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Prioritizing sites for gas distribution system decommissioning projects using geospatial data and decision support tools

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ABSTRACT

This study frames the prioritization of locations for decommissioning gas distribution system infrastructure as a geographic information system multi-criteria decision analysis (GIS-MCDA) problem. Within this framework, we identify several primary and secondary decision criteria that should be used to evaluate site suitability. We then describe a series of analytical methods by which publicly and private datasets can be sourced, transformed, and integrated to create geospatially explicit representations of these various site selection priorities. We demonstrated the application of this proposed framework for a Case Study area comprising the major investor-owned gas utility service territories throughout the State of California, aggregated to the census tract level. The development of this Case Study was informed by a series of stakeholder engagement and outreach activities that centered around a purpose-built web-mapping application which allowed for the collaborative exploration of geospatial data layers as well as the application of custom decision criteria weights to reflect different stakeholder value preferences. The study concludes with a discussion of the relative strengths and weaknesses of this approach within this problem domain and provides comments on additional datasets that could potentially improve its value to stakeholders and decision makers concerned with gas distribution system decommissioning project planning.

1. Introduction

Gas distribution systems are extensive pressurized pipeline networks comprising both above ground and below ground infrastructure assets (Folga, 2007). These distribution networks are regional in scale and interface with high pressure interstate transmission pipelines at key junctures known as *city gates*. (*Ibid.*) The primary function of these distribution networks is to transport and incrementally step down the pressure of the supplied gas such that it meets the specifications of individual customer service connections upon delivery. As such, the architectures of gas distribution networks mirror the characteristics and geographic distribution of the customers which they have evolved to serve.

Previous modeling studies have found that all viable pathways for the future decarbonization of state and national scale energy systems require extensive substitution of existing fossil gas end-use equipment with zero-emissions alternatives (Geels et al., 2017; Mahone et al., 2018; Meckling et al., 2017; Steinberg et al., 2017). At present, the most technically and economically feasible of these pathways involve significant electrification of existing fossil gas end-use equipment along with utilization of other energy carriers (such as hydrogen) in sectors that are particularly challenging to electrify (Aba et al., 2024; Jadun et al., 2017; Walker et al., 2022; Wei et al., 2013).

Due to the largely fixed revenue requirements for operating and maintaining gas distribution infrastructure, anticipated reductions in gas sales volumes and revenues resulting from successful gas fuel substitution efforts could result in escalating cost burdens for gas utility ratepayers (Aas et al., 2020; CPUC, 2024a; Gridworks, 2021a). Over the long term, absent any proactive protective measures, these trends could lead to spiraling increases in retail gas rates for customers who continue to rely on gas service. Such an outcome would likely disproportionately harm lower income customers, who face greater barriers to transitioning

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away from gas due to the high up-front capital costs of purchasing substitute equipment and integrating that equipment with the energy systems of their existing buildings.

Given these concerns there is currently active debate among utilities, regulators, and other interested stakeholders about what the long-term future of the gas system should be (Davis and Hausman, 2022; Gridworks, 2021b). Many gas providers argue that their infrastructure represents an enormous capital investment that must be recouped through continued use, albeit with renewable or otherwise decarbonized fuels (Newlander et al., 2020; Pendleton et al., 2020). Many State governments, including California, are advancing aggressive policy agendas designed to rapidly increase rates of gas fuel-substitution, particularly through end-use electrification (CARB, 2022). These include both the development of new regulations which would place restrictions on the sale of emissive appliances (i.e. those that combust gas) as well as major financial incentive programs intended to mitigate some of the up-front costs associated with purchasing and installing new substitute electrical equipment (Gold, 2021). Meanwhile, there are many representatives of local governments, community-based organizations (CBOs), as well as members of the general public, who remain unfamiliar with the concept of gas system decommissioning and seek basic, practical information about what it might practically entail.

Amidst all of these developments, the research reported on in this study seeks to address the following questions: (1) what are the relevant issues of concern in the identification of promising sites for decommissioning utility gas distribution infrastructure; (2) how should these issues be represented in data and evaluated relative to one another for different locations; and finally, (3) what types of decision support tools should be made available to stakeholders to aid in these determinations? Among its key results, the manuscript introduces a hierarchical index scheme for quantifying these various site selection criteria that is based upon geographically explicit data w. Furthermore, we go on to demonstrate results from the application of this scheme to the Case Study example of California, which has recently been undergoing a regulatory push to develop pilot decommissioning projects.

2. State of the art

2.1. Long-term gas system planning and regulatory developments

There are two broad categories of scenarios which have been identified in terms of what the end-of-life for the gas system might look like (Payne, 2020). The first are those that involve the entire infrastructure being deactivated *all-at-once*. In such cases, regulators and utility providers would come to an agreement on a specific future date to deactivate service for all customers, after which it would no longer be available. The second are those which would involve different components of the gas distribution infrastructure being deactivated *incrementally*. Note that these scenarios do not imply that all existing gas infrastructure will ever be decommissioned, necessarily. While such a phased approach would require more circumscribed regulatory coordination and public buy-in, from a technical perspective, piecemeal solutions can be more complex to implement, requiring detailed analysis of the hydraulic feasibility of shunting gas flows through certain lines and equipment. The challenges associated with which are likely to be highly contingent upon specific details of the distribution network's topology.

Recent policy and legislative developments in California and New York, two states which are at the forefront of gas decommissioning planning in the U.S., indicate that an *Incremental* approach is strongly preferred (CPUC, 2022). As currently envisioned by the CPUC, this approach will involve the strategic decommissioning of specific gas infrastructure assets (service mains, pressure regulators, drips, etc.) in a manner that is spatially and temporally coordinated with the implementation of fuel substitution measures (primarily electrification) for affected gas customers. The passage of Senate Bill 1221 (SB-1221) was a major milestone towards the operationalization of this strategy in California (Senate Bill No. 1221, SB-1221, 2024). Among the core provisions of SB-1221 is a requirement that the commission, on or before July 1, 2026, establish a voluntary program to create up to 30 pilot project neighborhood decarbonization zones that would result in the ultimate deactivation of utility gas service and decommissioning of associated infrastructure.

Relative to the scope of SB-1221, California's first formal gas decommissioning efforts are being explicitly framed as exploratory *pilot* projects. This emerging strategy has a number of favorable characteristics from economic and political perspectives. From an economic standpoint, it allows for the evaluation of the cost/benefit profiles associated both with different prioritization strategies and technical implementation approaches before California makes a broader legislative commitment to gas system decommissioning as a pillar of its decarbonization strategy, writ-large. It also allows for initial decommissioning efforts to opportunistically follow in locations where electrification and other fuel substitution measures have been proceeding at pace due to changing consumer preferences and evolving code requirements for new-construction. This minimizes capital investments by customers who may need to replace existing gas end-use equipment.

From a political standpoint, the pursuit of such a pilot program allows for the selection of decommissioning sites that pro-actively avoids locations with large numbers of customers who may be ideologically or otherwise opposed to fuel substitution measures. The bill also resolved an important source of uncertainty about the legality of decommissioning efforts related to gas utilities' obligation to serve. The bill stipulates that if at least two-thirds of existing gas customers located within a proposed pilot zone are supportive of a pilot project proposal, then the local gas utility is relieved of their legal obligation to serve all of the customers within the area (thus prohibiting a minority of opposing customers from derailing the effort). An important omission from the language of SB-1221 however, relates to the detailed mechanics of the process by which potential candidate pilot sites should be identified and evaluated relative to one another. Generally speaking, this process could be structured to proceed either from the bottom-up, using publicly available data and tools, or from the top-down, using privately accessible data and tools. Our approach to this project very much reflects a preference for the former. Though evidence suggests that this preference is not currently shared by other important stakeholders, for reasons that we elaborate on in the Discussion.

2.2. Previous related work

While there is a sparsity of peer-reviewed academic literature on this topic, Garibay-Rodriguez et al. have previously identified different characteristics of gas infrastructure assets that should be considered when planning decommissioning projects (Garibay-Rodriguez et al., 2025). These criteria generally include factors related to the cost of maintaining those assets relative to the revenue which they generate, the risk profile associated with various modes of failure, and the hydraulic feasibility of isolating certain portions of the network (Gridworks, 2021a). In line with this perspective, the CPUC, in its latest proposed decision providing guidance on the implementation of SB-1221, indicated its initial preference for the use of these types of monetary cost-effectiveness tests to inform the selection of pilot site proposals (CPUC, 2026). Such a narrow focus on cost-effectiveness implicitly limits the scope of factors which can be considered however, due to the challenge of expressing many decision criteria in monetary terms. Table 1 provides a high-level overview of some key classes of cost and benefits which should be considered relative to potential gas decommissioning projects. These are organized with respect to the class of stakeholder to which they will principally accrue and labeled according to their ease of monetization.

