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Joint Costs in Electricity and Natural Gas Distribution Infrastructures: The Role of Urban Factors

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Abstract: This paper analyzes the joint cost structure of electricity and natural gas distribution investments. Assessing the joint costs is critical for urban development and public policy regarding competition at the local level. The paper accounts for the urban and geographic factors at the local level, while the previous literature primarily used company-level data with a few or no site-specific variables in joint cost analyses. An empirical analysis of the multi-utility capital costs suggests that the local urban and geographic conditions affect such costs, with economies of scope present in electricity and natural gas both in terms of total costs and underground investment costs. Hence, the joint service provision makes economic and environmental sense for urban policy makers.

Keywords: infrastructure cost modeling; joint energy distribution; economies of scope; electricity distribution; natural gas distribution

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1. Introduction

The urban energy distribution infrastructure, which is composed of electricity and natural gas networks, is essential for sustaining daily life and economic activities. Energy infrastructure investments are expensive and often difficult to reverse, because it is costly to modify these systems once completed. Thus, understanding the cost structure of these systems is critical to make them sustainable and provide economical, safe and reliable energy to consumers. These costs can be expected to be related to the urban characteristics of the served areas and it is reasonable to consider such factors in cost analysis.

The urban utility companies provide either a single product (electricity, natural gas or water) or multiple products in different combinations. It is expected that there is an economic incentive for providing joint products in multi-product utilities, such as benefits and savings from sharing infrastructure and labor. These benefits are often termed as economies of scope and their analysis requires the definition and estimation of a utility cost model, with utility outputs, such as sales and numbers of customers, and input prices used as determinants. A few studies have examined the economics of multi-product utilities and utilized all data at the aggregate, company level [1,2]. However, it is very likely that the site-specific urban and geographic conditions have an impact on capital infrastructure costs, which are often neglected in the literature. The only factor that has been taken into account is density [2,3]. Some sites may be more suitable to joint provision due to soil conditions, topography and urban pattern, while other sites may present obstacles to the machinery operations needed for joint provision, such as excavation and filling. Another measure of the economic structure of utilities is the economies of scale, which are associated with the average costs declining with outputs. They are also critical for determining public policy in terms of competition at the local level and for understanding whether there are local urban and geographic conditions leading to diseconomies of scale.

The purpose of this study is to investigate the impact of local geographical factors on joint costs in multi-product utilities, making use of the detailed data on distribution investment costs for several gas and electric utilities in the state of New York. The total and underground capital investment costs are modeled separately, while the joint cost and economies of scale analyses are conducted. The basic spatial unit of observation is either a city, village or town. These data are used to estimate the distribution cost models with incorporation of sales, number of customers, input prices and local geographic and urban variables.

The remainder of the paper is organized as follows. Relevant literature is reviewed in Section 2. The cost modeling approach is outlined in Section 3. The study area and data are described in Section 4. The empirical results and their implications are discussed in Section 5. Section 6 concludes the paper.

2. Literature Review

A few studies have investigated whether it is more economical to provide electricity, gas and water separately or jointly. There has been some evidence for joint cost savings, although this often depends on firm size. All studies use the distribution costs as the dependent variable. Various functional forms, such as the quadratic and translog forms, are used in the model estimations. The areas where the data have been collected and the related sample sizes are presented in Table 1. All studies use output and price variables, while only two studies consider density [2,3]. Mayo used a quadratic cost function to analyze the costs of providing electricity only; natural gas only; and combined electricity and natural gas [1]. This study highlighted the savings at lower outputs and losses at higher outputs due to the absence of competition.

Table 1. Modeling Studies of Electricity–Gas Combinations.

Author(s) and Year	Independent Variables	Functional Form	Study Area and Sample Size
Mayo (1984)	Electricity output, gas output, dummies (electricity, gas)	Quadratic	US 200 utilities cross section
Chapell et al. (1986)	Electricity output using fossil fuel, electricity output using all types of fuels, gas output	Quadratic	US 88 utilities cross-section
Sing (1987)	Electricity output, gas output, prices (labor, capital, fuel), density, cost shares (labor, fuel, capital)	Generalized translog	US 108 utilities cross-section
Fraquelli et al. (2004)	Electricity output, gas output, water output, prices (labor, other), cost shares (labor, other)	Translog, Generalized translog, Separable quadratic, Composite	Italy 90 utilities 3-year pooled
Piacenza and Vannoni (2004)	Electricity output, gas output, water output, prices (labor, other)	Translog, Generalized translog, Separable quadratic, Composite	Italy 90 utilities 3-year pooled
Farsi et al. (2008)	Electricity output, gas output, water output, prices (labor, capital, electricity, gas), density, dummies (electricity, gas, water)	Quadratic	Switzerland 87 utilities 9-year panel

Chapell et al. extended the findings of Mayo by adding a technology variable to characterize electricity firms using fossil fuels and nuclear power [1,4]. The results are similar and suggest that joint cost savings are related to both technology and firm size. Fraquelli et al. and Piacenza and Vannoni used the same Italian data to analyze utilities with various combinations of gas, water and electricity services [5,6]. Cost is taken as a function of the amounts of gas, electricity and water delivered as well as the prices of labor and other inputs. The comparison of four cost models (standard translog, generalized translog, quadratic and composite) showed that the composite model with output and price interactions was most suitable in both studies. The largest savings were obtained from gas–water combinations in small firms. Small to medium firms enjoy global and product-specific economies of both scale and scope, suggesting that small firms should be multi-utilities in order to reduce their costs.

Farsi et al. analyzed the Swiss utilities providing various combinations of gas, electricity and water using a quadratic cost function [2]. In addition to electricity, gas and water outputs and input prices, the customer density was introduced into their model. Customer density was found to be statistically significant, with the expected negative sign. The results provide evidence that the smaller utilities benefit most from joint cost savings. However, by analyzing a combination of gas and electric utilities, Sing obtained contradictory results as they discovered losses for the average combination firm [3].

