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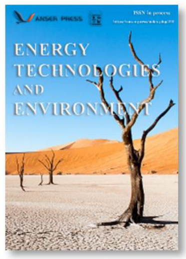

Geospatial Optimization of Location-Dependent Costs for Gravity Energy Storage Plants in a Mountainous Suburban Area: The Case of Fukuoka City, Japan

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ABSTRACT

Gravity Energy Storage (GES) systems are recently being considered as a viable solution for storing intermittent renewable energy power, specifically in high curtailment zones. While a few studies have analyzed the material costs of GES systems, there is a paucity of literature on analyzing the socioeconomic costs of GES systems. This study analyzes the location-dependent costs of GES plants using a multi-factor spatial parameterization model for evaluating the existence of a point of minimum cost in a suburban mountainous geography. A case study of 500x500 points in a 50x50km2 area in the suburban area of Fukuoka city in Japan is performed. It is found that the cost of material transportation and transmission is more dominant in determining the position of an optimal cost location than factors of excavation and land costs. The position of the minima is also related to the principal urban area in that the line connecting the Center Business District (CBD) and suburban flat areas (line 1) is where the potential minima lie. The intersection point of an orthogonal to the line connecting the CBD with a substation nearest to the flat area with line 1, is the potential zone of minima location. The findings of this study are critical for urban energy planners and reveals how socioeconomic cost factors can aid in geolocation a suitable GES installation site.

KEYWORDS

Gravity energy storage; location-dependent cost; suburban energy systems; cost optimization; spatial matrix modeling

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1. Introduction

In the search for reducing the impact of human caused climate change, renewable energy sources, specifically solar photovoltaics (SPV), have become the leading solution. Latest developments in material sciences and technology have enabled to reduce the material costs of solar panels, with instances of Levelized Cost of Energy (LCOE) of solar power dropping below fossil fuel generation (Kennedy, 2023). This is primarily due to novel fabrication techniques (Joseph et al., 2022), high-efficiency solar cells (Asim et al., 2012), engineering in transmission lines to reduce power losses (Mikulski and Tomczewski, 2021), etc. However, costs of SPV installation affected by social factors, such as land, labor and supply chain costs have only recently been explored in literature. A methodology to optimize location-dependent social costs of SPV plants by a multi-factor spatial parameterization (MUFSP) model is presented in (Basu et al., 2021). Such developments have increased the power parity of SPV more than any other renewable sources of energy.

Despite these developments, variable renewable energies (VRE) such as SPV power generation are subject to intermittency depending on the weather and time of day (Kennedy, 2023; Joseph et al., 2022; Basu et al., 2021). Due to the intermittency, in countries like Japan and Germany, SPV is subject to curtailment when supply exceeds demand (Dumlao and Ishihara, 2020; Frysztacki and Brown, 2020). This is specifically true for the Japanese region of Kyushu, which has a high penetration of SPV power (Dumlao and Ishihara, 2020). The primary issue associated with curtailment is that it drives the LCOE of SPV much higher (Dumlao and Ishihara, 2020; Darling et al., 2011). In large VRE targets due to the net-zero agenda, there is a chance of SPV's economic parity to drop below that of fossil fuel-fired power plants.

While energy storage mechanisms are the talk of the town, cost-optimization techniques for storage technologies are yet to be explored in literature. Several battery technologies have been proposed to penetrate into high-curtailment zones, but the capital costs (CAPEX) associated with batteries have resulted in LCOE estimations of SPV+battery systems to be much higher than that of SPV systems (Routhier et al., 2021). Policy changes such as introduction of time-of-charging of electric vehicles (EV) has been proposed in literature, along with subsidies (Dumlao and Ishihara, 2022). The results are quite mixed when it comes to decreasing the amount of curtailment, and even using EVs as proxy storage systems. The second issue is thus, a cheaper storage technology has to be explored in regions with high SPV penetration and curtailment.

This study focuses on gravity energy storage (GES), which has the advantage over battery technologies by not being dependent on critical raw materials like heavy metals (Berrada and Ben, 2022). The other advantage of GES systems is that it can be readily constructed with existing technology and materials (Berrada et al., 2017). The idea of GES has recently gained a lot of popularity. Although a large-scale GES is yet to be deployed due to high mechanical losses of the stored power (Tong et al., 2023), a few studies have already analyzed the economic feasibility of GES systems and have found that they can be more economical than batteries or chemical storage (Berrada, 2022; Berrada et al., 2021). However, no previous literature has delved into the social factors that can play a role in the CAPEX of GES plants.