As Table 1 illustrates, gas decommissioning projects are likely to result in the production of significant costs for a small, localized group of

Table 1
Overview of the distribution cost/benefit characteristics implied by gas distribution system decommissioning projects with a qualitative assessment of the relative ease of monetization for each.

Stakeholder	Costs	Benefits	Ease of Monetization
Utility	Loss of future gas sales revenue from customers served by decommissioned infrastructure. Physically decommissioning infrastructure assets and implementing ongoing safety monitoring protocols.	Reduction in capital spending requirements for infrastructure operations and maintenance or replacement.	Easy
Decommissioning Project Participant Utility Customers	Converting customer owned gas end-use equipment and energy conveyance systems to alternative fuel sources.	Avoided future exposure to hazards associated with catastrophic gas system failures/ accidents. Access to newer, cleaner, and safer end-use energy equipment.	Medium
	Loss of access to gas powered end-use equipment for which there may be personal preferences.	Avoided future public health impacts from exposure to local/ indoor criteria pollutant emissions generated from the combustion of gas that would otherwise be delivered by the infrastructure.	
All Other Utility Customers	Can potentially inherit utility costs, pending public regulatory commission or municipal authority approval.	Avoided future public health impacts from exposure to ambient criteria pollutant emissions generated from the combustion of gas that would otherwise be delivered by the infrastructure. Avoided future retail rate increases due to gas system death spiral.	Hard
All Other Persons	None	Avoided future climate change impacts from GHG emissions generated by the combustion of gas that would otherwise be delivered by the infrastructure.	

utility customers whose gas service would be terminated. These would be in exchange for the production of benefits that would, in part, be distributed across the rest of the customers in the utility's rate base. Similarly, there is also a likelihood that projects will result in additional benefits that would accrue to non-utility customers, such as with the abatement of criteria air pollution and greenhouse gas emissions. Because different classes of costs and benefits require different levels of effort to be expressed in monetary terms, it may not be appropriate, or indeed feasible, to frame the problem in cost-effectiveness terms, particularly during the initial site screening phases. Such an approach may become feasible, and perhaps even necessary, in the latter stages of the evaluation process. Once the set of candidate sites has already been reduced, the effort required to express their associated costs and benefits in monetary terms may be suitably justified.

3. Methods

This study proposes the use of a geographic information systems multi-criteria decision analysis (GIS-MCDA) approach to the prioritization of sites for gas decommissioning projects. This approach is a specialized application of established multi-criteria decision analysis (MCDA) techniques which allows for the non-compensatory consideration of sites for a given land-use application based upon properties of both discrete geographic objects and continuous geographic spaces. (Fishburn and Lavalle, 1999; Malczewski, 2006; Marttunen et al., 2017).

Fig. 1 below, provides a conceptual illustration of the key methodological steps in constructing the type of GIS-MCDA dataset proposed in this study. First, raw variables corresponding to various decision criteria are assembled for all decision alternatives (i.e. locations) of interest. Next, groups of variables are organized into a hierarchical structure of indices and sub-indices intended to represent different themes of concern. Then, at each level of the hierarchy, raw variables are first normalized, then binned into a set of unitless ordinal values. These are linearly combined for each level of the hierarchy until a final combined index has been created. As depicted in the figure, the process reflects a default application of uniform decision criteria weighting. However, the framework also allows for the application of custom weights at any level. Such weights can be determined through the type of Public-Participation GIS (PP-GIS) stakeholder engagement process that was conducted as part of our research Case Study (Higgs, 2006; Mahmoody, Vanolya et al., 2019; Malczewski and Rinner, 2015).

MCDA processes involve *Decision Makers* **-** entities with both the responsibility and the authority to make decisions, *Interest Groups* **-** entities with an interest or stake in the outcome of the decision, *Decision Alternatives* **-** the set of feasible alternatives that the decision maker may choose from, and *Decision Criteria* **-** the bases upon which decision alternatives are evaluated. Relative to our proposed GIS-MCDA approach, it can be useful to identify each of these within the context of gas decommissioning project site prioritization efforts.

In most regional contexts, the principal decision makers involved in gas decommissioning site selection processes are likely to be the politically appointed members of energy utility regulatory authorities. In the U.S., for example, such authorities would include State Public Utilities Commissions (PUCs) which are tasked with overseeing the operations of monopoly Investor-Owned Utilities (IOUs). In the early pilot phases of implementation, these regulators would be expected to either have final say over the initial choice of gas decommission project sites or at least the design of the process by which such sites would be selected. However, over the longer term, as decommissioning efforts eventually move beyond small pilot projects and given the value and extent of gas distribution infrastructure assets, it is likely that various other elected or appointed officials from executive, legislative, and even judicial branches of government will also come to play significant decision-making roles in site selection.

Due to the broad reach of utility cost recovery mechanisms and the fugitive nature of air emissions from both gas system leaks and combustion processes, the scope of the groups who might be interested in this decision process could be quite expansive. At a minimum, they include all utility customers who might be indirectly impacted by the changing revenue requirements associated with gas system decommissioning activities, as well as customers located in areas in which gas

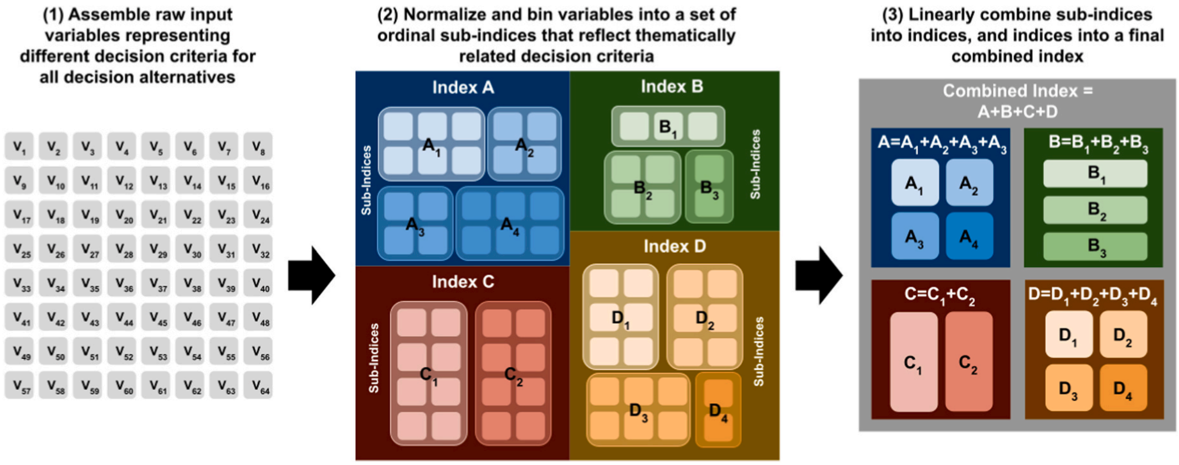

Fig. 1. Conceptual illustration of the key methodological steps involved in the development of the proposed GIS-MCDA hierarchical index structure.

system decommissioning projects might be implemented and therefore would be directly impacted by the loss of gas service. It is also anticipated that numerous local, regional, and even national and international issue-oriented, non-governmental organizations would eventually take an interest in the process.

The identification and prioritization of candidate sites for gas decommissioning projects requires simultaneous consideration of the characteristics of both discrete geographic objects (i.e. specific customer premises, & infrastructure assets) as well as continuous geographic spaces (i.e. pollutant concentrations, historical inequities). As such, a central consideration in the development of this GIS-MCDA problem formulation is the choice of an appropriate geographic unit of analysis. This choice is intrinsically related to the set of decision alternatives being evaluated. In an ideal scenario, the geographic unit of analysis used for site selection would be the same unit used for project implementation; which, in this context, would be all of the discrete segments of the gas distribution network that could readily be hydraulically isolated as part of a decommissioning effort. Unfortunately, and for reasons that we shall unpack in more detail later on, such a granular approach to the problem is not presently feasible due to persistent privacy and security concerns associated with the publication of detailed data on the geographic locations of gas utility customers and infrastructure assets (Warner, 2018). Moreover, due to the inherent complexities of decommissioning projects and the high likelihood of encountering insurmountable barriers to implementation, it may in fact be advantageous to identify areas or regions that would contain multiple potential sites with similar cost/benefit profiles, as a means of mitigating the risk of failure associated with any individual one.

As an alternative approach, we propose the use of aggregated data, specifically at the census tract level, for the application of the GIS-MCDA framework. Within the U.S., as a geographic unit of analysis, census tract geographies have several useful properties, especially within the context of preliminary site screening efforts. Firstly, they cleanly nest within the boundaries of larger municipal entities (i.e. Counties and States) which are likely to be important to interest groups involved in real world decommissioning project implementation. Secondly, they are guaranteed to have statistically equivalent populations; a requirement for census survey data collection and analysis. Thirdly, they are commonly used as the geographic unit of analysis for other data products which are particularly relevant to gas decommissioning site selection including, for example, attributes related to equity prepared by national scale sociodemographic census and energy system statistical bureaus. And finally, census tracts are large enough that they are unlikely to elicit privacy or security concerns when data are made public.