Literature has considered different combinations of other utilities. Water and sewerage systems have been historically characterized by both monopoly and competition. Some studies have highlighted the economic benefits of vertical and/or horizontal integration, while other studies argued that separation is more efficient, particularly for large firms. With few exceptions, the geographic and environmental variables have been overlooked. Kim and Clark observed cost savings for joint residential and non-residential water services [7]. Fraquelli and Giandrone found savings that resulted from the vertical integration of wastewater treatment plants [8]. Some studies suggest that joint cost savings depend on firm size. Hayes and Martins et al. observed such savings for small firms, but not for the large ones [9,10]. Similarly, Garcia et al. discovered economic efficiencies from vertical integration only for small firms [11]. By focusing on the cost structure of water and sewerage systems, Saal and Parker reached a different conclusion: costs remain the same, whether water and sewerage systems are separate or joint [12]. In contrast, Bottasso et al. found diseconomies in water and sewerage combinations, leading them to suggest that the two services should be separated [13].

Joint costs have also been analyzed in transportation systems. Viton found that the provision of different transportation modes is more cost effective for small companies than for larger ones [14]. Farsi et al. estimated the cost of Swiss urban public transportation with three outputs: trolley-bus, motor-bus and tramway [15]. They observed savings at all levels of output combinations. In contrast, Walter found diseconomies in German transportation systems, concluding that there should be competition rather than consolidation of services [16]. Di Giacomo and Ottoz and Ottoz and Di Giacomo analyzed the urban and intercity bus systems, concluding that cost savings are sensitive to model specification [17,18].

In summary, both joint cost savings and losses have been observed in previous studies, with results highly dependent on the selected functional form and the data. Several studies suggest that the savings decrease with increasing firm size. This implies that small firms should consolidate, while service unbundling may be the better strategy for very large firms. Very few studies have taken geographical and environmental factors into account.

3. Methodology

The cost modeling approach is rooted in the microeconomic theory of the firm. The multi-utility firm considered here provides the two outputs of electricity and natural gas, which makes up the output vector $\boldsymbol{Q}$. This output vector may be further disaggregated into sales and numbers of customers of electricity and natural gas in different sectors, such as residential, commercial, industrial, public authorities and street lighting. A transformation function summarizes all the feasible substitutions between the inputs and outputs. The inputs include labor (L), capital (K), and energy (E), which represents energy losses. Energy losses are an unavoidable feature of energy distribution systems, but they can be controlled by technological and capital investment choices to some extent. For instance, electricity losses are due to the resistance encountered by the electrons flowing along conductor lines and can be reduced by increasing the voltage of some lines at the cost of additional safety measures. Likewise, gas losses can take place along older gas pipes that may have leaks. In order to reduce these gas losses, new gas lines may be installed, which can sometimes occur by inserting the plastic pipes within the older pipes. The unit costs of these losses are the unit price of electricity as purchased from the electricity generating plant and the unit price of the gas purchased from interstate gas transmission companies. If these prices are higher, there is a subsequent stronger incentive to reduce the losses, hence leading to the trade-off between K and E. A vector of urban-specific variables ($\boldsymbol{ST}$), such as street network, housing stock characteristics and soil characteristics, is also part of the final function, with:

$$F(\boldsymbol{Q}, L, K, E, \boldsymbol{ST}) = 0. \tag{1}$$

Let P_K, P_L and P_E be the prices of capital, labor and energy. The firm is assumed to minimize its input costs subject to providing all the customers in its service territory as represented by the output $\boldsymbol{Q}$, with:

$$min\ C = P_K\ K + P_L\ L + P_E\ E, \tag{2}$$

subject to the production constraint represented by Equation (1). Let K^*, L^*, E^* be the optimal input values. The total cost function derived from the above cost minimization has the general form:

$$C(\boldsymbol{Q},\ \boldsymbol{P}, \boldsymbol{ST}) = P_K K^* + P_L L^* + P_E E^*, \tag{3}$$

where $\boldsymbol{P} = (P_K, P_L, P_E)$. The focus in this research is on the capital cost component, C_K, with:

$$C_K = P_K K^* = f_K(\boldsymbol{Q}, P_K, P_L, P_E, \boldsymbol{ST}). \tag{4}$$

Although the multi-utility firm also incurs labor and fuel purchase costs, the capital costs are the only costs with data available at the local urban level, which is the reason for the focus on these costs in this present study. After this, the input prices computed with data aggregated for the whole firm are uniformly applied to all the localities served by the firm.

There is no agreed-upon functional form for the capital cost function. Therefore, both log-log and Box-Cox regressions are considered. The former implies the logarithmic transformations of both the dependent and independent variables, while the latter implies more flexibility with the consideration of a whole range of forms through the endogenous determination of the Box-Cox transformation parameters. When these parameters are equal to one, the transformation is equivalent to the linear model. When they are equal to zero, it is equivalent to the log-log model.

The Box-Cox regression is defined as:

$$y^{(\theta)} = \alpha_0 + \alpha_1 x_1^{(\lambda)} + \alpha_2 x_2^{(\lambda)} + \cdots + \alpha_m x_m^{(\lambda)} + \gamma_1 z_1 + \cdots + \gamma_l z_l + \epsilon, \tag{5}$$

where the variables $y^{(\theta)}$ and $x_m^{(\lambda)}$ are defined by the transformations:

$$y^{(\theta)} = (Y^\theta - 1)/\theta \text{ and } x_m^{(\lambda)} = \left(X_m^\lambda - 1\right)/\lambda. \tag{6}$$

The variables Y and X represent the original dependent and independent variables in each observation, while y and x are the Box-Cox transformed versions of the original variables. The variables $z_1 \ldots z_l$ are not Box-Cox transformed, because the transformation is either not necessary or not possible as in the case of 0–1 dummy variables. In this study, all the variables are transformed.