The objective of this study is to assess the geospatial CAPEX factors of GES plants in a suburban mountainous terrain in the Japanese Kyushu region, which faces high curtailment of SPV generation (Dumlao and Ishihara, 2020, Dumlao and Ishihara, 2022). The reason for selecting mountainous terrains is that there can be additional challenges of excavation and critical construction codes associated with any construction in such regions (McDonald and McMillen, 1990). Fukuoka city is the most populated city in the Kyushu island of Japan (Estimation Methodology for Each Renewable Energy Type, 2010), and provides the perfect test case for analyzing the viability of GES plants in challenging construction conditions. This study is the first to analyze the optimization of social factors associated with GES systems in any terrain. This paper adopts the MUFSP model proposed in (Basu et al., 2021) to GES deployment in the Fukuoka city region of Japan, which is a part of the Kyushu grid. The aim of this model is to geolocate the minimum cost-optimized point for construction of a GES system based on social factors. This study also contributes to existing geo-optimization literature, in that, it attempts to see the applicability of the MUFSP model to energy storage technologies.

In this study, a 50x50 km^2 area in the suburban area of Fukuoka city is used as a case study to perform a geospatial matrix optimization, based on the MUFSP model, to optimize the location-dependent costs of GES near a suburban SPV plant. The novelty not only lies in GES geospatial cost considerations, but also in adopting policy-associated costs into the CAPEX of GES, such as excavation costs in mountainous terrains.

2. Methods and Materials

2.1. The Design of Gravity Energy Storage

While solid gravity energy storage (SGES) plants are abundantly classified, piston-type GES (P-GES) has modularity and adaptability and is less constrained by geographical conditions than other SGES (Tong et al., 2022). They can be constructed in a variety of terrains, including flat and mountainous terrains. In addition, the design and construction process can be standardized, making it easy to replicate and expand (Tong et al., 2022). Another major strength of P-GES is its hydraulic system, which allows for rapid response, including voltage and frequency adjustments and provision of reserve services (Tong et al., 2022). Reaction time is typically within seconds. Although more frictional and lossy than other GES, Heindl Energy is working to address the technical challenges and optimize the efficiency of P-GES systems by implementing innovative solutions such as rolling membranes (Heindl, 2023). The design of P-GES shows in (Frysztacki and Brown, 2020) to withstand underground pressure and water flow. *Figure 1* shows an overview of the P-GES system and *Table 1* shows the parameters, where the piston in the container moves repeatedly up and down to store and discharge energy through the conversion of positional energy and electric power. The capacity is 4 MWh, 1 MW. Steel and reinforced concrete are confirmed as superior GES plant structures in terms of durability, density, and material cost (Berrada and Ben, 2022; Berrada et al., 2021; Tong et al., 2022). Reinforced concrete is used for the container structure and steel for the piston structure. Based on the dimensions, significant excavation is required in a mountainous terrain for P-GES construction.

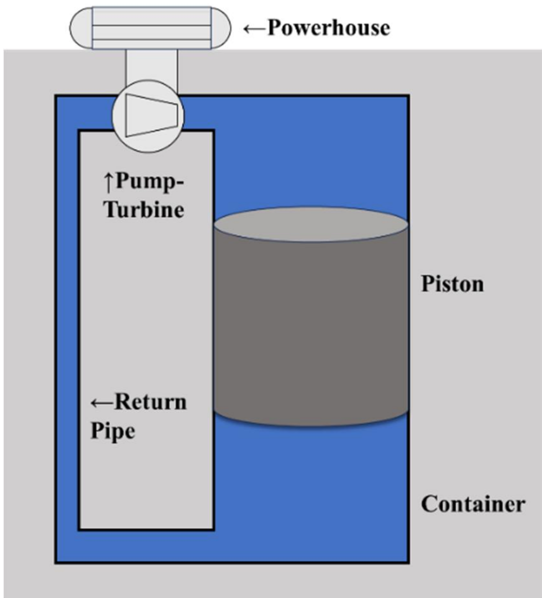


Figure 1. The Piston-GES system (Author’s Representation).

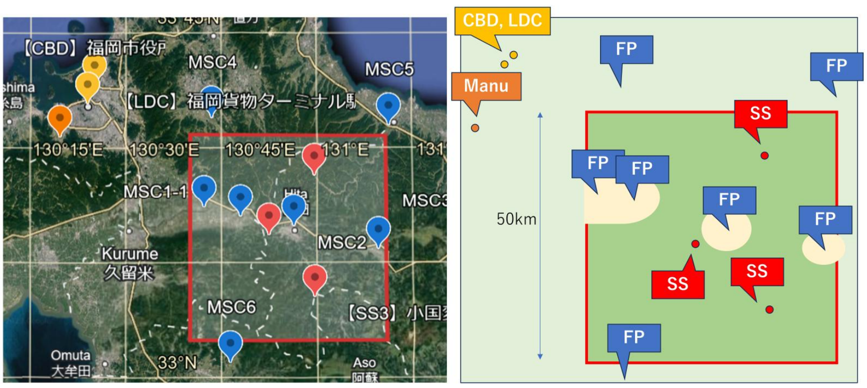
Table 1. The parameters of GES for this study (14, 15, 18).