3.1. *Value normalization & binning*

An important set of technical considerations in the development of a GIS-MCDA dataset relates to the normalization and standardization of raw input variables. Due to the heterogeneity of decision criteria which are likely to be considered, we recommend the application of the Fisher-Jenks clustering algorithm for these tasks in the preparation of GIS-MCDA datasets being developed for gas decommissioning project site selection. Fisher-Jenks is a clustering optimization algorithm (sometimes also referred to as the Goodness Variance Fit (GVF) method) which operates by minimizing the variance within a set of defined classes while simultaneously maximizing the variance between them. The Fisher-Jenks algorithm is superior to other commonly used approaches, such as constant width and constant frequency (e.g. quantile based) binning, due to its ability to preserve the essential shape of a variable's underlying distribution in its discretized outputs, while still providing flexibility to specify the desired number of output classes as a customizable input parameter.

There is an important interplay between the choice of discretization interval (i.e. the number of bins or classes) and the number of non-dominated decision alternatives that a GIS-MCDA dataset will produce. In this specific context, a non-dominated set consists of geographies which have all been assigned the same value or score within the normalized unit space, making them functionally equivalent. This is despite each potentially having different combinations of values for different decision criteria. Using larger interval ranges (say, 1-100 as opposed to 1-10) can reduce the effective size of these non-dominated sets and thus provide increased specificity in terms of relative prioritization of individual geographies. However, it can also result in a more uniform distribution of final combined index scores, which can potentially be more difficult to interpret and compare. After evaluating different alternatives (1-3, 1-10, 1-100, etc.), we settled on a 1-10 ordinal range for all indices and sub-indices. This choice provided the best combination of specificity and interpretability based upon the needs of the application and its diverse set of underlying variables.

4. Results

Determining the number and formulation of the decision criteria that should be considered relative to a gas system decommissioning prioritization GIS-MCDA problem is an explicit focus of this study. After extensive deliberation, we arrived at a proposed set of multi-tiered decision criteria that comprised of the following primary component indices.

1) *Gas Assets Index* **-** reflects the relative costs and benefits of the gas utility associated with decommissioning physical infrastructure assets. This includes information about the physical condition of existing gas distribution pipelines including their size, material, age, operational risks, as well as management and replacement costs, where available.
2) *Equity Index* - reflects the desire to implement gas decommissioning projects in communities which have historically been disadvantaged. This includes measures of inequities in terms of socio-economics, public health, energy burden, environmental pollution burden, accessibility of critical services, and the presence of sensitive populations.
3) *Non-Residential Customer Decommissioning Readiness Index* - reflects the readiness of non-residential customers to participate in decommissioning projects based on volume and end-use characteristics of their gas consumption. This includes measures of the diversity of installed end-use gas equipment, the availability of substitute technologies for gas in those existing end-uses within different commercial sub-sectors, and other potential challenges related to the implementation of fuel substitution measures in their location.
4) *Residential Customer Decommissioning Readiness Index* - reflects the readiness of residential customers to participate in decommissioning projects. This includes information about the condition of the existing building stock (in terms of its likely ability to support the addition of new electrical loads), the financial capacity of households to implement fuel-substitution measures, and the relative dependence of households upon gas as a primary energy resource.

These four top-level indices are composed of a total of 28 sub-indices, each of which are derived from linear combinations of 123 different input variables. Fig. 2 provides a network diagram illustrating this multi-tiered index structure. The central node of the network is shown as the Combined Index. This reflects the combination of all of the various index and sub-index values that feed into it. Across this index hierarchy, higher numerical values indicate locations which would be considered more suitable for the pursuit of a gas decommissioning project. The application of different weights to indices and/or sub-indices would represent the differential prioritizations of various issues of concern relative to others. When represented as a directed graph, as in the figure, most of the index/sub-index/variable hierarchy has tree-like structure. This indicates situations where each variable feeds into a single sub-index and index. However, a notable exception is the Gas Assets index whose various sub-indices draw upon different combinations of some of the same underlying variables. This is appropriate within the context of this index due to the possibility that some variables may be beneficial for the siting of a project from one perspective while negative from another. More details about the structure and content of this hierarchical index scheme are provided in Appendix A.

Fig. 3 provides a series of condensed count frequency histograms for each of the input variables used to develop the GIS-MCDA dataset for the California Case Study. These plots are merely intended to illustrate the wide range in the shape and structure of these variables' distributions prior to the application of the Fisher-Jenks binning procedures previously described.

4.1. Gas Assets Index

The Gas Assets Index comprises five separate sub-indices and was designed to reflect salient decision criteria relative to the condition of existing gas distribution infrastructure assets within different census tracts. All of the variables that feed into the California Case Study implementation of the Gas Assets Index are sourced from datasets disclosed by the State's major gas serving IOUs as part of the CPUC's new Long-Term Gas Planning Rulemaking 24-09-012 (CPUC, 2024b). Although a detailed specification of the requested fields was provided by the CPUC in this document, our analysis of the datasets submitted by each IOU revealed some minor discrepancies between them. The cause for these is not documented, but we suspect that they have to do with differences in the ways that individual IOUs quantify hazards, risks, and other attributes of concern. Such discrepancies may be problematic for attempts to assess differences in key attributes among the IOUs in absolute terms, but they are not as significant for the types of relative comparisons being made in this study. Table A1 in Appendix A details the various sub-indices and primary source variables used in the Gas Assets Index.

4.2. Equity Index

The Equity Index comprises seven sub-indices and was designed to represent community benefits anticipated from the implementation of gas decommissioning projects. High Equity Index scores correspond to communities that are disadvantaged, underserved or at elevated risk, and for whom early participation in gas decommissioning is most likely to deliver meaningful non-energy benefits (e.g., health, housing, jobs). This Index was informed by established energy justice frameworks, which emphasize the equitable distribution of the benefits and burdens of energy system transitions (Jenkins et al., 2016). Other costs and technical barriers which are likely to have to be overcome by decommissioning project participant customers are captured in two separate decommissioning readiness indices, so as to treat these issues as distinct, but related dimensions. In this way, we can independently assess where the benefits of gas decommissioning project participation are most urgently needed, as well as where implementation is most likely to encounter the greatest difficulties.

To construct the Equity Index, first, a desktop research process was conducted to review and identify publicly available equity metrics, frameworks, and screening tools, and resulted in a comprehensive set of indicators selected as proxies for community-level impacts to gas decommissioning. Relative to the project's California Case Study, relevant values for the proposed index and sub-indices were shared with partner CBOs and tribal representatives for discussion and refinement. Feedback was gathered through a set of public webinars, as well as a series of invited Case Study feedback sessions. This engagement attempted to ensure that the selected indicators aligned with community perspectives and priorities. A more detailed discussion of the community engagement component is discussed in Section 5.2. Additionally, Table A2 in Appendix A details the various sub-index components and primary variables used in the Equity Index. These included data from the U.S. EPA's EJ Screen, the U.S. Department of Energy (US DOE's) Low-income Energy Affordability tool data, and more.

4.3. Non-residential customer decommissioning readiness

The Non-Residential Decommissioning Readiness Index comprises thirteen sub-index components. The index was designed to represent the feasibility of requiring different types of non-residential customers to transition away from the use of gas for various end-uses. Fundamentally, the Non-Residential Decommissioning Readiness Index seeks to quantify the total volume of gas use among non-residential customers in different sub-sectors, weighted by the anticipated difficulty associated with substituting the use of gas in each different context. The decision to structure the Non-Residential Decommissioning Readiness Index in this way, with an explicit focus on technical readiness factors, reflects the prevailing wisdom that gas substitute technologies are either not yet commercially available, or at least economically competitive, for a number of different gas end-use activities within non-residential customer facilities. Moreover, commercial property owners are much more likely to be sensitive to the costs (both those incurred up-front and over the long term) that result from implementing the types of fuel substitution measures implied by participation in gas decommissioning projects. Table A3 in Appendix A details the various sub-index components and primary source variables used in the Non-Residential Decommissioning Readiness Index.

