Spatial Analysis of the Energy-Transport Vulnerability Index in Greater Urban Communities

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1. Introduction

The decarbonizing of cities and transportation systems has become an urgent agenda item to fighting climate changes in the US. Many urban strategies were initiated to actuate this commitment: such as, smart energy infrastructure, energy-efficient building design, and alternative fuel vehicles. Envisioning a post-carbon urban environment through these strategies requires an initial assessment of the urban environment itself, where one important aspect is energy vulnerability in society. However, methods for reducing the carbon footprint of urban communities and their outlying suburban areas can further exacerbate domestic energy and transportation poverty; therefore, sustainability strategies should be strategically implemented to support the communities equitably while combating climate change (Martiskainen et al., 2021, Robinson & Mattioli, 2020).

One failure example of a decarbonizing policy that lacked consideration on poor communities can be observed through France's past tried and failed "green taxes". In 2014, France implemented a "green tax" with a flat rate for decreasing the national carbon emission without an adjustment based on communities' income and demographic profile (Wehrle, R. et al., 2020). While the government continued to increase this tax rate in 2018, 'yellow vest' protests erupted across France resonating how the raising taxes hit hard the lower-income and working classes and resulted in violence, property damage, and a complete halt of public infrastructure' services. Carattini et al. (2019) explained that an increase in a bill influenced by carbon tax for a poor person may increase from \$50 to \$100, whereas a rich person may see an increase from \$100 to \$200. However, considering the price sensitivity and affordability of poor communities, the increase without redistribution of tax dividends would hit the poor person harder. This past record shows that it is important to understand the existing vulnerability and the potential equity impact across communities in implementing urban decarbonizing strategies.

Martiskainen et al. (2021) and Robinson et al. (2020) introduced two poverty indexes as new dimensions in describing energy vulnerability in cities: domestic energy poverty (DEP) and transportation poverty (TP). Energy poverty refers to the inability to attain the level of domestic energy one needs. Transportation poverty refers to the inability to attain the needed level of transportation services. Both poverties have direct impacts on the daily lives of the individuals suffering. While domestic energy poverty does not definitively mean transportation poverty, there is a strong correlation between the two indexes: homes that have difficulty paying necessary heating bills would also have a higher likelihood of having difficulty affording transportation costs relative to those who do not have difficulty paying energy bills. Spatial implementation of carbon-reducing strategies and cost redistribution methods can help policymakers locate the vulnerable clusters and not further push residents suffering from domestic energy and transportation poverty deeper into economic depression.

This project aims to conduct a spatial analysis of the Energy-Transport Vulnerability Index (ETVI) to understand Chicago's energy vulnerabilities. We leverage open-source databases to collect and curate sociodemographic, environmental quality, transportation, and energy consumption data for the city of Chicago. Then, we evaluate the spatial pattern of ETVI and its implication to urban decarbonization strategies. Additionally, our project will research the effectiveness of the spatial implementation of strategies and analyze the effects of different carbon-reducing strategies for Chicago with elevated domestic energy and transportation poverty levels.

2. Methodology

2.1 Indicators

The project considers three main groups of indicators, i.e., DEP, TP, and environmental quality, and due to interconnected nature, some indicators are attributed to multiple group characteristics. Domestic energy poverty (DEP) would include the share of energy expenditures of the household income, the total household energy uses. Transport poverty (TP) includes the accessibility to refueling/recharge infrastructures, the alternative transport modes except for vehicles (i.e., walking and public transit), the transportation fuel expenditure. Both DEP and TP are additionally characterized by the similar community and household demographics (e.g., income status, minority status, and family with dependents). Both DEP and TP are interconnected and attributed to these demographic characteristics and can characterize their joint vulnerability. Environmental quality (EQ) is characterized by Climate Policy, PM 2.5, NO_2, Urban Heat Island (UHI), Tree Cover, Tree Loss, which measure the environment and social inclusion index to existing urban conditions (Data Driven Envirolab, 2018). Combining EQ with DEP, TP, and demographic characteristics, we can construct a composite indicator ETVI to quantitively evaluate the energy-transport vulnerability. We can then reveal the environment outcome equity and further understand the spatial variability.