Parameter (m)	Container	Piston	Return pipe
Height	137.64	68.82	137.64
Diameter	8	8	0.12
Thickness	2.09	-	0.014

2.2. Simulation Area

Figure 2 represents the simulation boundary for the MUFSP model, for the case study of Fukuoka. The simulation area is a squared 2,500 km^2 area southeast of Fukuoka City. Most of the area is mountainous and includes parts of Oita and Kumamoto prefectures. The Fukuoka area is chosen because it is located in the Kyushu region, where SPV curtailment is notorious (Dumlao and Ishihara, 2020; 2022). As a result, there is a demand for utility-scale power storage in the Kyushu region for SPV systems. *Table 2* presents the nomenclature of marked points in *Figure 2.*

(a)



(b)

Figure 2. (a) Fukuoka location in Japan and (b) a 2,500 km2 simulation area in suburban mountainous region of Fukuoka is divided into a 500x500 matrix.

Table 2. List of Marked Points.

Nomenclature	Full forms (Meanings)
CBD	Center Business District
LDC	Load Distribution Center
Manu	Manufacturing plants for GES

SS	Substation (1~3)
FP	Flat Point (1~7)

2.3. Location-Dependent Cost functions

Although the MUFSP model is used according to (Basu et al., 2021), SPV plants and GES systems differ in nature in several respects, including in materials, practical use and functionality. However, the base location-dependent cost function is quite similar, with transmission land and supply chain costs being directly dependent on the functions (Amjad and Shah, 2020). The 2,500 km^2 simulation area, in *Figure 2*, is programmed into MATLAB and SIMULINK R2023a environment and is divided into a 500x500 mesh (each element having a 100 m^2 geographical resolution). Each of the 250,000-mesh elements is programmed to contain the objective function of equation 2, and the values are stored in the form of a 500x500 matrix (C_{loc}), as shown in *Figure 3*. The existence of minimized cost locations is examined in this simulation area, for the location-dependent costs $C_{loc}(x)$

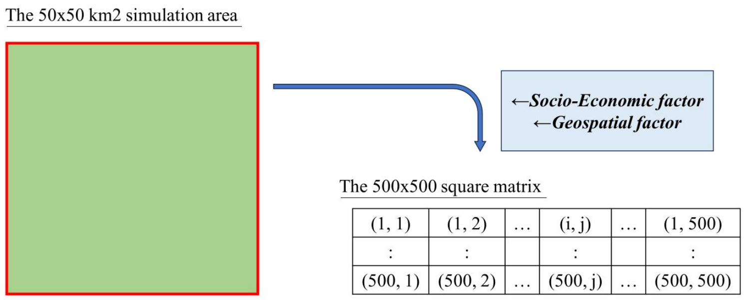


Figure 3. The values are stored in the form of a 500x500 matrix for each cost function.

The total cost function for installing a GES plant may be written as in equation 1:

$$C_{tot}(x) = C_{loc}(x) + C_{non-loc} \quad (1)$$

where C_{tot} includes the total installation costs, C_{loc} are the location-dependent costs while $C_{non\text{-}loc}$ are the costs that are not spatially variable in a limited geography, and x represents a spatial influencing variable. Thus, the total costs are ultimately spatially dependent because of $C_{loc}(x)$. MUFSP modelling involves GIS interface and statistical socio-economics to determine the location-dependent costs $C_{loc}(x)$ for the suburban, mountainous P-GES plant installation. Equation 2 below represents the objective function of the MUFSP model, with the focus on land, transmission, supply chain, and excavation costs, which are all spatial in nature, due to socio-economic and technical factors.

$$C_{loc}(x) = C_{trans}(x) + C_{land}(x) + C_{sc}(x) + C_{exc}(x) \quad (2)$$

where C_{trans} is the transmission cost, C_{land} is the land cost, Csc is the supply chain cost, and C_{exc} represents the excavation cost at the suburban location. Each of the location-dependent cost functions are constructed based on relevant geospatial socio-economic parameters (x). Using 3D simulation and GIS, the MUFSP model empirically determines each of the costs at every 500x500 location, within the limited suburban boundary. The modelling problem is defined to identify which of the spatial factors (x) can minimize the total location-dependent costs $C_{loc}(x)$.

2.3.1. The Transmission Cost Function (Ctrans)

The transmission cost function is composed of the various costs that are needed for joining a power supply source to the substation, which includes conductor material, labor, grid upgradation and land-use costs as well as taxes associated with the costs. According to a report by the Ministry of Land, Infrastructure, Transport and Tourism, the cost of constructing 1 km of 66 kV transmission line in Japan is generally 35 million yen (Kyushu Electric Power Company, 2023). Equation 3 is the transmission line cost function for each element of the matrix (C_{loc}).

$$C_{trans}(x) = c_{ckt-km} \cdot L_{min} \tag{3}$$

where $c_{ckt\text{-}km}$ is the cost of transmission per km of a circuit (JPY/km), and L_{min} is the horizontal distance in km to the nearest substation from the mesh element.