Once estimated, the cost function may be used to assess the extent of the economies of scale. The cost elasticity with regard to the output Q_i (ε_{Qi}) measures the percent change in the cost (C_K) with regard to a percent change in Q_i and is calculated as follows:

$$\varepsilon_{Qi} = (\partial C_K / \partial Q_i) * (Q_i / C_K). \tag{7}$$

The economies of scale in the multi-utility firm (ε_R) are measured as the sum of the cost elasticities for the different outputs under the assumption of the same rate of expansion for all outputs. In the case of two outputs, we can obtain the following:

$$\varepsilon_R = \textstyle\sum_{i=1}^{2} \varepsilon_{Qi}. \tag{8}$$

Joint cost savings take place if the outputs (Q_1, Q_2) are more cheaply provided together as compared to the costs of providing them separately through two distinct firms, which holds if:

$$C(Q_1, Q_2, P_K, P_L, P_E, \boldsymbol{ST}) < C(0, Q_2, P_K, P_L, P_E, \boldsymbol{ST}) + C(Q_1, 0, P_K, P_L, P_E, \boldsymbol{ST}). \tag{9}$$

The extent of joint cost savings may be measured by the following ratio:

$$S_C = \frac{[C(0, Q_2, P_K, P_L, P_E, \boldsymbol{ST}) + C(Q_1, P_K, P_L, P_E, \boldsymbol{ST}, 0)] - C(Q_1, Q_2, P_K, P_L, P_E, \boldsymbol{ST})}{C(Q_1, Q_2, P_K, P_L, P_E, \boldsymbol{ST})}. \tag{10}$$

Positive values of S_C imply joint cost savings and negative values imply losses.

4. Data and Study Area

4.1. Data Sources

There are three categories of data used: company, census of population and geographic features. These are all available at the tax district level, which can be cities, villages or towns. The data of four electricity and natural gas companies (Central Hudson Gas and Electric Company, Long Island Lighting Company, Niagara Mohawk Power Company, and Orange and Rockland Companies) serving customers in the state of New York (NYS) in 1980 include sales, number of customers, distribution plant investment as well as capital labor and fuel prices. The data for 1980 were deemed acceptable because the distribution technologies have not so far changed significantly in contrast to telecommunications. The American Society of Civil Engineers (ASCE) indicated that the U.S. energy grid, which is composed of electricity and natural gas systems, has been aging considerably, with some areas still using components dating back to the 1880s [19]. This may change in the future if the electricity grid is entirely converted to a smart grid. However, this is not the case for now and the most significant recent change in some areas has been the replacement of electric meters with advanced metering infrastructure (AMI). However, the electric meters constitute a small share of distribution costs (e.g., only 4% in this study). Moreover, AMI has been implemented in less than 25% of the U.S. and the conversion in NYS has been even more limited, which has been estimated to be around 5% [20]. In any case, the metering equipment is a very small component of the total electric distribution plant. Electricity systems continue to operate with traditional system components (conductors, poles, transformers, etc.). The major changes in the electricity sector have been the relatively recent introduction of new generation technologies: dual gas turbines, wind generators and solar power plants. These technologies do not affect the layout of electricity distribution systems. However, changes could take place in the future if the whole system shifts from centralized power generation to distributed power generation, in which each end-user becomes capable of generating and trading electricity. However, such comprehensive changes will require much time and resources and are unlikely in the short- and medium-term. Innovations have been even more limited in natural distribution, which continues to operate with the same system components (pipes, services, pressure regulators, compressors and short-term gas holders) as in the past. Apart from petroleum gas containers distributed by trucks to isolated rural customers, pipelines will remain the only way to carry significant amounts of gas to residential, commercial and industrial end users in urban areas. In addition, it should be noted that most of the data that were available in 1980 are no longer available today due to competition and confidentiality concerns.

The census of Population and geographical data are available for the whole State of New York. The population and housing data for 1980 are used, which is consistent with the timeline of company data. The geographic data include land-use, soil, slope and street variables, which are all organized within Geographical Information Systems (GIS). The street map database is drawn from the Environmental Systems Research Institute (ESRI). Soil data are derived from the U.S. Department of Agriculture's State Soil Geographic (STATSGO) database. After considering various combinations of variables, the best fitted capital investment cost model includes the share of old housing units as the socio-economic variable, while the number of street intersections and soil steel corrosivity is assigned as the geographical variable. The street and soil maps are presented in the Appendix A.

Among all the possible data, this paper will use joint distribution costs, annual electricity and natural gas sales, electricity and natural gas prices, the number of street intersections, the share of old houses and the steel corrosivity of the soil. The cost refers to the replacement cost of the whole capital stock. All the data are cross-sectional. Soil is a time-independent variable. The cross-sections are made of 246 tax districts for the total capital investment cost and 234 tax districts for the underground capital investment cost.

4.2. Overview of the Study Area

The basic spatial unit of analysis is the tax district, which can be a city, a village or a town. The company data are available for 246 tax districts out of the 1619 tax districts in NYS. Although only 15% of the tax districts are included, the data cover most of the highly populated areas in the State, except New York City. It is important to note that not all tax districts have data on both electricity and gas, which is illustrated in Figure 1.