2.2 Scale of Analysis and Data Sources

We choose the city of Chicago in community (See Appendix 1 and 2) level as the spatial scale to implement the method and analyze spatial characters of DEP, TP, EQ, and ETVI. The data sources include American Community Survey (ACS), Energy Information Administration (EIA), Data Driven Envirolab, Chicago GIS, CMAP, etc. Some of the variables are available for census tracts, and some are available for communities. We use the JOIN tool in ArcGIS to convert all of the data to the community level.

Domestic Energy Poverty	
Indicators	Database
Energy Consumption, Energy Price	Chicago GIS, EIA
Transport Poverty	
Indicators	Database
Fuel station density	EERE-Alternative Fuels Data Center
Availability of walking	Smart Location Database
Availability of transit	Chicago Transit Authority, Data Driven Envirolab
Environment Quality	
Indicators	Database
Urban environment and social equity	Data Driven Envirolab
Green cover	EnviroAtlas, Chicago GIS
Others	
Indicators	Database
Household Demographics (income, population density, etc.)	United States Census Bureau (2000)
Travel behavior (VMT, trip mode, trip duration, etc.)	CMAP, LATCH

Figure 1. Indicators and Data Sources

2.4 Analysis Approach

In the first step, each index (i.e., DEP, TP, and EQ) needs to be measured individually. Min-max normalization method is utilized to re-scale each variable that contributes to DEP, TP, and EQ in [0, 1] to avoid outlier issues. DEP, which represent the exposure of households to energy poverty, is given by the percentage of energy expenditure to the household income as Equation 1 shows:

$$DEP_i = energy\_cost_i \div income_i \tag{1}$$

where $energy\_cost_i$ is the average energy cost in community i, and $income_i$ is the median income in community i. The domain of DEP_i is [0, 1].

TP, which represent the transportation vulnerability, is given by Equation 2:

$$TP_i = EVSTAT_i + Walking_i + Transit_i + Transit\_cover_i - Travel\_time_i - Fuel\_poverty_i \tag{2}$$

$$Fuel\_poverty_i = VMT_i \div Fuel\_efficiency_i \times Fuel\_price_i \tag{3}$$

where $EVSTAT_i$ is the amount of electric vehicle charging stations, $Walking_i$ is the walking accessibility, $Transit_i$ is the transit accessibility, $Transit\_cover_i$ is the cover of transit system, $Travel\_time_i$ is the time residents commuting, $Fuel\_poverty_i$ is the percentage of transportation fuel expenditure to the household income, VMT_i is the vehicle mileage, $Fuel\_efficiency_i$ and $Fuel\_price_i$ are the fuel efficiency of light duty vehicles and the price of general gasoline. The domain of TP_i is [-2, 4].

EQ is given by the summation of the variables from Envirolab as Equation 4 shows:

$$EQ_i = \mathrm{CLIMPOL}_i + \mathrm{NO2}_i + \mathrm{PM25}_i + \mathrm{PM25EX}_i + \mathrm{TREECAP}_i + \mathrm{TREELOSS}_i + \mathrm{UHI}_i \tag{4}$$

where $\mathrm{CLIMPOL}_i$ is the climate policy score, $\mathrm{NO2}_i$ is the nitrogen dioxide concentration score, $\mathrm{PM25}_i$ and $\mathrm{PM25EX}_i$ are the small particulate matter, $\mathrm{TREECAP}_i$ is tree cover per capita score, $\mathrm{TREELOSS}_i$ is the tree loss score, and UHI_i is the urban heat island score. We use the UESI score of these variables directly. The domain of EQ_i is [0, 7].

From the definition and calculation method of each index, we can find that the higher DEP score corresponds to more vulnerable, while the higher TP score and EQ score means lower vulnerability. Then, we utilize this pattern to construct the ETVI using the addictive equation as follows:

$$ETVI = -\alpha DEP + \beta TP + \gamma EQ \tag{5}$$

Note that we set the weight of these three indices equally, i.e., $\alpha = \beta = \gamma$. Otherwise, we can apply such as Grey Relation Analysis (GRA) to determine the weight of each index.

We use ArcGIS to illustration the spatial patterns of DEP, TP, EQ, and ETVI respectively. Combining with the spatial distribution of the green roofs, EV charging stations, and tax burden, we analyze the relations among them and propose a series of policy implementation recommendations.