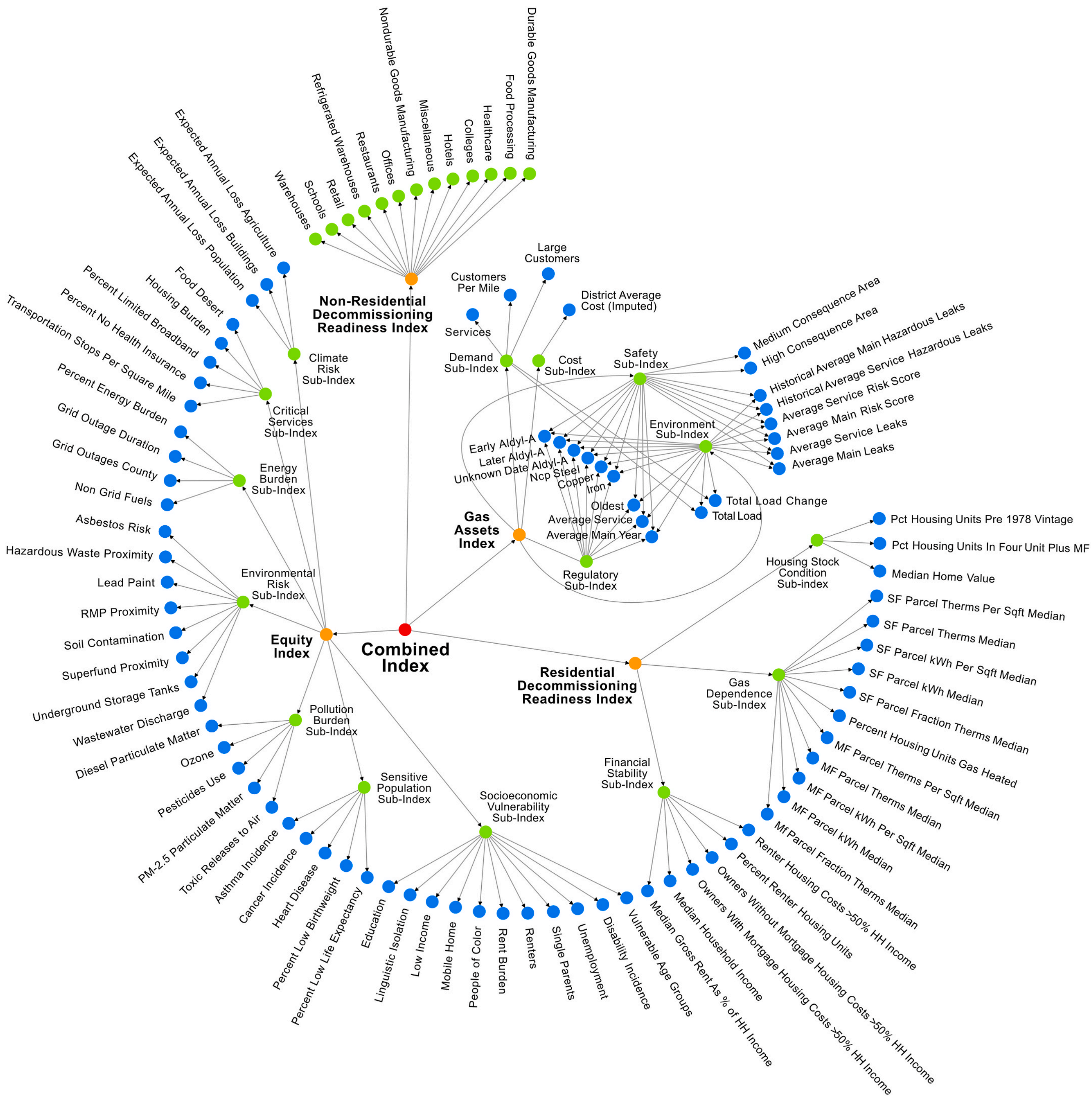

Fig. 2. Network diagram of the multi-tiered index developed by the project team for gas decommissioning project site prioritization.[2].

[2] Input variables for the Non-Residential Decommissioning Readiness Index are not depicted in this figure. This is because the disaggregated data used cannot be made public due to CPUC mandated utility customer data privacy protection rules

To generate values for each of the Non-Residential Decommissioning Readiness sub-indices for the California Case Study, a private database of utility non-residential customer account information was used to assign each customer account to one of 13 commercial sub-sectors defined in the CEC's Commercial End-Use Survey (CEUS). These data were provided to UCLA researchers through a data-sharing agreement established with CPUC's Energy Division that is subject to terms of non-disclosure. Customer sub-sectoral assignments were based upon self-reported six-digit North American Industrial Classification System (NAICS) codes for each non-residential gas customer. Total annual gas usage for the year 2021 was then aggregated by sub-sector for each census tract throughout the State. Decommissioning readiness weighting coefficients were then assigned for specific end-uses of gas. The end-use categories used corresponded to those identified in the CEUS and the

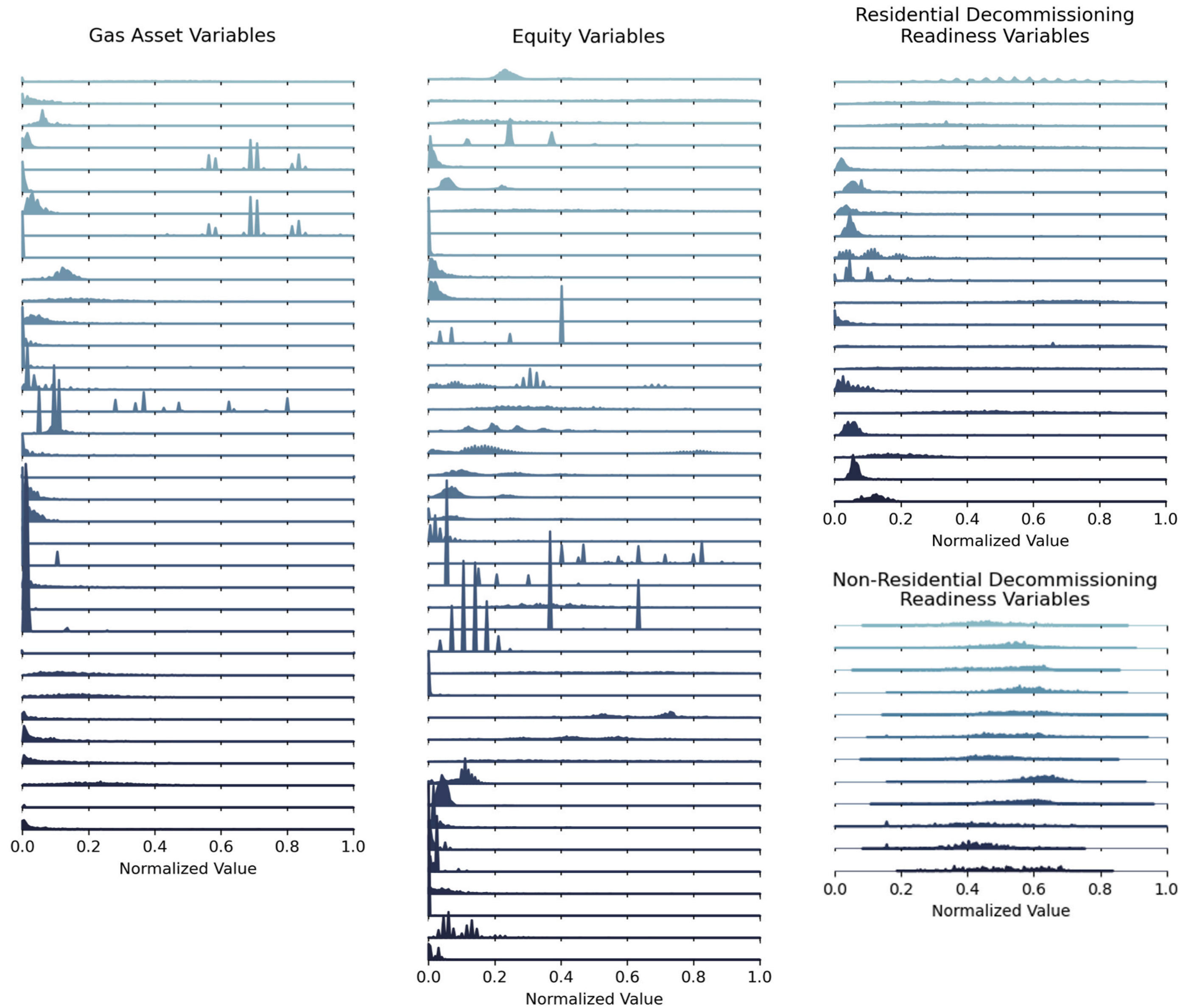

Fig. 3. Count frequency histograms of normalized values for each component variable used as inputs to three of the analysis' four top-level indices as defined relative to the California Case Study implementation.

US EIA's Manufacturing End-Use Consumption Survey (MECS). These weights ranged from 1 to 3, corresponding to Low, Medium, and High levels of technical difficulty, respectively. Further details about the methods and data sources used to develop these weights relative to different categories of gas end-uses and non-residential sub-sectors are provided in Tables B1 and B2 in Appendix B.