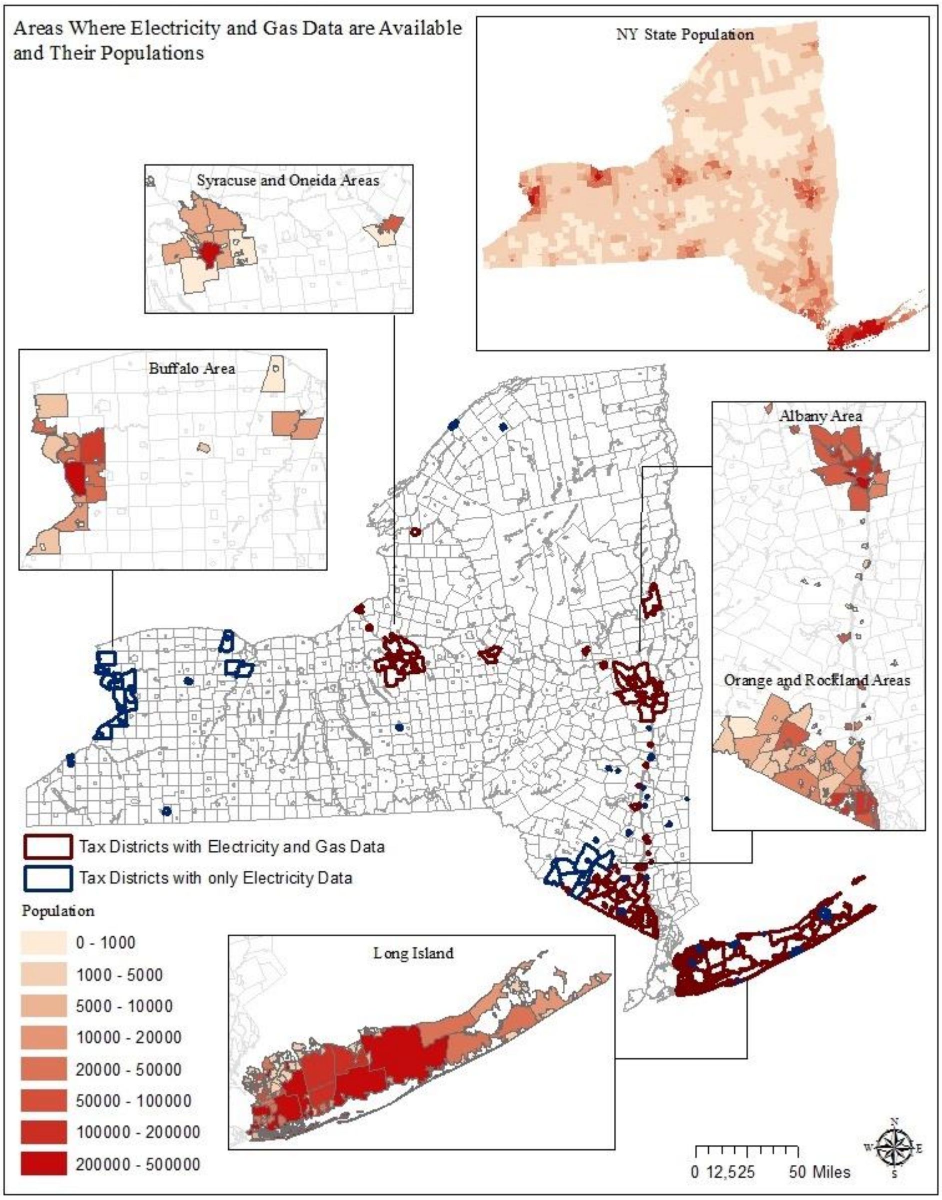


Figure 1. Tax Districts and Population Distribution.

There are 60 districts where electricity is served by one company and 186 where electricity and gas are jointly served. Out of the 246 tax districts, 25 are served by Central Hudson, 112 by Long Island Lighting, 56 by Niagara Mohawk and 53 by Orange and Rockland.

The detailed company historical plant (i.e., investment) data by vintage year (i.e., the year that a specific piece of equipment, such as a gas pipe, was installed for use in the company's system) and tax districts were provided by the New York State Division of Equalization and Assessment (NYSDEA). These vintage data were weighted by the Handy-Whitman index, which is a commonly used index in the utility industry [21]. After this, these data were summed up into replacement plant values, which represents the cost of capital considered here. All natural gas plant investments are underground. However, this is not the case for electricity as it can be delivered through overhead or underground conductors. Underground investment is expected to be costlier due to excavation and filling. Therefore, not all districts prefer (or have) to invest in underground electricity lines. As a result, the tax district sample is smaller regarding underground investments. There are 48 districts with the underground system providing only electricity. The 186 tax districts providing both electricity and gas have both underground systems. The 234 tax districts with underground systems include 20 served by Central Hudson, 111 by Long Island Lighting, 54 by Niagara Mohawk and 49 by Orange and Rockland.

5. Results

5.1. Investment Cost Model

After extensive exploratory analyses accounting for multicollinearity, statistical significance and overall model performance (R^2, log-likelihood), the following model was selected:

$$C = F(S_{TE}, S_{TG}, FUEL_E, FUEL_G, INT, AGE\_P_{40}, SOIL_{STEEL}) \tag{11}$$

where:

S_{TE} = Total electricity sales (kWh)
S_{TG} = Total natural gas sales (mcf)
$FUEL_E$ = Electricity fuel price ($/kwh)
$FUEL_G$ = Natural gas fuel price ($/mcf)
INT = Number of street intersections (#)
AGE_P_{40} = Share of 40+ year-old houses (%)
$SOIL_{STEEL}$ = Steel corrosivity of the soil (%)

Following Mayo, a dummy variable was initially added to distinguish electricity-only firms, but this variable was found to be insignificant and was dropped from the final model [1]. The unit capital prices and wage rates were also insignificant, which was probably due to the small variations in such prices within a relatively small geographic area. The descriptive statistics for the above variables are presented in Table 2 for the total cost model and in Table 3 for the underground cost model. The regression results (Table 4) show that the Box-Cox form is superior to the log-log form for both the total and underground cost models based on the log-likelihood test. All the variables are significant, with the expected signs. All the above-mentioned variables are common in the total and underground investment cost models apart from the steel corrosivity of the soil. This variable did not have a statistically significant effect on total investment costs, but significantly affected underground investment costs. This is plausible because soil corrosivity increases the costs of underground gas pipes and electricity conductors as corrosion requires special precautions and extra coating.

As expected, the outputs (electricity and gas sales) and fuel prices have positive and significant effects on costs. The number of street intersections, reflecting the effect of urban form on costs, is significant. A larger number of street intersections complicates the construction of a distribution network, therefore increasing costs. The proportion of old houses (houses that are more than 40 years old) is positive and significant and can be considered a proxy for the concentration of densely built-up neighborhoods close to city centers. Older housing stocks increase distribution costs due to their central location, with pavements, narrow streets and requirement of more maintenance. Steel corrosivity is positive and significant in the underground cost model only, as increasing corrosivity requires more precautionary measures, such as the use of more durable materials or extra coating.

Table 2. Descriptive Statistics for the Total Investment Cost Model (*n* = 246).

Variable	Minimum	Maximum	Mean	Std. Deviation
C ($)	3236	319,335,460	16,713,214	37,500,000
S_{TE} (kWh)	83,415	3,113,865,373	135,749,892	364,172,187
S_{TG} (mcf)	142	13,035,016	719,058	1,497,039
FUEL_E ($/kwh)	2.07	3.63	3.14	0.59
FUEL_G ($/mcf)	2.4	2.78	2.64	0.16
INT (#)	13	15,114	742	1665
AGE_P_{40} (%)	0.003	0.90	0.37	0.21

Table 3. Descriptive Statistics for the Underground Investment Cost Model (*n* = 234).