3. Results and Discussions

In this section, we examine the spatial pattern of DEP, TP, and EQ scores across the Chicago neighborhoods and use these scores to build up the EVTI in the society. (See

Appendix 1 and 2 for the detailed Chicago Communities Map) The DEP score is shown in Figure 2, where the higher score represents the higher domestic energy vulnerability in neighborhoods. From Figure 2, the DEP score indicates that most Chicago neighborhoods experience a relatively similar domestic burden in terms of domestic energy cost per unit income. However, we observe that the neighborhood Fuller Park has the highest score among the neighborhoods. The vulnerability occurs due to high energy consumption, leading to high energy costs per household across neighborhood Fuller Park. Also, the income per household is relatively low compared to other neighborhoods in Chicago. The combination of high energy consumption and low income leads to a high domestic energy burden.

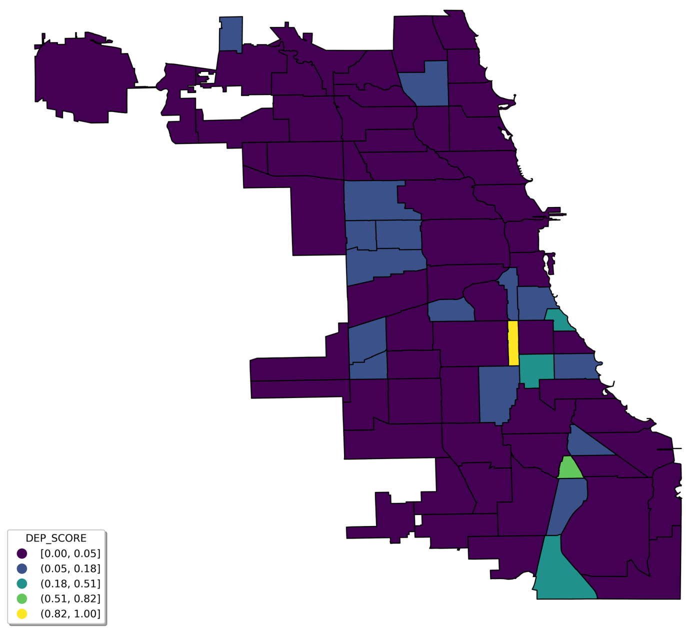

Figure 2. Domestic Energy Poverty (DEP) Score in Chicago Neighborhood

For the transportation vulnerability, the TP score is shown in Figure 3, where the higher score represents a lower vulnerability in the transportation perspective. From Figure 3, there are three main patterns across Chicago neighborhoods. The North region and Mid-region experience relatively similar transportation burdens. Next, the city center (the Loop and North Side neighborhoods) has the highest poverty score, leading to the low transportation burden. The observed pattern is expected because, in the city center, there is dense availability of refueling stations and high accessibility to public transit access. We also notice that the neighborhoods inside the city center have shorter commute times and lower VMT. These conditions are also expected as the center of activity is concentrated in the city center. Each household in the city center could access their work within a shorter distance than other households in distanced neighborhoods. The short commute time and low VMT lead to a lower fuel cost burden. The last observation is the South region, where experiences the most vulnerable region in the Chicago area. This region has lower availability of refueling stations and access to public transit compared to the other neighborhoods. For the income rate, the households inside the South region have relatively low income than other regions in the Chicago area. We also observe that the neighborhoods inside the South region have longer commute time and longer VMT, leading to a higher fuel cost burden in each neighborhood.