Once these raw inputs are assembled, an initial set of decommissioning readiness scores for each census tract and sub-sector ($S_{t,s}$) are computed according to Equation (1), which involves multiplying the aggregated total gas usage volumes for each sub-sector and census tract ($U_{t,s}$) by the fraction of gas consumption associated with each end-use category within each sub-sector ($F_{s,e}$) and the associated weighting coefficients assigned to each end-use category and sub-sector combination ($W_{s,e}$).

$$S_{t,s} = \sum_{e=1}^{E} U_{t,s} \cdot F_{s,e} \cdot W_{s,e} \qquad \text{Equation 1}$$

These raw scores are then transformed into a set of normalized final outputs through a binning and normalization process (detailed in section 2.6) to produce final output scores reported as ordinal values ranging from 1 to 10, reflecting low to high non-residential customer decommissioning readiness.

4.4. *Residential customer decommissioning readiness*

The residential decommissioning readiness index is intended to represent the relative feasibility of gas service disconnection for different groups of residential customers. The index's sub-components are based upon collection variables which are known to be correlated with barriers to the adoption of gas substitute technologies (primarily electric), including the integration of those technologies into the electrical and mechanical systems of existing buildings. Fundamentally, the residential gas decommissioning index seeks to quantify.

1) The relative dependence of residential customers on gas as a primary fuel source as well as metrics related to the intensity and overall magnitude of total site energy use (gas + electricity).

2) Socio-economic factors likely to affect a household's capacity to independently support the financial and logistical burdens of purchasing and installing gas substitute technologies.
3) Constraints related to the age and physical condition of the existing building stock that are likely to make gas substitute technology integration more challenging.

The primary barriers for residential gas customers to participate in a gas distribution system decommissioning project are likely to be different from those facing non-residential customers as there is already a wide range of commercially available alternative fuel end-use equipment that can immediately be used as substitutes for all existing domestic gas end-uses. The majority of these existing residential gas-substitute equipment make use of electricity as their primary energy source. In most cases, this is because modern heat pump technologies are well suited to efficiently deliver the relatively modest temperatures and pressures that are required for domestic end-use energy services. Because alternatives to gas-powered domestic appliances are readily available, our quantification of residential sector decommissioning readiness is oriented around the assessment of different non-technical barriers to residential end-use electrification which have previously been identified, both by ourselves, as well as in other previous studies. Table A4 in Appendix A details the various sub-index components and primary source variables used in the Residential Decommissioning Readiness Index.

The main source of public data used to assemble the residential decommissioning readiness index values for the California Case Study was the 2022 American Community Survey (ACS) 5-Year estimates census tract attributes related to housing tenure and costs, as well as the physical condition of the residential housing stock and certain classes of installed end-use energy equipment. An additional source of private data was the same database of IOU customer account level electricity and natural gas consumption data used previously as inputs to the Non-Residential Decommissioning Readiness Index. For the purposes of this analysis, residential customer account addresses were geocoded to the parcel level and linked to parcel level building attribute information compiled by county tax assessor offices. These annualized consumption data were then normalized using different parcel attributes to generate a number of derived fields as described relative to the Household Gas Dependence sub-index in Table A4 of the Appendix.

5. Case study

As a Case Study exercise, the project team developed a GIS-MCDA dataset using the proposed framework and methods for the 8651 census tracts served by California's four major IOU gas providers (PG&E, SoCalGas, SDG&E, and Southwest Gas). This region represents 94% of California's total census tracts, 58% of its total land area, 96% of its total population, and the full set of eligible geographies from which pilot decommissioning project sites may be proposed under SB-1221. This Case Study exercise was additionally supported by a formal stakeholder engagement process which involved structured outreach to community-based organizations (CBOs) and tribal representatives located throughout California. The purpose of this engagement was to discuss and refine our approach to the development of the Equity Index and Decommissioning Readiness indices. In the sections below, we describe our approach to this process and its outcomes. We additionally provide detailed quantitative analysis of the full Case Study dataset and discussion of various relevant implications.

5.1. Stakeholder engagement process and scope

As part of the California Case Study, the project team undertook a series of stakeholder engagement activities to refine the GIS-MCDA framework and ensure that the Equity and Decommissioning Readiness indices reflected community priorities and lived experiences alongside publicly available data, consistent with procedural and recognition-based approaches to environmental justice (Jenkins et al., 2016). The stakeholder engagement process had three primary objectives.

1) Introduce stakeholders to the concept of gas system decommissioning when unfamiliar.
2) Gather stakeholder perspectives on gas system decommissioning and understand preferences regarding the potential siting of future decommissioning projects within their communities.
3) Solicit feedback on the GIS-MCDA methodology, the use of quantitative decision criteria for decommissioning site selection.

The GIS-MCDA dataset was validated through a participatory process consisting of two community workshops, a series of targeted community engagement meetings with representatives from community-based organizations (CBOs), and a concluding one public webinar showcasing an interactive web-GIS Tool (detailed in Appendix C) that was developed to showcase attributes of the Case Study dataset. Initially, the locations of community partners were systematically identified by utilizing this tool to filter for census tracts with the highest Equity Sub-Index values ($\geq$7), while seeking representation across urban, suburban, rural regions as well as varied climate zones. Initial outreach included CBOs in Clear Lake and Arcata, and Tribal Governments in Tule River and Palomar Mountains. However, many of these communities faced capacity limitations or competing priorities that prevented participation. Consequently, although all participating communities retained high Equity scores, final recruitment relied in part on existing relationships and established environmental justice networks. This represents a limitation of the study and highlights the structural challenges of conducting participatory research in under-resourced communities.

Ten CBOs were initially recruited from communities including Oxnard, North Fair Oaks, Richmond, Stockton, Sacramento, Visalia, Wilmington, Blue Lake Rancheria, San Francisco, and the La Jolla Reservation. Due to organizational capacity constraints, participation declined over the course of the project, resulting in five fully engaged community partners: Blue Lake Rancheria, Richmond, Stockton, the Central Valley, and Oxnard. Each community partner participated in approximately three engagement sessions (conducted virtually or in person), totaling approximately 10–15 h of participation, supplemented by follow-up email correspondence and document review. Although the exact format varied slightly among partners, the engagement process followed a consistent three-stage structure. The first meeting introduced the GIS-MCDA framework, its indices, and the overall community engagement process, after which participants identified three to five census tracts they considered local priorities for gas system decommissioning. The second meeting focused on validating the Equity and Decommissioning Readiness Indices by reviewing sub-index scores, indicator values, and underlying variables against participants' lived experiences and local knowledge. Feedback from these discussions informed consideration of additional indicators and revisions to variable weighting where appropriate. The final meeting reviewed proposed revisions, documented community feedback, and provided participants with an opportunity to validate the revised methodology and ensure their perspectives were incorporated.

5.2. Stakeholder feedback

The project's stakeholder engagement process revealed that, although many participating organizations were actively involved in climate and environmental justice initiatives, most had limited prior familiarity with the concept of gas system decommissioning. Participants therefore sought additional information regarding the purpose of decommissioning, the anticipated scale of projects, how existing gas infrastructure and customer equipment would be managed, and how costs and benefits would be distributed. Because many aspects of future decommissioning programs remain uncertain, discussions necessarily relied on hypothetical scenarios, highlighting both the novelty of the concept and the need for continued stakeholder education as decommissioning planning advances.

Participant feedback resulted in the incorporation of additional variables into the hierarchical index structure, particularly climate risk and public health related Equity indicators. In several cases, stakeholders noted discrepancies between their lived experiences and the Equity Index scores assigned to their communities. These observations highlighted an important methodological limitation: because the Equity Index is normalized across all California census tracts, statewide rankings do not always reflect how residents perceive the severity or urgency of local conditions. Communities experiencing significant local challenges may receive comparatively lower scores when similar or greater levels of disadvantage exist elsewhere in the State.

The stakeholder engagement process also highlighted several important dimensions of community capacity that are difficult to quantify using publicly available statewide datasets. Factors such as the presence and capacity of community-based organizations, local political leadership, municipal policy priorities, building code adoption, institutional capacity, existing climate and energy initiatives, and the strength of community networks can substantially influence a community's readiness to participate in or benefit from gas system decommissioning. These characteristics frequently shaped stakeholder perspectives on implementation feasibility but are not readily represented within a statewide screening framework. Participants indicated that such quantitative indicators are most informative when interpreted alongside local knowledge and community perspectives, which provide critical context that cannot be fully captured through spatial datasets alone.

Overall, the engagement process demonstrated that the GIS-MCDA dataset was most effective as a screening and prioritization framework rather than a definitive measure of community need or readiness. Participants provided valuable feedback on the underlying datasets, suggested additional community-relevant indicators, and identified opportunities to improve the Equity Index and the team's broader GIS-MCDA approach. A full report on the stakeholder engagement conducted as part of this research has been provided by DNV to the CEC and is publicly available through the Healthy, Equitable, Energy Transition (HEET) working group website (CEC, 2026a).