Additionally, the peak-capacity of the GES installation, centered at each point of simulation area, will be influenced by the voltage rating and properties of the transmission line. Aluminum Cable Steel Reinforced (ACSR) conductors are considered for the 66 kV transmission lines. The resistances and the length of transmission line are used to calculate the peak-capacity in Equation 4 at each mesh element for a given transmission line voltage.

$$P_{peak}(x) = \frac{V^2}{2(R \cdot L_{min}(x))} \tag{4}$$

where P_{peak} is peak capacity of the GES plant at each element of the mesh (MW), V is the maximum continuous operable voltage of transmission line (66 kV), and R is the resistance per km of the 66kV line (0.262 Ω/km[1]). Thus, the capacity of the GES plant is determined by the parameters and limitations of the transmission line, making the capacity endogenous in the model.

2.3.2. The Land Cost Function (Cland)

The land cost of the MUFSP model is guided by the principle of Hedonic pricing, which is an Ordinary Least Squares (OLS) regression model for determining property/land prices. Several studies have established the hedonic method to estimate the land costs in urban and suburban areas, as a function of distance from the CBD of a city along with other socio-economic predictors of land costs (Basu et al., 2021; Kain and Quigley, 1970; Ottensmann et al., 2008; Mondal et al., 2018). A land value calculation method for metropolitan suburbs is based on distances from CBD is presented in (Basu et al., 2021; Ottensmann et al., 2008; Mondal et al., 2018), where CBD distance was the most sensitive parameter for spatial land-cost distribution. Equation 5 below represents the basic structure of the hedonic land cost function.

$$ln(C_{land}) = \left(\beta_0 + \sum_{i=1}^{n} \beta_i X_i + \varepsilon_0\right) \tag{5}$$

where C_{land} is a vector consisting of 934 samples of land prices, corresponding to public notice of land prices in all areas of Fukuoka Prefecture integrated into GIS interface (Google Earth on web). The β_0 is the intercept, the β_i correspond to regression coefficients for X_i respectively, and ε_0 is the standard error for regression. X_i is the radial distance from the CBD of Fukuoka city.

The results of the hedonic regression model are tested with the Analysis of Variance (ANOVA) regression interface and displayed in *Table 4*. The 2nd CBD in the Table is the center of Kurume city in Fukuoka prefecture, which is the populated city near the area. Two CBDs are considered here as opposed to that of Kolkata city in (Basu et al., 2021; Mondal et al., 2018), since the land costs would be affected by two population zones. LDC is the distribution center of the GES construction materials, which is hypothesized to affect the land cost in mountainous regions as well.

In Table 4, it is seen that all the distance factors are statistically significant, with distance from CBD 1 and LDC being extremely sensitive for land cost estimations in the suburban regions. The distance from CBD 2 has a very

[1] Transmission Cables in Japan: http://www.hst-cable.co.jp/products/pdf/cableg3_2.pdf. (Dec 15, 2023)

minor impact on land cost estimations in the simulation area, and thus will not be considered in the model or discussions.

Table 4. The Hedonic Land cost function result.

Variables	Reg. Coefficient	Standard Error	P-Value
Intercept	12.392	0.0921	0.0000
Distance from 1st CBD ($\boldsymbol{X_1}$)	0.108	0.0400	0.0068
Distance from LDC ($\boldsymbol{X_2}$)	-0.136	0.0367	0.0002
Distance from 2nd CBD ($\boldsymbol{X_3}$)	-0.00128	0.0056	0.0819
R-Square: 0.88			

2.3.3. The Supply Chain Cost Function (Csc)

For the purposes of modelling, it is firstly assumed that the GES plant modules, power houses, pump/turbines, containers, and other structures are produced domestically in Japan and transported from manufacturing plants near the simulation area, YAMAU HOLDING CO., LYD., which is a company that manufactures a variety of concrete block products in the Kyushu area, is considered as the Local Distribution Center (LDC) (Basu et al., 2021).

Difference between transportation to the plains and to the mountains is also took into consideration. Most of the target area in Fukuoka Prefecture is mountainous as seen in *Figure 2*. It is assumed that in order to build P-GES utility-scale projects in a mountainous area, transportation roads must be built to transport materials to each simulation point. The plains have existing road infrastructure, and no road construction is assumed for these. Equation 6 takes these factors into account. It represents the process of first transporting the materials from the factory to the nearest flat point of each simulation point, and then transporting the materials from there to the mountainous area while maintaining the roads.