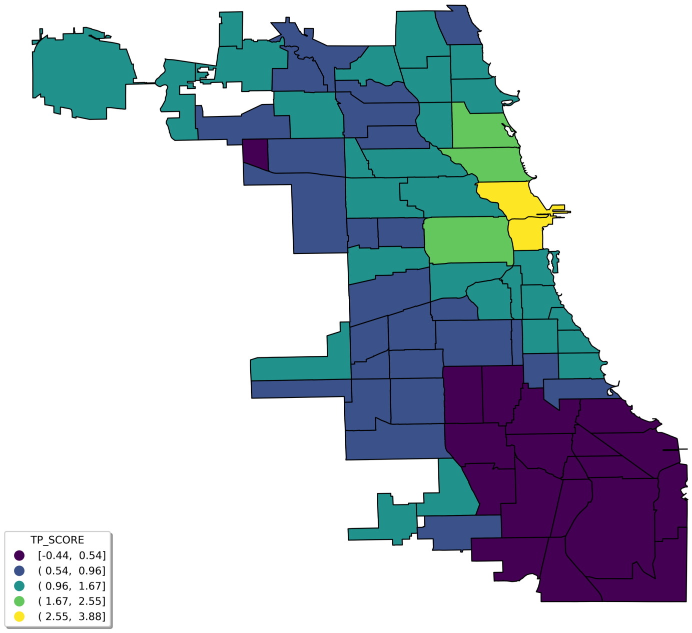

Figure 3. Transportation Poverty (TP) Score in Chicago Neighborhoods

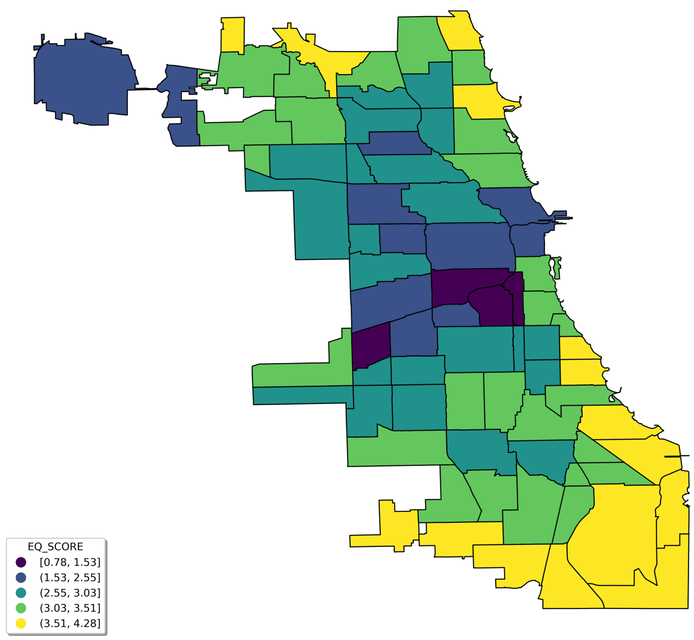

Figure 4. Environmental Quality (EQ) Score in Chicago Neighborhoods

The environmental quality of Chicago neighborhoods is represented in Figure 4, where a higher score leads to a better environmental quality. The Mid-region and city center regions are shown to experience a similar pattern indicating low environmental quality. Note that the city center is highly dominated by economics and daily activity, and there is Central Manufacturing District located in the Mid-region. These dense public activities and production activities might lead to low environmental quality. We also observe that the North region experience low environmental quality, while the South region has a higher environmental quality. Both regions produce high emissions of NO2 and PM2.5. The tree loss rate is also high in both regions due to land development for residential areas. However, regardless of the similar emission rate and tree loss rate, the tree cover per capita in the South region remains the highest coverage across Chicago. This reasoning might base the pattern of environment quality shown in Figure 4.

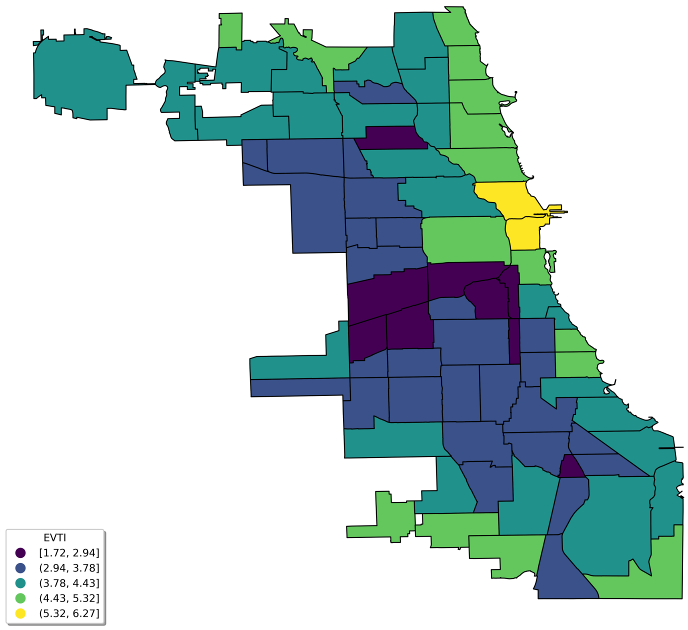

Figure 5. Energy Transportation Vulnerability Index (ETVI) in Chicago Neighborhoods