5.3. Analysis of the California Case Study GIS-MCDA dataset

Fig. 4 plots an empirical cumulative density function (ECDF) computed over the final set of combined index values generated for this Case Study region. These values are derived by summing and renormalizing the four top-level index scores - which themselves were derived from a similar summing and renormalization of the various component sub-indices - in each case using equal weights when performing the summation. The shape of this ECDF illustrates how sequential application of the Fisher-Jenks algorithm to construct this type of hierarchical index results in set of tract level scores that closely approximate a normal distribution with parameters: $\mu = 5$, $\sigma = 3$. The shape of this distribution is actually quite useful for the prioritization of sites because it means that there are roughly equivalent numbers of high and low-priority tracts (~10% each, respectively), with the remaining majority (~80%) ranked somewhere in between. This makes it easier to identify meaningful differences between tracts within localized regions that otherwise might be obscured by global extremes in the data. The maps provided in Fig. 5, show the geographic distribution of these Composite Index Scores across the State, with detailed inset views of the State's Central and Southern regions.

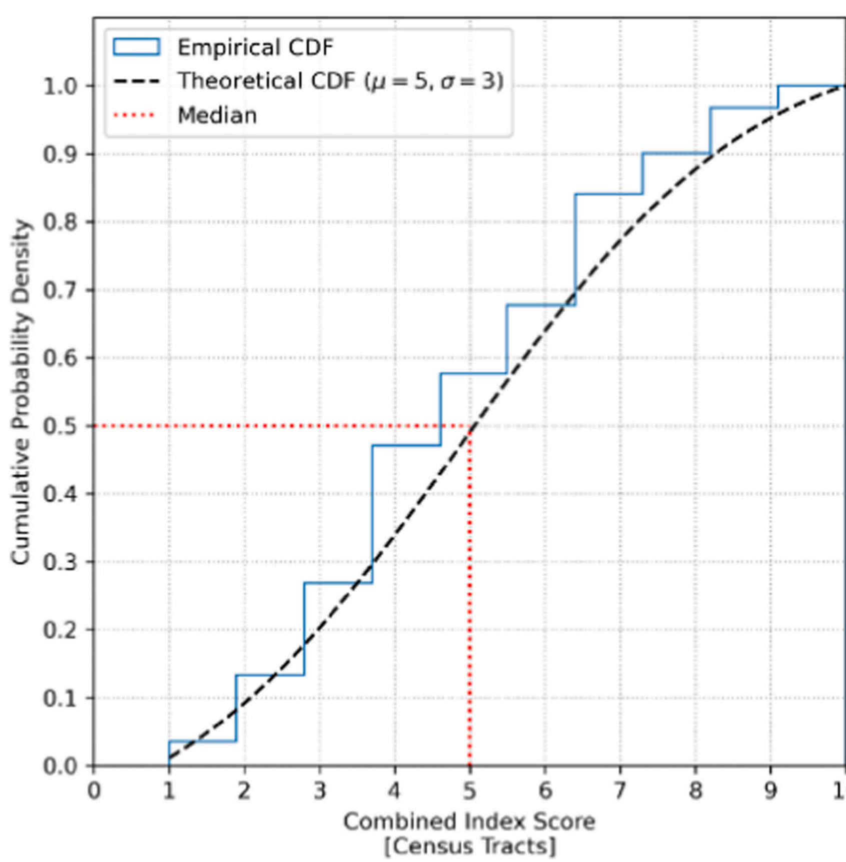

Fig. 4. Empirical cumulative density function (ECDF) for the calculated combined index scores in reference to a theoretical CDF for a normal distribution of ($\mu = 5$, $\sigma = 3$).

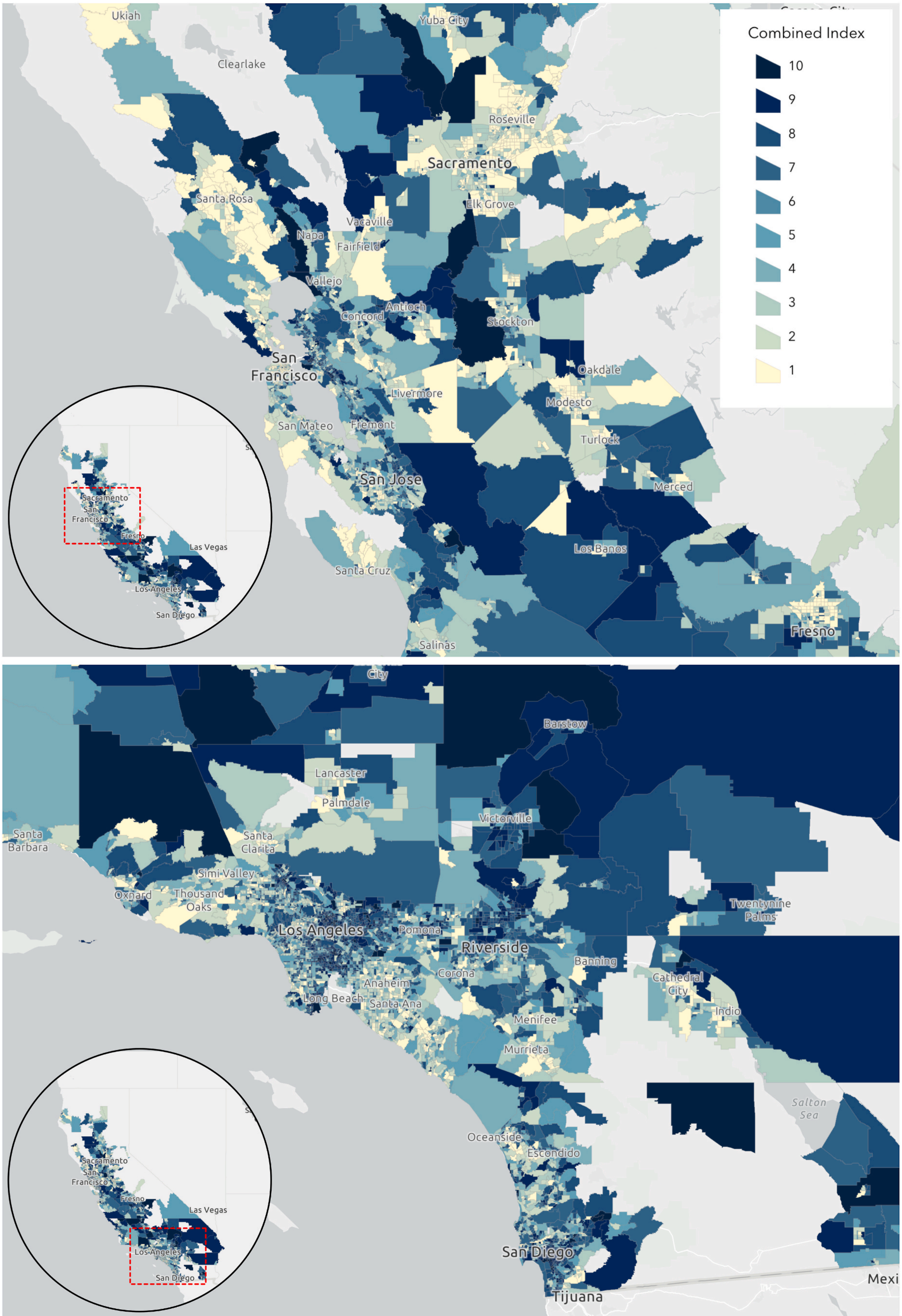

Fig. 5. Map illustration of the final Combined Index scores (1 = Less Promising: 10 = More Promising) defined at the census tract level across all of California's gas IOU service territories with detailed inset maps for the Central (top) and Southern (bottom) regions.