The area within 3 km of the flat point is considered flatland as well, and new-road maintenance costs are not added. The k-nearest neighbor method of MATLAB is used to find the nearest neighbor flat points. A factor of 2.05 is assumed to convert the horizontal distances to road distances. This is an average of the ratio of the road distance to the horizontal distance for the four sides and two diagonals of the 50x50 km^2 target area, using Google Maps.

$$C_{sc}(x) = P_{peak} \cdot F_L \cdot \left[c_{ft-km} \cdot (D_{manu} + D_{msc})\right] + c_{road-km} \cdot D_{msc} \quad (6)$$

where Csc is the total supply chain cost (JPY) at each point of simulation area according to peak-capacity P_{peak}, F_L (ton/MW) is the load of material to be transported, D_{manu} is the distance in km from the manufacturing plant, and D_{msc} is the distance from the nearest flat points to a simulation area point, where the GES plant site will be centered. The values of each coefficient are shown in *Table 5*. This equation represents a first major methodological contribution of this study for GES geospatial cost optimization analysis.

Table 5. Assumptions for the supply chain cost function.

Parameter	Content	Value
$\boldsymbol{F_L}$	Freight load (ton/MW)	11,536
$\boldsymbol{c_{ft-km}}$	Unit cost (JPY/km-t) for transportation by trucks	15.95[2]
$\boldsymbol{c_{road-km}}$	Unit cost (JPY/km) for new road construction	85,000,000[3]

Table 6. Unit cost of Excavation.

Function	Parameter	Variable

[2] Ministry of Land, Infrastructure, Transport and Tourism: Standard Freight Rates for General Cargo Trucking Business
[3] Ministry of Land, Infrastructure, Transport and Tourism: 3. Estimation Methodology for Each Renewable Energy Type

$\boldsymbol{Cexc}$ (JPY/m3)	In flatland area	1,882[4]
	In mountainous area	1,441[5]

2.3.4. The Excavation Cost Function (Cexc)

Installation of the GES plant requires 22,410 m[3] of excavation per MW. Excavation costs vary for each simulation point due to geographic factors such as geology and social factors such as building codes. In this study, two types of excavation costs in JPY/m[3] are used to differentiate between excavation costs in mountainous and flat areas. For excavation costs in flatlands, data from the Metropolitan Area Outer Underground Discharge Channel (MAOUDC) is used, and for mountainous areas, data from tunnel construction in Nagano Prefecture, which is famous for its mountain area, is cited. Building codes in mountains are more or less uniform in Japan, and hence, Nagano can be assumed instead of Fukuoka The values are shown in *Table 6*. Equation 7 shows the excavation cost function:

$$C_{exc}(x) = c_{exc} \cdot V_{exc} \tag{7}$$

where c_{exc} is the unit excavation cost in the two of *Table 6 and* V_{exc} is the volume of the excavation. This equation represents a second major methodological contribution of this study for GES geospatial cost optimization analysis.

3. Results

3.1. Variation of Cost Functions in the Simulation Area

The graph in *Figure 4* illustrates the variations of cost functions within the 2500 km^2 simulation area in the MUFSP model for GES. This variation represents the constant peak capacity of 1 MW GES storage across all 500x500 points in the simulation area, operating at a transmission line voltage of 66 kV. The 3D visualization's perspective originates from the southwest of *Figure 2*.

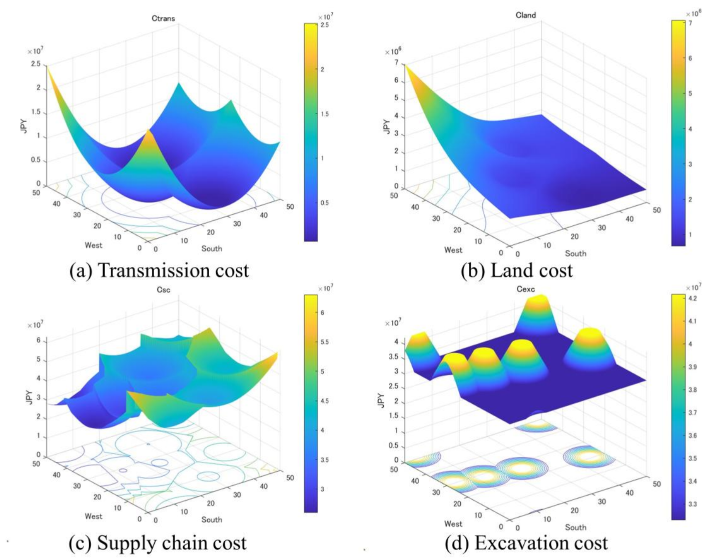


Figure 4. Variation of (a) transmission (107), (b) land (106), (c) supply chain (107), (d) excavation (107) costs across the 500x500 simulation area for a 1 MW GES plant with 66 kV transmission line.