Compositing the DEP, TP, and EQ scores, we develop the ETVI score in Figure 5, where a higher score leads to a lower vulnerability in a neighborhood. Recall that, in this composition, we consider equal weight between DEP, TP, and EQ indicators. The first observation shows that the Mid-region neighborhoods are the most vulnerable neighborhoods considering the energy-transportation-environment condition. Next, the North and South regions experience similar high-level vulnerability in the Chicago area. Finally, the last vulnerable region is the city center region (the Loop and North Side neighborhoods). The ETVI is formulated to better identify the most disadvantaged individuals and groups due to existing social dynamics and urban energy-transportation form. From the result, the ETVI can separate and highlight the most disadvantaged communities from the privileged communities. This identification of vulnerable populaces through the ETVI will allow for the improved study of urban climate mitigation strategies and the possible impact these strategies could have relative to community energy-transport vulnerability.

4. Policy Implementations and Recommendations

In order for decarbonizing urban strategies to be successful, there must be community buy-in. A large component of 'buy-in' is to ensure that one already vulnerable group of the community will not be unduly subjugated to worsened conditions due to decarbonizing policy. In conjunction with the previously defined vulnerability index parameters, proposed decarbonizing policies can be aptly evaluated. This study will look at the decarbonizing policies of increased electric vehicle charging stations, increased green roofs, and an energy tax.

Electric vehicles and increasing their prominence are parts of the main keys in decarbonizing urban strategies. In order to make them more popular and feasible to use, increased charging stations are required across the city. The determination of new EV locations can be proposed by evaluating current locations while also considering the existing vulnerabilities. The current spread of electric vehicle charging (EV) stations and the average number of vehicles per household aggregated at the neighborhood level are displayed in Figure 6. The majority of stations are currently centered in the urban core, with a few in the northern suburbs, where households own lower cars. When evaluated in conjunction with the TP and ETVI index heat map, it can be seen that the South region is extremely vulnerable to transport poverty. As more and more cars transition to electric vehicles, if the south side is not targeted for more EV stations, this community will fall increasingly behind as this new technology continues to emerge and further exacerbates their vulnerability.

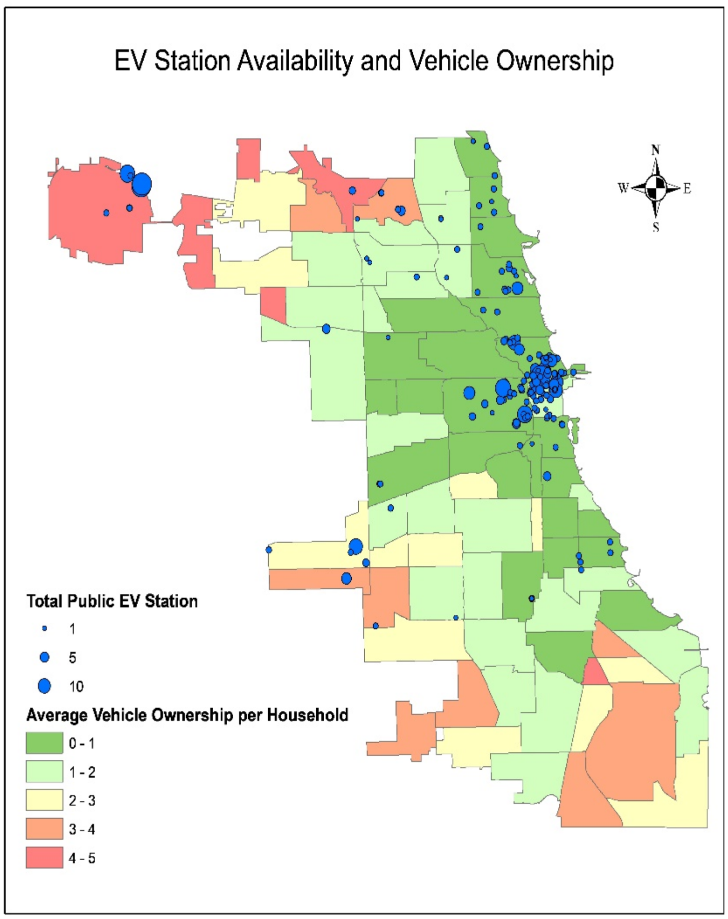

Figure 6. EV Charging Station Deployment and Average Vehicle Ownership per Household in Chicago Neighborhoods