Variable	Minimum	Maximum	Mean	Std. Deviation
C ($)	944	159,542,601	7,580,208	18,100,000
S_{TE} (kWh)	304,336	3,113,865,373	143,000,000	364,172,187
S_{TG} (mcf)	142	13,035,016	719,058	1,497,039
FUEL_E ($)	2.07	3.63	3.13	0.58
FUEL_G ($)	2.4	2.78	2.65	0.15
INT (#)	13	15,114	769	1701
AGE_P_{40} (%)	0.003	0.90	0.37	0.20
SOIL_{STEEL} (%)	0.01	0.98	0.31	0.26

Table 4. Cost Functions for the Total Capital Investment (*n* = 246) and the Underground Capital Investment (*n* = 234).

	Total Capital Investment Cost (*n* = 246)		**Underground Capital Investment Cost (*n* = 234)**	
Coefficient	Models		Models	
	Log-log	Box-Cox(λ, θ) [a]	Log-log	Box-Cox(λ, θ) [a]
Constant	0.158	−51.279	−2.674	−42.48
S_{TE}	0.664 ***	0.416 ***	0.674 ***	0.281 ***
S_{TG}	0.025 ***	0.388 ***	0.059 ***	0.293 ***
FUEL_E	0.458 *	9.915 **	0.197 *	7.74 **
FUEL_G	1.682 **	50.132 ***	3.264 **	37.77 **
INT	0.309 ***	4.437 ***	0.249 **	0.929 **
AGE_{P40}	0.206 ***	10.011 ***	0.267 *	3.051 **
SOIL_{STEEL}	—	—	0.028 *	0.729 **
λ		0.213 ***		0.186 ***
θ		0.229 ***		0.173 ***
R^2	0.854	0.924	0.679	0.758
Log-likelihood	−4009.96	−3947.95	−3688.47	−3659.42
H0: θ = λ = 0 [b]	Chi-sq = 124.02 ***		Chi-sq = 58.1 ***	
H0: θ = λ = 1	Chi-sq = 896.68 ***		Chi-sq = 831.51 ***	

[a] Selected model; [b] Log-likelihood test results;*** Significant at the 1% level; ** Significant at the 5% level; * Significant at the 10% level.

5.2. Analysis of Scale Effects

The cost elasticities at the sample mean for the total system are presented in Table 5, which have been calculated for all the independent variables using Equation (8). The price of natural gas has the strongest impact on total costs. When the price of natural gas increases by 1%, the total capital cost increases by 1.29%. Total electricity sales have the second greatest impact, with an increase in 1% resulting in an increase of 0.47% in cost. As the joint distribution system covers the two products of electricity and natural gas, the returns to scale with regard to both outputs are measured by the sum of the respective cost elasticities, which can be expressed as $\varepsilon_R = 0.469 + 0.143 = 0.612$. When both outputs increase by 1%, the total capital costs increase by 0.612%.

Table 5. Total Capital Investment Cost Elasticities (*n* = 246).

Variable	Elasticity
Total electricity sales (kWh)	0.469
Total natural gas sales (mcf)	0.143
Electricity fuel price ($/kWh)	0.264
Natural gas fuel price ($/mcf)	1.287
Number of street intersections (#)	0.379
Share of 40+ year-old houses (%)	0.169

The cost elasticities were also computed for underground capital investments (Table 6). The results are similar to those in Table 5. The effect of natural gas fuel price has the greatest impact on underground costs, with an increase of 1% resulting in an increase of 1.97% in underground costs. The steel corrosivity has the smallest impact, with an increase of 1% in corrosivity leading to an increase of 0.02% in the underground capital investment cost.

Table 6. Underground Capital Investment Cost Elasticities (*n* = 234).

Variable	Elasticity
Total electricity sales (kWh)	0.402
Total natural gas sales (mcf)	0.157
Electricity fuel price ($/kWh)	0.416
Natural gas fuel price ($/mcf)	1.970
Number of street intersections (#)	0.139
Share of 40+ year-old houses (%)	0.110
Steel corrosivity of the soil (%)	0.026

5.3. Analysis of Joint Costs Effects

The joint cost savings indicator *S* defined by Equation (10) has been computed using the Box-Cox functions presented in Table 6. Positive values of *S* indicate the presence of savings, while the negative values indicate losses. The values of *S* were calculated for different combinations of electricity and natural gas outputs, S_{TE} and S_{TG}, using the mean values of all the other variables (Tables 7 and 8). The ranges between the minimum and the maximum values of S_{TE} and S_{TG}, which are (83–3,113,865 kwh) and (0.14–13,035 mcf), respectively, are divided into 10 equal intervals and S was computed for each output combination. *S* is in the range of 0.352–0.859 when using the total cost function and in the range of 0.182–0.665 when using the underground cost function. These results provide evidence for joint cost savings. However, those savings decrease with increasing electricity and natural gas outputs (Figure 2, Tables 7 and 8). The savings are higher for the total system as compared to the underground system.

The highest levels of savings (*S* = 0.859 and 0.665) are obtained when both sectors' outputs are minimal (83 Mwh and 0.14 mmcf), while the lowest levels of savings (*S* = 0.352 and 0.182) are obtained when both sectors' outputs are maximal (3,113,865 Mwh and 13,035 mmcf). The higher savings in smaller markets may be related to the easier coordination of investments in both distribution systems. These results are consistent with literature results that were reported in Section 2, while large economies are observed for smaller firms.

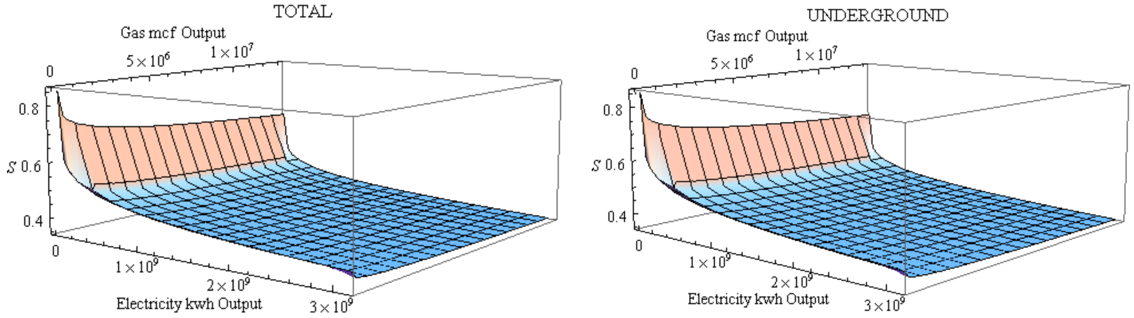


Figure 2. Savings Indicator for Different Levels of Electricity and Natural Gas Outputs.