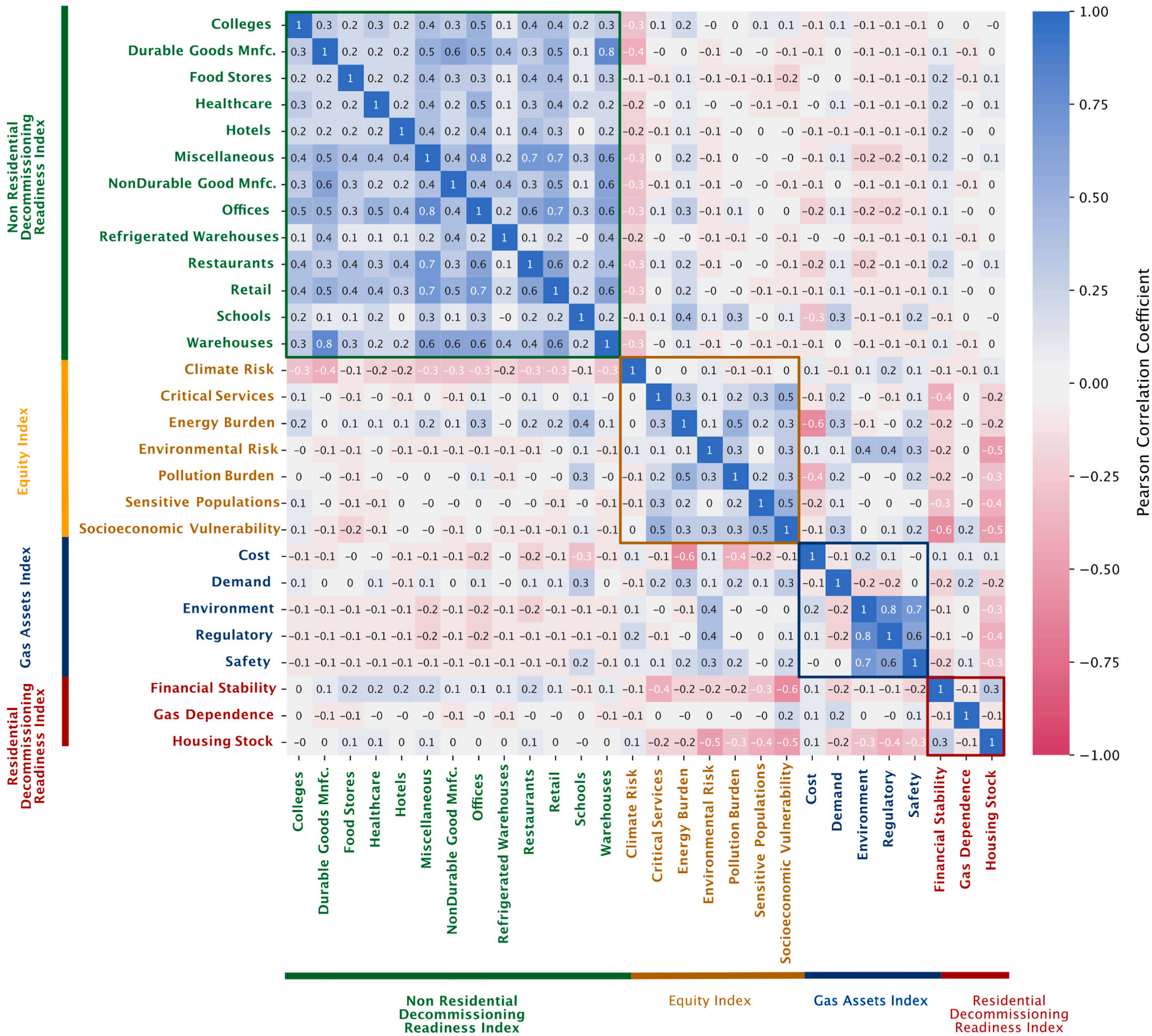

Fig. 6. Pairwise correlation coefficients for each sub-index and labeled according to their corresponding top level indices (Residential Decommissioning Readiness = red, Non-Residential Decommissioning Readiness = green, Gas Assets = blue, Equity = orange).

To evaluate the correlation structure among the different component sub-indices, a set of pairwise correlation coefficients were computed and are depicted by the heatmap plotted in Fig. 6. The row and column labels, which correspond to the various sub-indices, are colored according to each of the four top-level indices to which they belong. For the matrix of correlation coefficient values, a diverging red to blue colormap illustrates the difference between negative (red) and positive (blue) correlations between the various pairwise combinations of sub-indices.

There are several noteworthy structural features in the data that can be appreciated from this heatmap. Firstly, all of the sub-indices associated with Non-Residential Decommissioning Readiness tend to have stronger positive correlations with one another than among those in any other index category. This is likely due to the geographic colocation of various non-residential facilities at the census tract level, occurring as a by-product of local property zoning regulations which strongly favor the geographic separation and thus, clustering, of residential and non-residential property use-types. Secondly, relative to the Equity index's components, Climate Risk does not appear to be as positively correlated with the index's other components as they appear to be with one another. This is likely due to the fact that Climate Risks are driven by physical geographic variables (elevation, land cover types, etc.) as opposed to many of the sub-indices which relate to the geographic distribution of specific sub-populations and infrastructure. Finally, relative to the Gas Assets index's components, the apparent divergent correlations between its Environment, Safety, and Regulatory sub-indices (all positively correlated) with the Cost and Demand components (both negatively correlated) reflects internal competition between these component decision criteria. The presence of such a push-pull dynamic within the scope of a single index indicates that custom weights applied at the sub-index level would likely have significant effect on site prioritization outcomes.

6. Discussion

6.1. Recent developments in California

Despite the CPUC's recent release of its proposed decision "Establishing an Application Process for SB-1221 Neighborhood Decarbonization Pilots," there remains a great deal of uncertainty about how the process will actually unfold within California (CPUC, 2026). This is evident in the content of public comments which have been submitted relative to this proposed decision, many of which expressed grave concerns about the feasibility of meeting the legislation's ambitious timeline for program milestone completion.

Relative to the objectives of this study, an important sticking point in this process has related to SB-1221's requirement that California's gas IOUs create publicly available maps to help identify priority zones for electrification. Many observers had assumed that compliance with this order would involve the release of granular GIS data for utility gas distribution infrastructure. However, since the completion of this project's research, the State's major gas IOUs have complied with this order by releasing public web-maps whose only new data products are a set of defined Neighborhood Decarbonization Priority Zones (NDPZs). These NPDZs have been defined at the census tract level, primarily based upon the location of future planned utility investments in the maintenance or replacement of existing gas service mains. And while this choice of aggregation unit supports the approach taken in this research, many parties to the CPUC's long-term gas planning proceeding have been upset by the utilities apparent failure to incorporate many of the types of decision criteria included in this study as part of their processes for selecting these NDPZs. This is because the manner in which these NDPZs reflect a compensatory approach to site selection, that limits the consideration of alternatives to only those meeting certain, utility prescribed, criteria.

6.2. Data privacy and confidentiality rules

In California, as in most other U.S. States, the PUC determines what privacy protecting measures must be applied to gas infrastructure data in a manner that seeks to balance public safety, transparency (i.e. knowing where hazards are), and critical infrastructure security (i.e. preventing sabotage). Current CPUC regulations generally classify granular gas distribution data—specifically, detailed GIS maps showing the precise location of mains and valves—as confidential Critical Energy Infrastructure Information (CEII). The primary regulation controlling this data is General Order (GO) 66-D, which allows the California IOUs to submit data to the CPUC with a "claim of confidentiality." To support such claims, the burden of proof is on the utilities to demonstrate that this infrastructure meets the standard of CEII. Here, the State's gas IOUs have generally argued that releasing precise GIS data (e.g. shapefiles of pipeline segments) would allow bad actors to identify vulnerabilities, such as pressure regulation stations or critical valves, to plan coordinated attacks. The CPUC generally enforces several distinctions between location and attribute data, as summarized in Table 2 below.

Table 2
Summary overview of different classes of gas infrastructure system data and their current confidential status as determined by the CPUC.

Data Type	Status	Context
Granular GIS Data	Confidential	Precise shapefiles of distribution mains, service lines, and valve locations are almost always withheld from the general public to prevent sabotage.
Aggregated Maps	Public	Maps showing infrastructure density by zip code, census tract, or general service territory are typically public.
Safety Reports	Public	After the 2010 San Bruno gas pipeline explosion, the CPUC moved to make safety performance reports and general hazard maps more transparent, though they often redact specific street addresses of critical assets. (Ariaratnam, 2014)
Customer Usage	Confidential	Data linking infrastructure to specific customer loads is strictly private unless aggregated (e.g. "15/15 Rule" for anonymity).

In response to the CPUC's Rulemaking PG&E, SoCalGas, and SDG&E filed a joint motion arguing that the "granular geospatial pipeline segment mapping" required by the law is confidential CEII (Newlander et al., 2024). The CPUC has previously allowed this type of sensitive data to be released only to approved parties such as researchers, local governments, or intervenors who sign a Non-Disclosure Agreement (NDA). As we have argued, census tract aggregated data can be useful for high level planning and organizing around gas decommissioning site selection. However, long term, more detailed, infrastructure asset level data will be required to facilitate final site cost effectiveness evaluations and actual project implementation planning studies. The persistent treatment of detailed gas distribution infrastructure data as CEII stands in stark contrast to how similar data for electricity distribution infrastructure are currently handled within California. In 2014 the CPUC initiated the Distribution Resources Plan (DRP) Proceeding (R.14-08-013). The core mandate was simple but revolutionary: Utilities must treat the electrical distribution grid as an open platform and publicly disclose detailed data about it, accordingly.