Chicago already has worked to create a strong green roof initiate to help decarbonize the city. Most of the current green roof square footage is concentrated into the downtown urban core as seen in Figure 7. While there are some green rooms in the outer city areas, they are of much smaller magnitude. The urban core green roofs have helped improve the EQ and thus ETVI of these areas. Chicago's current initiative targets commercial buildings and has provided incentives for these roofs' creation. However, since the initiative prioritizes commercial, outer areas with more residential structures and higher indexed vulnerability have been more left out. Going forward, Chicago should attempt to prioritize non-commercial buildings such as residential apartments that would be well suited for green roof additions. This prioritization will help spread the green roofs throughout the city and help target other more vulnerable areas.

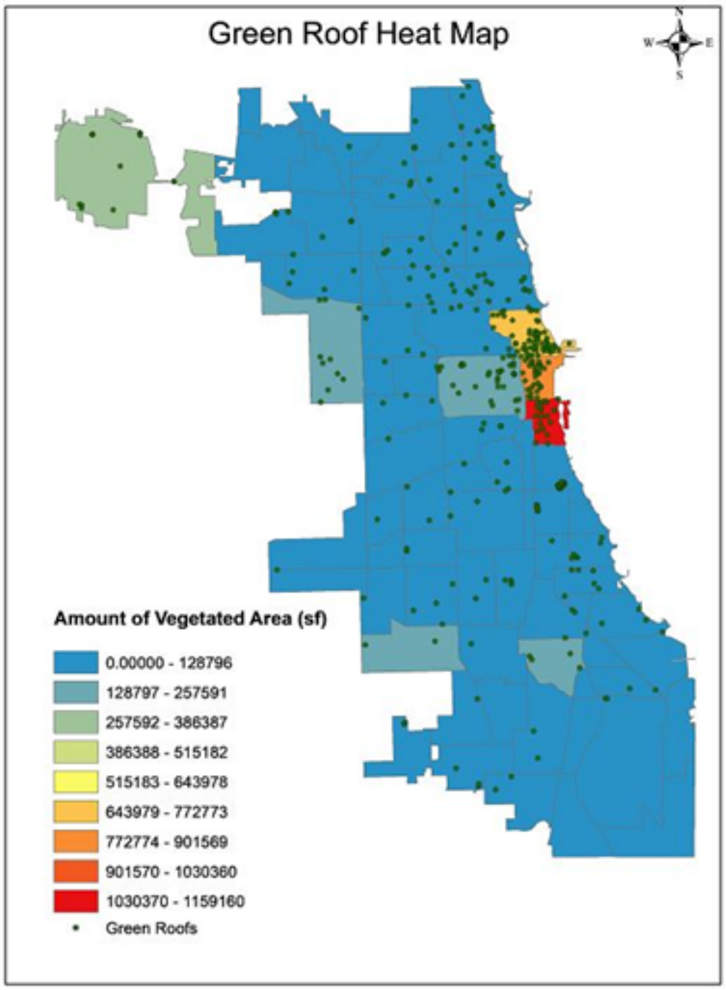

Figure 7. Green Roofs Implementation in Chicago Neighborhoods

Proposed green energy taxes have gained traction in recent years as a decarbonizing strategy. These taxes put costs on carbon-emitting energy practices in order to then place the collected fees to off-set these emissions. Especially if energy-use changes are harder and slower to change since much is tied to infrastructure, these taxes create more immediate solutions to offset carbon emissions. A hypothetical energy tax was proposed for Chicago based off the failed French green tax. The French tax failed because it failed to address how further exacerbating the most vulnerable would be prevented. The hypothetical tax for Chicago was based on three variables: 1) household energy consumption 2) VMT to represent amount of transport energy expenditure 3) number of vehicles (to penalize for not utilizing public transit, biking, walking, etc.). The tax was calculated at neighborhood level and normalized based on average income of neighborhood to display the tax's burden. A heat map demonstrating the varying level of tax burden (highest number being most burden placed) is shown in Figure 8. In comparison with ETVI, some of the most vulnerable neighborhoods coincide with the greatest tax burden. Therefore, careful consideration and further possible concessions or tax breaks would need to be considered to avoid further disadvantaging this more vulnerable group with a tax. While tax would aid carbon off-set, if the community ultimately does not back the tax because they are unduly burdened as in France the policy will fail and the city's carbon status will remain the same.