[4] The Metropolitan Area Outer Underground Discharge Channel: https://www.ktr.mlit.go.jp/ktr_content/content/000053312.pdf
[5] Shiozaka tunnel: https://www.pref.nagano.lg.jp/omachiken/nyusatsu/documents/uchu2tn_keiyaku.pdf

The value of C_{trans}, C_{sc} and C_{exc} have the same order of magnitude while land cost is one order of magnitude lesser. With respect to the transmission line cost, it is clear from Equation 3 that costs are low near SS and increase in proportion to distance from the SS. The land cost has the smallest impact of the four functions, although closer to the CBD it is higher. This is because GES has a very small land area requirement as opposed to SPV plants. The supply chain cost is the most significant cost factor, and the change of cost at every point is complex. C_{sc} is significant across the area because GES systems require large material mass of 50,720 tons/MW of material. Reducing mass of materials of GES, which uses potential energy as its energy source, is not effective. If actual supply chain costs are to be reduced, it would be better to locate a plant for the GES plant in the vicinity of an SPV plant, where existing infrastructure is already transported. Near the flatland point (FP), transportation of the material is the only cost, but at distances greater than 3 km from the flat points, the cost of building a new road in the mountains is incurred. Therefore, the cost is highest in the southeastern part of the area, which is mountainous and far from the flatland point. The change of the excavation cost is very simple as it takes only two different values. The cost is as large as the supply chain cost in terms of order of magnitude.

3.2. Existence of the optima

The variation of the location-dependent costs $C_{loc}(x)$, across the simulation area of 2,500 km^2, is shown in *Figure 5*. This variation represents the constant peak capacity of 1 MW across all 500x500 points in the simulation area, operating at a transmission line voltage of 66 kV. Optima, FP and SS are shown in the contour on the right figure. The minimum C_{loc} is located in the vicinity of each FP and SS, and the lowest cost point denoted as optima, is in vicinity of FP2, FP3 and SS1 of *Figure 2*.

Explorative understanding of Figure 5 is required to uncover the cumulative $C_{loc}(x)$ variations in the simulation area. In the south-west part of the simulation area, the region is closer to the CBD 1, where we see that the total cost becomes significantly higher. Due to C_{sc} and C_{trans} being of the same order of magnitude, overlapping of *Figures 4a and 4c* could result in *Figure 5* for the rest of the area unaffected by elevated land cost due to proximity to CBD 1, with minor variations added by C_{exc}. One of the most significant outcomes is that transmission and supply chain are the dominating cost factors. This can be proved by the fact that C_{exc} is lower in the mountainous suburban region, yet the optimal cost point is near the FP. In fact, in *Figure 5*, the lower costs are all in the FP vicinities.

Thus, the dominating geospatial factor is supply chain and transmission costs for GES plants, whereas for SPV plants it is land and transmission costs as shown in (Basu et al., 2021). From a policy aspect, this can be addressed that the most optimal SPV+GES deployment would be to construct GES plants near SPV plants to reduce higher supply chain costs.

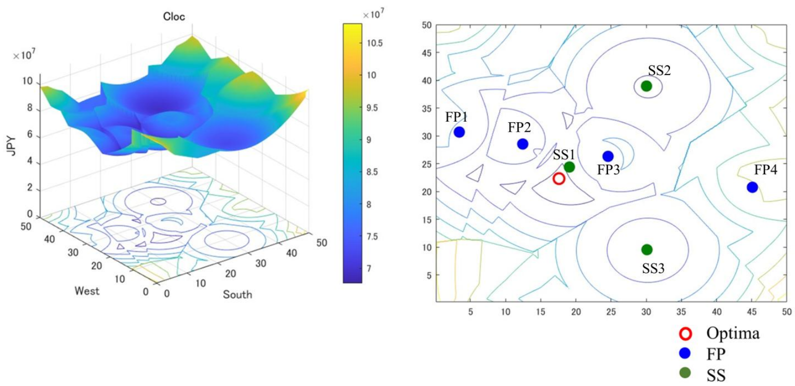


Figure 5. The total cost variation in the 500x500 simulation area and optimal location point.

4. Discussion of Geospatial Cost Optimization for GES

4.1. Discussion of Factors for Minima

One advantage of the results of the MUFSP model is that all costs are expressed as distance functions, specifically distances of D_{CBD} and D_{LDC}. (Basu et al., 2021), (McDonald and McMillen, 1990) and (Kain and Quigley, 1970) demonstrated that in major urban hubs, manufacturing distribution centers and CBDs are geographically quite close. In suburban renewable energy planning, CBD and LDC can hence, be assumed to be the same point since the distance from CBD to LDC is negligible compared to the distance of remote suburban areas from CBD. As shown in Figure 2, CBD and LDC are quite close to each other even in the case of Fukuoka city. In this light two cost factor relations are quite important to be discussed.

