes by 2025 and all new construction by 2030 [115]. Although some cities have already successfully passed ordinances limiting natural gas construction, the challenge of doing so is immense. Cities are challenged to start and achieve low carbon initiatives because they are dependent on other actors for support in achieving these goals [122,123]. The Commonwealth of PA still actively incentivizes customers to transition to natural gas, citing the GHG emission reductions that are associated with transitioning from coal to natural gas [124]. This is compared to New York City, where natural gas energy will be banned in new construction and renovation projects in the coming years [115]. The complexities and variety of strategies for energy-sector emission reductions across the corridor further demonstrate the need for a coordinated approach.

Exploration of the varied CAP and climate policies across the cities and states in the BosWash corridor is important to understand the shared interests and challenges that are associated with transitioning away from natural gas infrastructure. Challenges in implementing effective policy across a diverse and vast political landscape can result because of the wide variety of interests, politics, and more localized concerns [7]. This complex political ecosystem strengthens the argument for a regional policy approach to enable the achievement of the GHG emission reduction goals and begin limiting the amount of environmental and public health damage that is associated with the continued use of natural gas infrastructure.

4. Policy Recommendations

The infrastructure biome concept enables regional policy and management and can be applied to other regions across the world. The BosWash corridor exemplifies an infrastructure biome that is primed for energy succession. The complexity of regionally integrated infrastructure systems, the shared challenge of aging gas pipelines, and the common interest of protecting climate vulnerable communities and reducing GHG emissions make the BosWash corridor a region that would benefit from a regional natural gas transition policy. The BosWash corridor would benefit from regional energy policy because a coordinated policy approach could allow stakeholders to collaborate across city and state lines, share and promote the use of the existing and emerging energy grid technologies, and help to manage the supply and demand of renewable energy sources as they come online [125,126]. Outlined below are policy recommendations resulting from this case study and infrastructure biome analysis for a regional natural gas transition policy in BosWash.

Re-evaluate natural gas pipeline replacement projects to prioritize safety, while promoting a focus on pipeline repair over replacement where possible—To improve the allocation of resources that are dedicated to natural gas pipeline replacement projects, the priority for pipeline repair should be safety. Limiting pipeline replacement projects to hazardous cast iron and bare steel pipes that pose the greatest threat to public safety allows for the reallocation of pipeline replacement funds. Revising and asserting new leak-classification guidelines can promote pipeline repair projects that are localized to where they create the largest benefit to people and the environment [82]. The local benefits of repairing leak-prone gas infrastructure include limiting CH_4 emissions from gas leaks, limiting damage to street trees from leaking pipes, and ultimately protecting climate-vulnerable communities. A regional policy that refines the criteria for pipeline replacement projects and promotes repair over replacement, where possible, would limit investment in stranded assets and allow for the re-allocation of funds for electrification and decarbonization efforts. Re-allocated funds can be used to promote the enhanced monitoring of gas systems and pilot energy-transition projects that are aimed at electrifying homes and businesses. Within the infrastructure biome concept, this represents and requires a synergistic interaction between political and physical infrastructure systems.

Improved natural gas data for municipal evaluation—Aged and leak-prone pipeline concentrations in urban areas are a reason for concern. Previously researched patterns of social injustice in the time that is taken to repair natural gas leaks in environmental justice communities further threatens already vulnerable populations across MA [60]. The discovery of this disparity was possible only because of the MA state law requiring the location of reported natural gas leaks to be made publicly available. A regional policy that improves natural gas data availability for cities and states would allow cities and states to measure the impacts of leaking natural gas pipelines with improved accuracy, allowing the generation of more spatially explicit and need-based natural gas transition plans [60].

Regional policy to amend preemption laws and existing limitations between and across state and city energy jurisdiction, helping states and cities to reach CAP targets efficiently and providing incentives for an equitable transition. Regional policy would allow smaller local governments to implement more stringent climate policy than their home state by authorizing municipalities to limit natural gas energy hookups, in order to achieve their climate action goals. Policy at the regional level would alleviate the state/city conflict that is evaluated in this paper by developing an optional compliance for municipalities to pass ordinances limiting natural gas usage to achieve their clean-energy goals. Best practices could be shared among cities and states in helping interested communities to successfully and equitably transition away from natural gas, building on the variety of incentives for customers to transition away from natural gas energy that already exist [127]. A market-based program, like that of RGGI, could be designed for the natural gas network, with elements of a CH_4 budget trading program including allowances and allowance auctions to encourage states to limit CH_4 emissions from the natural gas network. An example of methane production offsets can be seen in the subsidies that are provided to dairy farmers in California to turn animal waste into biogas and providing dairy farms the opportunity to sell methane offset credits. This program is intended to reduce farm emissions while allowing natural gas companies to mitigate their own GHG emissions by buying the offsets from dairy farms [128,129]. While the California model of producing biomethane as a commodity to offset natural gas leaks is arguably ineffective in reducing overall methane leakage, a regional market mechanism could instead credit verifiable methane emissions reductions, pricing methane as a climate pollutant.

5. Conclusions

This study utilized an ecological perspective to describe a regional infrastructure biome. This concept was then applied for the first time to evaluate and prescribe regional policy, in order to address the aging natural gas infrastructure across the BosWash infrastructure biome. One limitation of this approach is in the concept of succession, which in natural ecosystems emerges rather than being imposed, as policy and regulation are in the proposed infrastructure biome. Policy discussed here is more akin to ecosystem management, a well-developed field of applied ecology. Within the ecological framework, practical ecosystem/biome management measures promoting safety and environment include: (1) refinement of leak-classification guidelines to promote replacement for safety and environmental significance, and focus more on pipeline repair; (2) requiring gas operators to repair 7% of all the largest grade 3 leaks; (3) requiring gas companies to create active live gas-leak maps and improve the monitoring of leak-prone pipes; (4) requiring operators to monitor gas systems with spectrometer technology; (5) requiring utilities to classify leak-prone pipes based on class location (local population density) and physical characteristics.

These policy suggestions may appear overwhelming to implement at a regional level, but advocacy organizations and coalitions across the region are already working in this space to research and encourage a transition away from natural gas. Regional advocacy organizations and coalitions could convene to develop and facilitate policymakers and stakeholders across traditional jurisdictions. Organizations with missions that are relevant to this transition, which already have the state-level and/or city level organization across the BosWash biome, include the Sierra Club, Rocky Mountain Institute, the Gas Leaks Allies, and Clean Water Action. Although the data that are presented here are specific to the BosWash region, the methodologies and the infrastructure biome conceptualization can be applied to other regions across the world that are interested in energy transition and cohesive infrastructure management.

From natural infrastructure systems to built, social, and political systems, the BosWash corridor is an ideal candidate for a cohesive and collaborative approach to infrastructure management and development moving towards the goal of GHG emission reductions. Any large-scale energy transition would go beyond municipal and state boundaries. In some cases, energy-transition policies may succeed in one municipality but fail in another because of political or budget constraints leaving areas unable to benefit from them. Regionalizing natural gas transition policy would allow the environmental and public health benefits of a gas transition to extend beyond the jurisdictional boundaries within the region [126,127]. A regional policy that reallocates natural gas development funding, improves natural gas data reporting, and builds on existing regional programs to encourage an equitable transition away from gas is fit to achieve the targets of GHG emission reduction and clean energy implementation goals, remediate the challenges of regional aging infrastructure, and provide an energy future that is resilient to a changing climate.

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