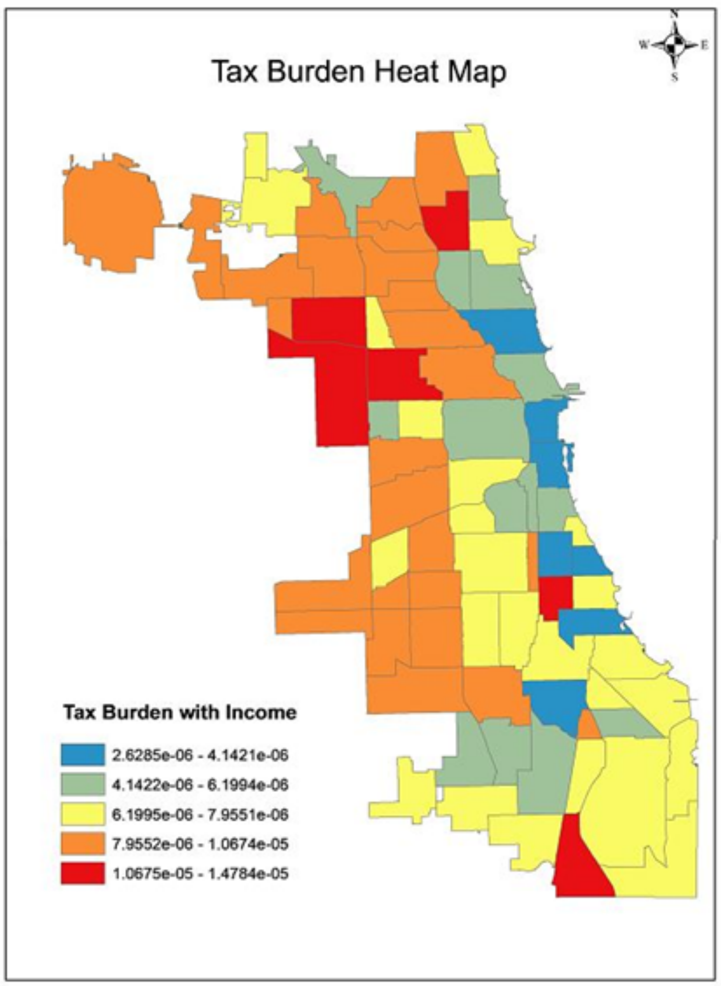

Figure 8. Tax Burden Heat Map in Chicago Neighborhoods

4. Conclusion

This section will be established for our final submission of the project.