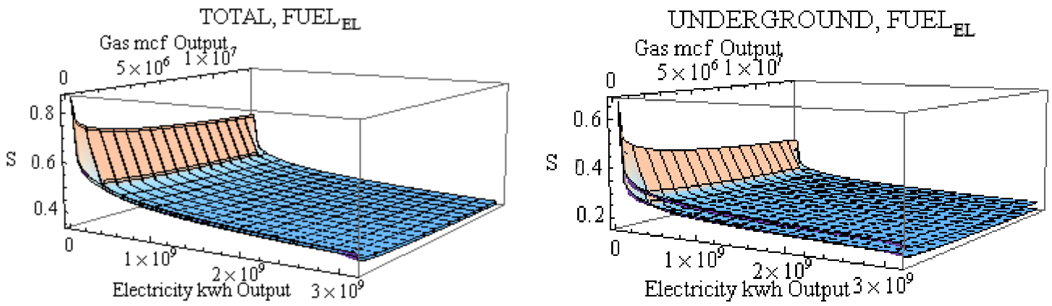
Table 7. Savings Indicator for Different Levels of Electricity and Natural Gas Outputs in the Total Cost Function.

		Electricity (1000 kwh)									
		83	**346,061**	**692,039**	**1,038,018**	**1,383,996**	**1,729,974**	**2,075,952**	**2,421,930**	**2,767,908**	**3,113,865**
Natural Gas (1000 mcf)	**0.14**	0.859	0.522	0.485	0.464	0.449	0.437	0.428	0.420	0.413	0.407
	1448	0.719	0.467	0.437	0.420	0.408	0.398	0.390	0.384	0.378	0.373
	2896	0.698	0.458	0.429	0.413	0.401	0.391	0.384	0.377	0.372	0.367
	4345	0.685	0.452	0.424	0.408	0.396	0.387	0.380	0.374	0.368	0.363
	5793	0.675	0.448	0.421	0.405	0.393	0.384	0.377	0.371	0.365	0.361
	7241	0.668	0.444	0.418	0.402	0.390	0.382	0.374	0.368	0.363	0.358
	8690	0.661	0.442	0.415	0.399	0.388	0.380	0.372	0.366	0.361	0.357
	10,138	0.656	0.439	0.413	0.397	0.386	0.378	0.371	0.365	0.359	0.355
	11,586	0.651	0.437	0.411	0.396	0.385	0.376	0.369	0.363	0.358	0.353
	13,035	0.646	0.435	0.409	0.394	0.383	0.375	0.368	0.362	0.357	0.352

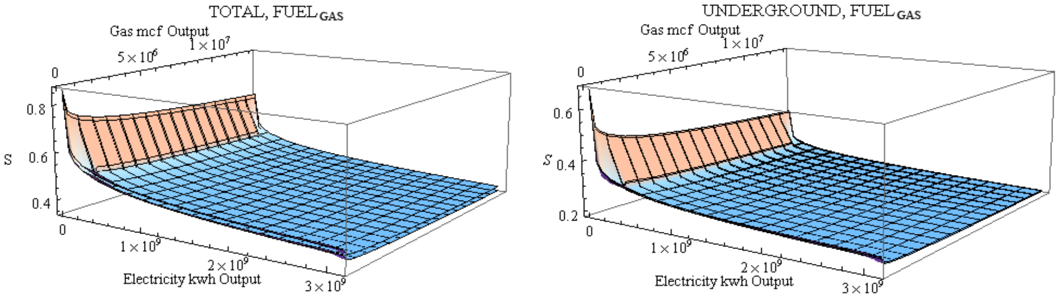
Table 8. Savings Indicator for Different Levels of Electricity and Natural Gas Outputs in the Underground Cost Function.

		Electricity (1000 kwh)									
		83	**346,061**	**692,039**	**1,038,018**	**1,383,996**	**1,729,974**	**2,075,952**	**2,421,930**	**2,767,908**	**3,113,865**
Natural Gas (1000 mcf)	**0.14**	0.665	0.307	0.280	0.266	0.255	0.248	0.241	0.236	0.232	0.228
	1448	0.456	0.253	0.235	0.225	0.217	0.212	0.207	0.203	0.200	0.197
	2896	0.433	0.246	0.229	0.219	0.212	0.207	0.202	0.199	0.195	0.193
	4345	0.420	0.242	0.225	0.215	0.209	0.203	0.199	0.196	0.193	0.190
	5793	0.410	0.238	0.222	0.213	0.206	0.201	0.197	0.194	0.191	0.188
	7241	0.403	0.236	0.220	0.211	0.204	0.199	0.195	0.192	0.189	0.186
	8690	0.396	0.234	0.218	0.209	0.203	0.198	0.194	0.190	0.188	0.185
	10,138	0.391	0.232	0.216	0.208	0.201	0.196	0.192	0.189	0.186	0.184
	11,586	0.386	0.230	0.215	0.206	0.200	0.195	0.191	0.188	0.185	0.183
	13,035	0.382	0.229	0.214	0.205	0.199	0.194	0.190	0.187	0.184	0.182

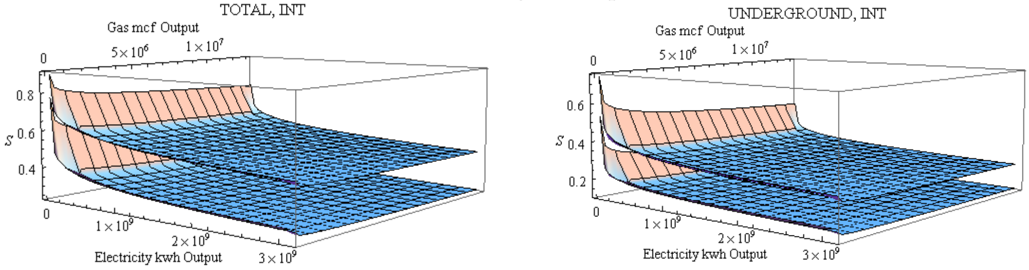
The values of S are calculated for the same output levels using the minimum and maximum values of the other variables: electricity fuel price, natural gas fuel price, number of street intersections and the proportion of houses that were 40 years old for both cost functions. The steel corrosivity was considered for the underground cost function only. The S values for the four combinations of outputs and at the minimum/maximum values of the other variables are presented in Tables 9 and 10. The indicator surfaces are graphically represented in Figures 3 and 4.