To do this, the CPUC ordered California's three large IOUs — PG&E, SCE, and SDG&E – to perform a circuit-by-circuit analysis of their grids and publicly disclose the results. The IOUs initially argued that releasing detailed circuit maps posed a physical security risk, classifying the data as CEII. However, the CPUC ruled that while valid security concerns exist, the benefits of grid transparency outweighed the risks for most distribution-level data. CPUC reached a compromise involving the redaction of precise sub-station locations and schematics (these are still generally visible using publicly available satellite imagery and mapping data). Additionally, aggregation or redaction of calculated loads must be performed if a circuit section has fewer than 15 customers or if one customer makes up more than 15% of the load. And, as a final protective measure, users must typically register for an account to download the raw data, ensuring some level of usage tracking. Today, all three of California's major electric IOUs maintain public publicly accessible data portals where detailed grid infrastructure data are disclosed and updated on an ongoing (typically monthly) basis. The public availability of such detailed data for electrical grid infrastructure assets, without evidence of serious injury or harm having been incurred as a result, seriously undercuts gas utilities' claims that similarly detailed data for gas distribution infrastructure should be classified as CEII.

6.3. End-use technology adoption tracking

As described previously, detailed data on gas infrastructure and customer energy usage patterns already exist, with the major outstanding issue being the need to negotiate enhanced public access to them. As our study has revealed, however, there are other important classes of information relevant to gas decommissioning site prioritization that do not presently exist, indicating that new data collection efforts are needed. The most important of these relates the current penetration of gas substitute technologies for different end-use categories and within different customer segments. In California, the CEC currently administers two repeat customer survey efforts that collect related information: the Residential Appliance Saturation Survey (RASS) and Commercial End-Use Saturation Survey (CEUS). However, the problem with these surveys is that they lack the requisite spatial resolution to provide operational information relevant to gas decommissioning site selection and project planning. The CEC is aware of this need and is currently overseeing an active proceeding (24-OIR-03) which has issued requests for information (RFIs) about a proposal to develop a device-level tracking system for space and water heating equipment sales in California (CEC, 2026b). As of this writing, this RFI process is now in its third iteration and persistent pushback from industry stakeholders suggests that it may not be feasible to collect such detailed data in practice.

7. Conclusions

This study describes a novel, geospatially explicit methodology, for integrating disparate sources of primary data representing four core sets of thematically related decision criteria relevant to the prioritization of sites for the decommissioning of gas distribution infrastructure. It is among the first pieces of academic scholarship focused on the problem of how to actually operationalize state led gas system decommissioning policy agendas through the development of practical decision support tools. Moreover, its findings represent a significant departure from previous published work on the topic of gas decommissioning which have largely been concerned with highlighting the scale of existing gas distribution infrastructure and the various technical, economic, and social challenges which its substitution represents.

The study's Case Study application of the proposed GIS-MCDA framework to California surfaced a number of important issues related to the availability, consistency, and privacy protections applicable to essential data resources needed to quantify key decision criteria. These are likely to be shared in other states and regional contexts where similar gas decommissioning planning efforts are pursued. On this point however, it is worth noting that the specific choice of raw input variables used to construct the GIS-MCDA dataset for the California Case Study draws upon both private and context specific sources that will not be available in different regional contexts. And, in the former case, the use of private data limits our ability to document the data processing methods used to develop the Case Study dataset that are fully reproducible. Consequently, practitioners seeking to implement the proposed framework in other regional contexts will likely need to identify substitute primary data sources in some instances as necessary. However, the core elements of the study that are intended to be fully reproducible relate to the hierarchical structure of the proposed index scheme and the methods used for its construction (aggregation, value normalization, binning, etc.).

7.1. Reflections on an emergent gas decommissioning planning process

As one of the first movers on the issue of long-term gas infrastructure planning, both within the U.S. and globally, much can be learned from the Case Study of California's pursuit of pilot gas decommissioning projects and addressing complex questions related to site prioritization. To date, not a single pilot decommissioning project has been completed within the State, whether that be under the aegis of SB-1221 or otherwise. This is despite previous efforts on behalf of some utilities, most notably PG&E, to propose candidate projects. Ultimately PG&E withdrew its first major project proposal due to feasibility challenges (Pendleton and Warner, 2025) Moreover, most of the discussions around the need to decommission underperforming gas distribution infrastructure assets have taken place among a small, select group of energy system regulators, researchers, and utility engineers. Based upon the content of previously published studies and reports, many of these parties seem to implicitly presume that the most critical determinants of future decommissioning project success will be those related to the physical characteristics and cost recovery potentials of the gas infrastructure assets involved.

The experiences of this project's stakeholder engagement activities suggest the opposite, however. We observed that members of the general public are not aware of some of the most basic concepts related to gas decommissioning. This is despite the fact that the operationalization of gas decommissioning activities implies significant and lasting changes be made to customer owned end-use energy appliances and equipment as well as, possibly, the energy systems installed in their properties. Moreover, CBOs and other stakeholders consistently cited concerns around affordability, the potential invasiveness of these measures, future escalation in electricity rates, and the risk of residents feeling as if they were being forced to experiment with unproven technologies. To us, this reality suggests that the concerns of customers whose gas service stands to be terminated as a result of their participation in decommissioning projects are likely to be of at least equivalent, if not greater importance, as a criteria for evaluating potential site suitability than are the characteristics of the existing gas infrastructure which serve them. The structure of the GIS-MCDA index which we developed reflects this belief by implicitly weighting categories of customer-oriented impacts/benefits more strongly (at a level of 3 to 1) relative to the set of criteria, defined within the Gas Assets Index, that are narrowly circumscribed to the conditions of gas infrastructure.

7.2. Recommendations for future improvements

The findings of this study suggest that feasible future approaches to the screening, prioritization, and ultimate selection of candidate sites for gas decommissioning projects should be.

1) *Open* - referring to both the scope of the stakeholders involved in the decision-making process as well as the transparency of the information upon which decisions are based.
2) *Engaged* - referring processes for reaching out to stakeholders, notifying them of decision makers' deliberations about different decision alternatives, as well as the ultimate intent to take a decision, such that their feedback can be captured and addressed at each stage of the process.
3) *Iterative* - referring to the need for incremental cycles of comparative evaluation occurring at different levels of geographic and analytical detail.
4) *Adaptive* - referring to the need to have mechanisms, or off-ramps, for shifting course based upon new information that may come to light through subsequent rounds of stakeholder engagement or technical analyses.

Plans for the decommissioning of gas distribution infrastructure will not be successful if they have been conceived of behind closed doors making exclusive use of privately accessible data and tools. The infrastructure involved may often be privately owned - as in the case of investor-owned utilities - however, public entities still maintain ultimate regulatory authority over it. Individual gas customers face significant responsibilities, and thus have decision authority, associated with project participation, potentially including procuring new substitute end-use equipment, incurring different operational energy expenditures (that could involve net-savings), as well as sharing the costs associated with expanding the capacity of alternative energy distribution infrastructure systems (most likely, electricity). Indeed, SB-1221 requires that at least two thirds of gas utility customers directly impacted by a proposed decommissioning pilot project must approve of a project in order to override the utility's legal "obligation to serve" the entire group.

Unfortunately, there is already evidence that many gas utilities prefer a more top-down planning process that makes use of private data sets and tools. This preference is evident from their opposition to increased public disclosures of more detailed infrastructure and customer energy usage data based upon claims of security and privacy concerns. Such closed planning processes implicitly permit the introduction of biases reflected in the increased weighting of utility operational concerns, such as those related to the cost or practicality of managing the physical infrastructure under different decommissioning scenarios.

While gas utilities have the most knowledge about the design and operational characteristics of their distribution infrastructure systems, they may lack sufficient understanding of customer preferences or barriers to participation in decommissioning projects and may make selfserving assumptions about what these are for the purposes of planning. We believe that the dataset and associated Tool which we have developed in this project clearly demonstrates the value that the GIS-MCDA framework can bring to gas decommissioning site selection processes. Moreover, we believe that this approach can support planning processes which are more open, engaged, iterative, and adaptive. In the future, we envision that data and tools such as those documented here could readily be made public and used in concert with other, private utility-developed information to facilitate public discourse about the prioritization of gas decommissioning pilot project sites in a way that protects customer privacy and the confidentiality of sensitive, critical infrastructure assets.

CRediT authorship contribution statement

Eric D. Fournier: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jacob Moul:** Writing – review & editing, Methodology, Formal analysis. **Maya Ofek:** Writing – review & editing, Formal analysis. **Julia Skrovan:** Writing – review & editing, Validation. **Spencer Mathews:** Software, Data curation. **Robert Cudd:** Writing – review & editing. **Stephanie Pincetl:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Stephanie Pincetl reports financial support was provided by the California Energy Commission (CEC), GFO-21-504. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jup.2026.102322.

Data availability

Data will be made available on request.

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