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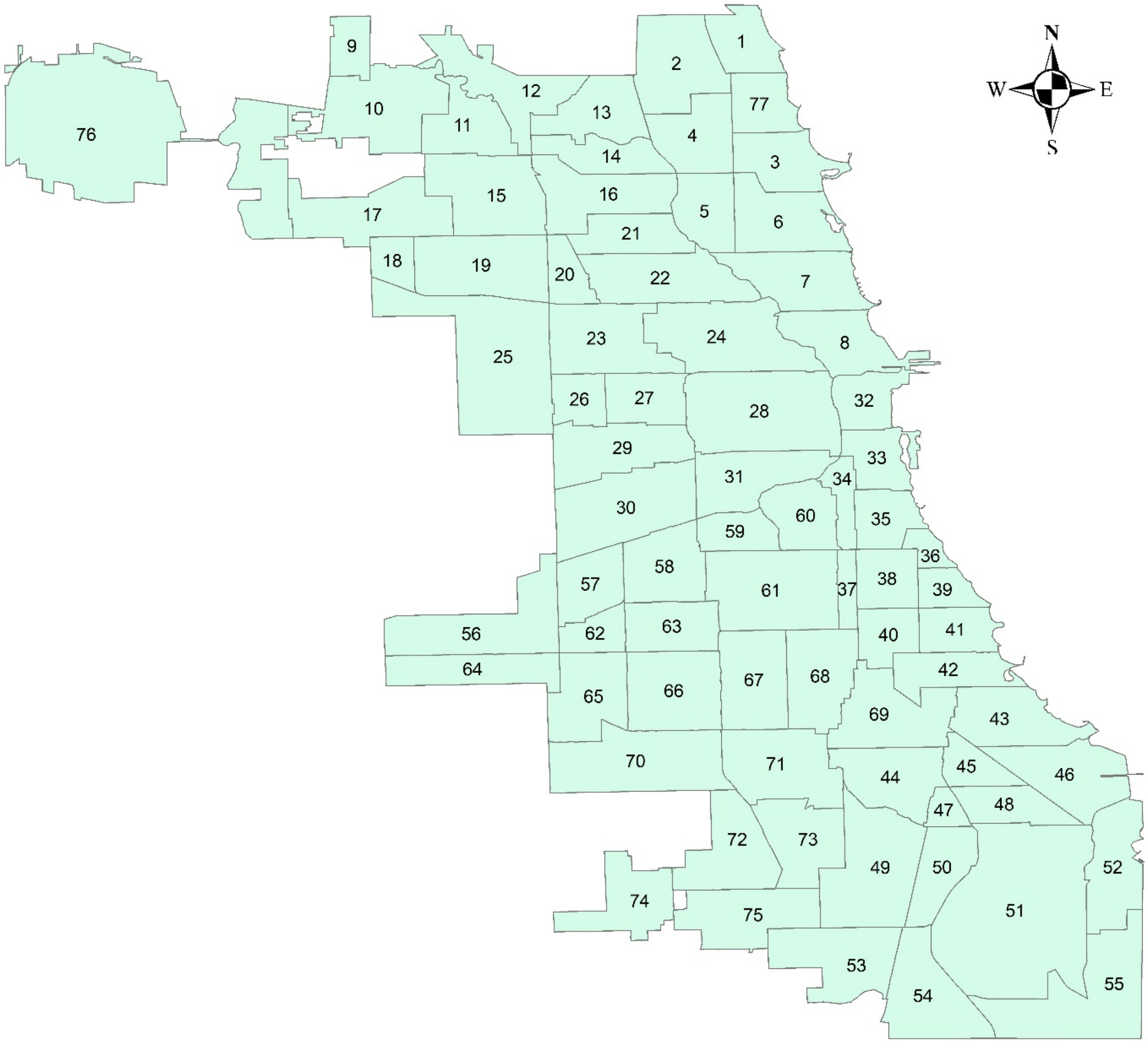
APPENDIX 1 Chicago Communities (Neighborhoods) Code Map



APPENDIX 2 Chicago Communities (Neighborhoods) Code

Communities	Code	Communities	Code	Communities	Code
Rogers Park	1	East Garfield Park	27	West Pullman	53
West Ridge	2	Near West Side	28	Riverdale	54
Uptown	3	North Lawndale	29	Hegewisch	55
Lincoln Square	4	South Lawndale	30	Garfield Ridge	56
North Center	5	Lower West Side	31	Archer Heights	57
Lake View	6	Loop	32	Brighton Park	58
Lincoln Park	7	Near South Side	33	Mckinley Park	59
Near North Side	8	Armour Square	34	Bridgeport	60
Edison Park	9	Douglas	35	New City	61
Norwood Park	10	Oakland	36	West Elsdon	62
Jefferson Park	11	Fuller Park	37	Gage Park	63
Forest Glen	12	Grand Boulevard	38	Clearing	64
North Park	13	Kenwood	39	West Lawn	65
Albany Park	14	Washington Park	40	Chicago Lawn	66
Portage Park	15	Hyde Park	41	West Englewood	67
Irving Park	16	Woodlawn	42	Englewood	68
Dunning	17	South Shore	43	Greater Grand Crossing	69
Montclare	18	Chatham	44	Ashburn	70
Belmont Cragin	19	Avalon Park	45	Auburn Gresham	71
Hermosa	20	South Chicago	46	Beverly	72
Avondale	21	Burnside	47	Washington Heights	73
Logan Square	22	Calumet Heights	48	Mount Greenwood	74
Humboldt Park	23	Roseland	49	Morgan Park	75
West Town	24	Pullman	50	OHare	76
Austin	25	South Deering	51	Edgewater	77
West Garfield Park	26	East Side	52		