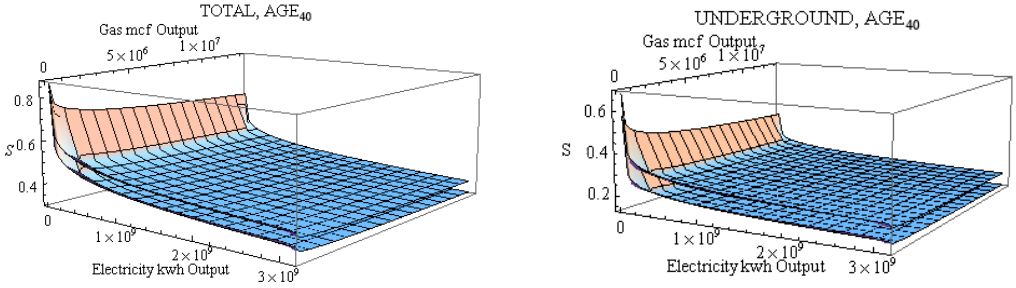
(**a**) Electricity fuel price



(**b**) Natural gas fuel price



(**c**) Number of street intersections (INT)



(**d**) Share of 40+ year old houses (AGE_P40)

Figure 3. Savings Indicator for Different Values of Electricity and Natural Gas Sales and for Different Levels of Price and Urban Variables.

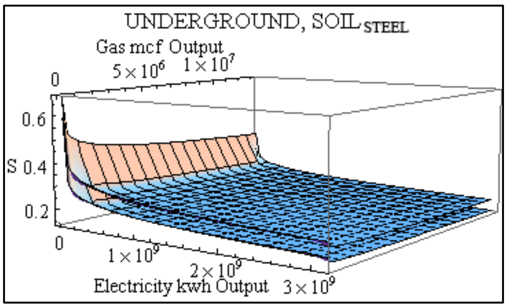


Figure 4. Savings Indicator for Different Values of Electricity and Natural Gas Sales for Different Levels of Steel Corrosivity in Underground Investment.

Table 9. Savings Indicator for Different Levels of Fuel Prices and Urban Variables at Different Output Combinations: Total Cost Function.

Site-Specific Variables		Output Levels (Electricity; Natural Gas)			
		(83; 0.14)	**(3,113,865; 13,035)**	**(83; 13,035)**	**(3,113,865; 0.14)**
$FUEL_{EL}$	**min**	0.855	0.344	0.638	0.398
	max	0.861	0.355	0.649	0.410
$FUEL_{GAS}$	**min**	0.855	0.345	0.639	0.400
	max	0.863	0.360	0.654	0.415
INTR	**min**	0.781	0.242	0.517	0.287
	max	0.904	0.456	0.738	0.514
AGE_{P40}	**min**	0.835	0.310	0.602	0.362
	max	0.866	0.365	0.659	0.420

Table 10. Savings Indicator for Different Levels of Fuel Prices and Site-specific Variables at Different Output Combinations: Underground Cost Function.

Site-Specific Variables		Output Levels (Electricity; Natural Gas)			
		(83; 0.14)	**(3,113,865; 13,035)**	**(83; 13,035)**	**(3,113,865; 0.14)**
$FUEL_{EL}$	**min**	0.629	0.160	0.346	0.201
	max	0.676	0.190	0.395	0.237
$FUEL_{GAS}$	**min**	0.623	0.156	0.340	0.197
	max	0.682	0.194	0.402	0.242
INTR	**min**	0.535	0.114	0.264	0.146
	max	0.746	0.248	0.479	0.305
AGE_{P40}	**min**	0.580	0.134	0.301	0.170
	max	0.684	0.196	0.404	0.244
$SOIL_{STEEL}$	**min**	0.601	0.144	0.320	0.183
	max	0.679	0.192	0.398	0.240

The results for the electricity and natural gas fuel prices are very close. The savings are higher when the fuel prices are maximal, which suggests that multi-utility investments are more feasible in areas where fuel is expensive. The savings are higher in areas where the proportion of older houses is maximal, which suggests that older neighborhoods with paved sidewalks may provide more opportunities for the efficient design of joint underground systems, hence leading to lower costs. The largest difference takes place when varying the number of street intersections. Higher savings are achieved for the maximum number of intersections, suggesting that such intersections facilitate the joint design of both networks, thus reducing costs. The overall lowest scores (0.242 and 0.182) are obtained for the maximal outputs and lowest number of street intersections. The S scores are higher in areas where the soil is more susceptible to steel corrosion, since joint underground design is more feasible in such areas.

6. Conclusions

This paper has analyzed the cost savings achieved through the joint distribution of gas and electricity. The results show that urban and geographical variables have significant impacts on the capital costs of electricity and natural gas distribution systems. In particular, the number of street intersections and the proportion of old housing stock both influence total and underground costs, while soil corrosivity is an additional factor that increases underground costs. In contrast to the earlier literature that focused only on company-level data, this study uses urban and geographic data at a detailed local level.

Overall, for the range of outputs considered, it is more cost-efficient to invest jointly in electricity and natural gas distribution networks than doing so separately. The savings indicator is in the range of 0.352–0.859 for the total cost and in the range of 0.182–0.665 for the underground cost at different levels of electricity and natural gas outputs. Furthermore, this decreases with increasing electricity and natural gas outputs. When different values of fuel prices and urban variables are considered, the number of street intersections was found to have the greatest impact. The savings in joint costs are the highest for a maximum number of street intersections, which suggests that joint capital investment is a rational economic approach in more densified and complex urban areas, such as city centers, apart from aesthetic and safety concerns. The joint construction of underground systems for both electricity and gas would reduce undergrounding costs. Therefore, we should encourage a shift from overhead to underground electricity distribution systems, especially when considering the safety and beautification advantages such a shift would entail.