C_{land} and C_{trans} are inversely related as a function of D_{CBD}. While C_{land} decreases with increasing distance from D_{CBD}, C_{trans} increases with distance from SS. (Basu et al., 2021) showed that the optimal cost point for suburban SPV installations is located on a straight line that is subtended from the CBD to the SS. In order to examine the impact of these two factors on $C_{loc}(x)$ of suburban GES installations, one substation (SS1) out of the three is selected from Figure 2. *Figure 6* shows the C_{trans} and C_{land} variations limited to the substation closest to the CBD (SS1). C_{land} decreases exponentially with increasing CBD distance, while C_{trans} linearly increases with increasing distance from SS1, which behaves exactly how (Basu et al., 2021) demonstrated the spatial modelling for SPV plants. This confirms that the spatial modeling defined in (Basu et al., 2021) is applicable for SPV and GES systems in suburban areas. However, due to the land footprint of GES being minimal, the variation of the minima is quite insignificant for consideration of a specific point, and the mountainous terrain requires further examination.

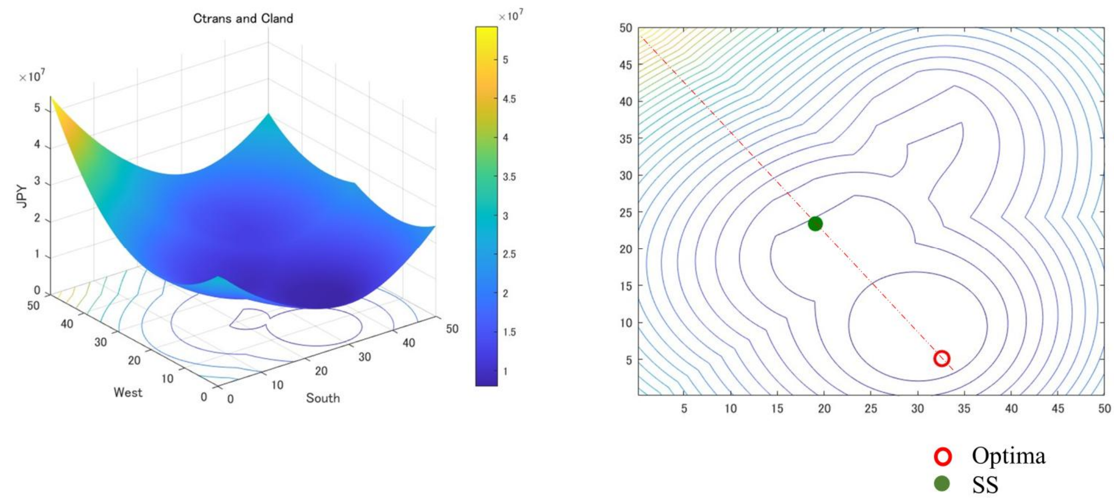


Figure 6. Relationship between Ctrans and Cland, when SS is limited to one.

C_{land} and C_{sc} are inversely related as a function of D_{CBD}. While C_{land} decreases with increasing distance from D_{CBD}, C_{sc} increases with distance from CBD (LDC). The closest of the flat points to the CBD is FP1, and the cumulative effect of just C_{sc} and C_{land}, considering only FP1, is shown in *Figure 7*. In Figure 7 the optimal cost point is more defined than that of Figure 6, due to a higher density of contours around the optima. With the optima being very close to the FP, it can be inferenced that the contribution of C_{land} is much less than the contribution of C_{sc} for determining the total $C_{loc}(x)$. From figures 6 and 7, it can be concluded that the supply chain cost and transmission cost are the primary factors to determine the existence of the minimum location-dependent cost point for GES construction in suburban mountainous terrain.