In conclusion, urban policy makers and utility managers should consider both joint distribution costs and the role of site-specific urban factors when planning the construction of energy distribution infrastructure. Joint service provision was found to be economically more efficient than separate provision. The study can be expanded to other urban services, such as water and wastewater systems. Joint cost analysis of urban energy and water services at a detailed local level with the inclusion of urban and geographic factors can provide deeper insights into urban planning.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Street Network and Soil Groups Maps

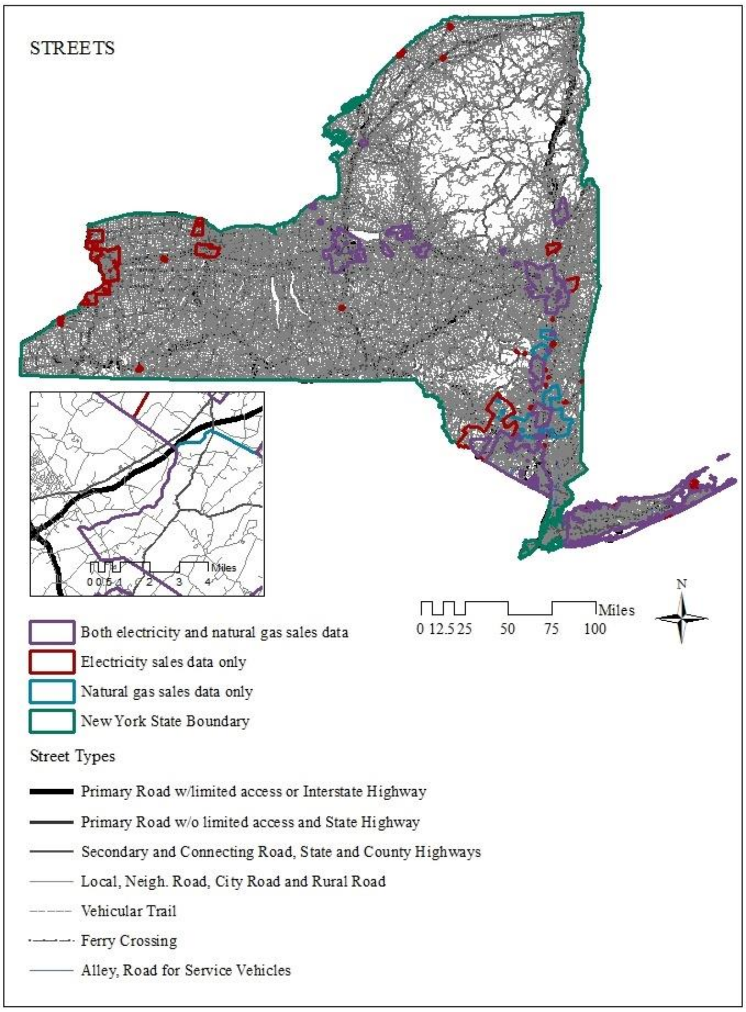

Figure A1. Street Network Map in the State of New York.

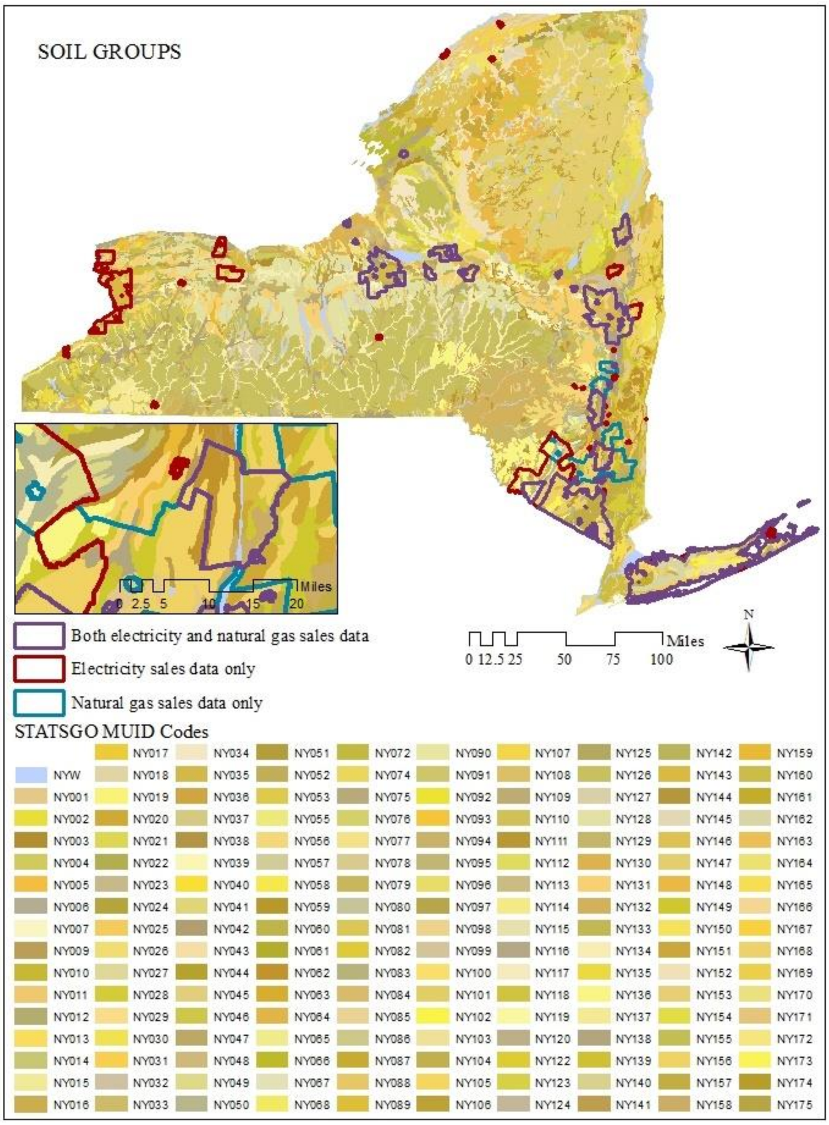

Figure A2. Soil Groups Map in the State of New York.

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