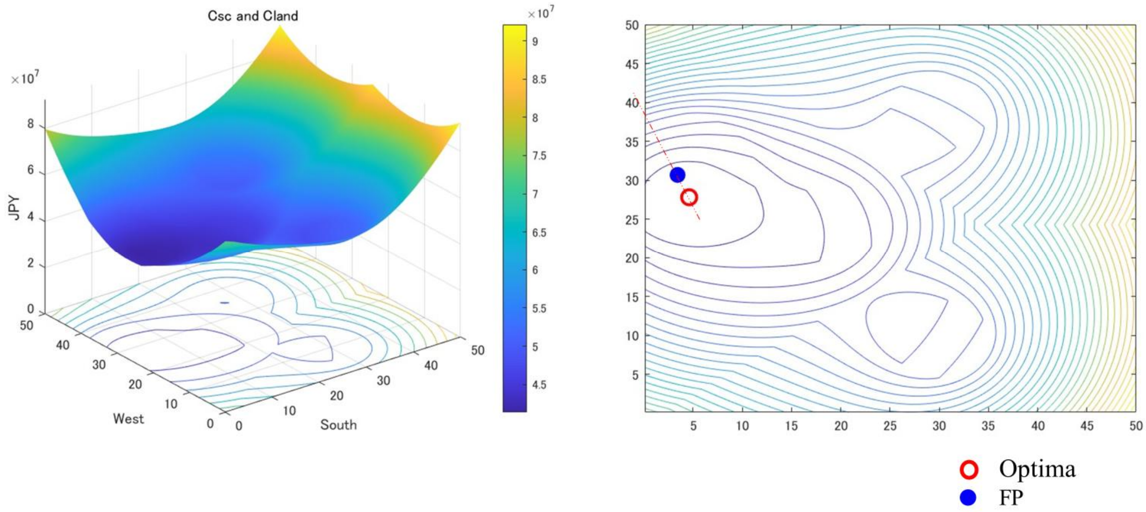


Figure 7. Relationship between Csc and Cland, when FP is limited to one.

4.2. The MUFSP Optimization Principle for GES with Csc and Ctrans

This section discusses the major finding with regards to the geometry of the optimal cost location for GES installations in a suburban mountainous terrain. Having concluded that transmission and supply chain costs are the key factors, a closer examination of *Figure 5* is performed. It is observed that the optimal cost location lies on the line connecting CBD and FP2 (say line 1). Thereafter, the orthogonal to the line connecting the CBD with SS1 (say line 2) intersects with line 1. This point of intersection is where the optima lies, and the intersection happens at right angles. *Figure 8* shows the representative version of this concept.

This geometrical approximation has major implications for suburban renewable energy planning and storage deployments in any terrain (since mountainous terrain is revealed to be non-optimal locations). While (Basu et al., 2021) revealed that SPV geolocation in a suburban region is one-dimensional from a geometric standpoint, this study shows that suburban GES geolocation involves planar (or two-dimensional) geometry. The CBD is considered in this study as a focal point of origin for land and supply chain cost functions. However, from an urban planner's viewpoint the CBD can be replaced with any point of economic rationality, as long as the economic focal point is within the city and the GES plant consideration is in a suburban region. This urban planner can readily ignore mountainous regions, even though excavation costs can be cheaper. The economic focal point, a substation and a portion of flat-land in between mountainous terrain are the only factors that needs to be considered. This adds to the existing literature of (Amjad and Shah, 2020) and (Ottensmann et al., 2008), where economic focal points are not only related to real-estate urban planning, but also suburban renewable energy planning.

While this study attempted to apply the MUFSP model for GES installations as standalone, future research needs to consider a hybrid SPV-GES deployment, incorporating factors such as LCOE and Levelized Cost of Storage (LCOS). This geometrical approximation can also be validated in future studies for other mountainous suburban terrains in Japan and globally. A major limitation of this study is that it is limited to suburban cases only, and therefore another future direction of research could tackle non-suburban regions.

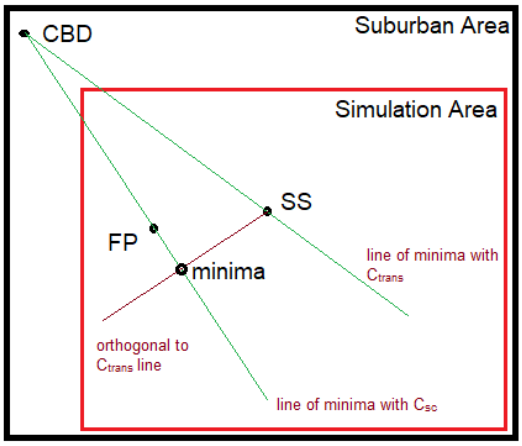


Figure 8. The theoretical existence of a minimum point of location-dependent costs for constructing a GES system in a suburban mountainous geography.

5. Conclusion

Using a multi-factor spatial parameterization (MUFSP) model, this study explored the mechanism of the existence of minima based on the spatially varying costs for constructing Gravity Energy Storage (GES) systems. Transmission and supply chain costs were the key factors for determining the existence of the point of optimized location dependent costs. The socioeconomic variables that plays a part in geolocating an optimal cost point for a suburban GES installation are distance of plains from central business district (CBD) of a city, location of a substation in the suburban region and distance of the flat zone from the substation. The major findings of the study are as follows, with regards to suburban socioeconomics of GES plants:

- The GES system is not feasible to construct in a mountainous land.
- The CBD plays a key role in determining the optimal cost location.
- The optima lie on the line connecting the CBD with a flat zone.
- The optima lie on the orthogonal of the line connecting the CBD and substation.
- The optima lie at the intersection of the lines of points (c) and (d) and such intersection will happen at right angles.

This study provides a geometrical solution for geolocating GES systems in suburban mountainous regions and would be very useful for energy planners and academicians in understanding the interactions of socioeconomics and energy storage development.

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Conflict of interest

All the authors claim that the manuscript is completely original. The authors also declare no conflict of interest.

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