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Waterfront redevelopment methodology for optimal energy demand and solar energy production: Shinagawa river side in Tokyo

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ABSTRACT

Designing waterfront redevelopment generally focuses on amenity, hobby and beauty, resulting in various types of building and block shapes. However, increasing climate change impacts necessitates these buildings to be sustainable, resilient, and zero CO_2 emissions. Here, we investigate how building morphology affects energy consumption and PV generation in the context of Shinagawa, Tokyo at waterfront for possible redevelopments. For our analyses, we utilized 'Rhinoceros 3D' and its plugin 'Grasshopper', which is a commonly used architecture program applicable to building energy analysis. It is found that among considered scenarios high-rise buildings had the least energy demand and CO_2 emission, emphasizing that building morphology is one of the critical factors, leading to low CO_2 emission buildings.

Keywords: Energy demand, photovoltaics, waterfront, urban context, CO_2 emission, building

NONMENCLATURE

Abbreviations	
PV	Photovoltaics
FAR	Floor Area Ratio
BCR	Building Coverage ratio
GWh	Gigawatt-hour
HDD	Heating District Demand
CDD	Cooling District Demand
3D	3 Dimensions

1. INTRODUCTION

70% of global energy consumption and greenhouse gas emissions originate from cities, but also cities are the center of economic competitiveness and innovation. Smart city is one of the solutions to urban sustainability, responding to recent urban challenges such as rapid expansion of urban population [1]. To achieve a sustainable smart city, it is increasingly clear that energy consumption must be reduced in an early planning phase of buildings and self-generating energy such as by roof-top PV must be maximized.

For this purpose, Natanian [2] analyzed various zero energy building types between courtyard, slab and high-rise, and courtyard was found to be the best option. Zhang [3] compared solar potentials of different block types, and found that depending on block types solar energy harvesting amount can increase by 200% maintaining other variables constant except morphology.

Evolving concept of waterfront in urban environments has changed from the past from a living place to a place for amenity, hobby, or open space for resting [4]. Currently, many redevelopments of river or coastal sides are happening around the world with benefits including;

• To increase economic values.
• To improve environmental conditions.
• Better services of transport and social service.

• To provide economic investment opportunities on degraded area.

In this study, we chose Shinagawa, Tokyo as a test site. Shinagara will become a terminal station for Chuo-Shinkansen, a super bullet train that connects between Tokyo and Osaka in 67 minutes, which likely induces large changes in its urban structure. As Shinagawa is located near large river and harbor, the urban redevelopments including its waterfront should integrate renewable energy such as tidal power, hydroelectric power, and solar power toward sustainable urban planning. This study is one of the first contributions for Shinagawa's urban planning.

2. MATERIAL AND METHODS

2.1 Building energy analysis tools

ArcGIS, a GIS program, was utilized to create GIS database and mapping, and buildings are extended into 3D by Rhinoceros 3D [5]. Rhinoceros 3D and its plugin, Grasshopper, provide various analysis tools for building designers, allowing them to work with validated energy, daylighting, and shading programs such as EnergyPlus, Radiance, and Daysim [6]. EnergyPlus is a program for building energy analysis, integrated with Grasshopper as a plugin. We used these programs for energy consumption estimates for buildings [7]. It considers building usage patterns, materials of wall, windows and roof-tops, weather, and urban context. Accuracy of EnergyPlus has been validated. According to a study by Sao Paulo university, 80% of estimates are within ± 13% of measured data [8].

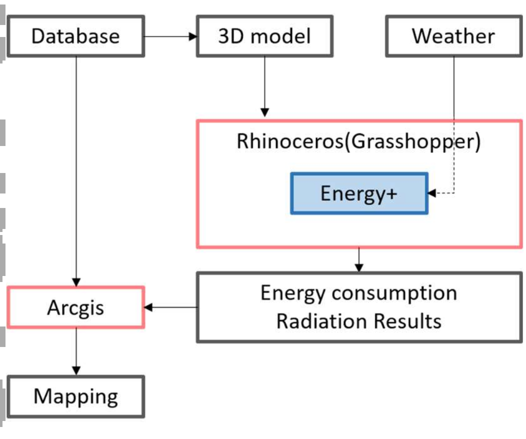


Fig 1 Sequence of energy demand analysis using ArcGIS, Rhinocerous, and Grasshopper.

The analyses between the programs are smoothly linked (Fig. 1). 2D map data in ArcGIS can be extended into 3D by Rhinoceros 3D. Then, Grasshopper can analyze building energy consumption and PV potential, etc. within the program. Although importing results to ArcGIS need some conversion from Excel, the methodology has been established and can be applied to a large urban area.

2.2 Shinagawa

Shinagawa is in southern part of Tokyo, Japan. There is harbor in the eastside, and canals go through middle of the central district. Currently, the harbor and canals are not fully utilized considering their potentials. The Shinagawa station is one of the largest stations in Tokyo with annual 380 thousand users [9]. Land use of Shinagawa is divided by the central Shinagawa station. West side is mainly for residential area, and east side is office area. Central area is primarily commercial area for passengers of the station.

Fig 2 Map of the target area surrounded by red line. Office buildings are blue, commercial buildings are pink, educational buildings are yellow.

2.3. Theory and scenarios

In this study, we consider three-types of building morphology in comparison to existing buildings on the site (Fig 2 and 3). To make the comparison more effective, we used floor area ratio (FAR) as a control variable.

$$FAR = \frac{Total\ floor\ area}{site\ area} \tag{a}$$

Generally, when developers consider projects, they maximize benefit by having large floor area with maximum possible height in urban environments. In this study, we set FAR as 400% as existing buildings has 400% of FAR with building heights from 6m to 96m (Fig 3).

In order to make different footprint scenarios, we set building coverage ratio (BCR) as variables.

$$BCR = \frac{building\ area}{site\ area} \tag{b}$$

We set building width in a range from 15m to 50m as general building width in the residential area in this site is around 15 m, and office building width is around 35 m. Different building types are considered with scenario 1: low-rise buildings, scenario 2: high-rise buildings, and scenario 3: buildings with a central corridor (Fig. 3 and Table 1). Low-rise buildings in the scenario 1 gives pedestrian continuity. Therefore, they have advantages for small shops. High-rise buildings in the scenario 2 are more independent to other buildings, which tends to foster unique identity to represent one company or residential apartment. Buildings with the center corridor in the scenario 3 have common open space between buildings. This open space offers spaces for many community activities to users, shops, and offices. We assume that all the building is used as offices for the following analyses. The analyses were conducted hourly with weather information in 2018.

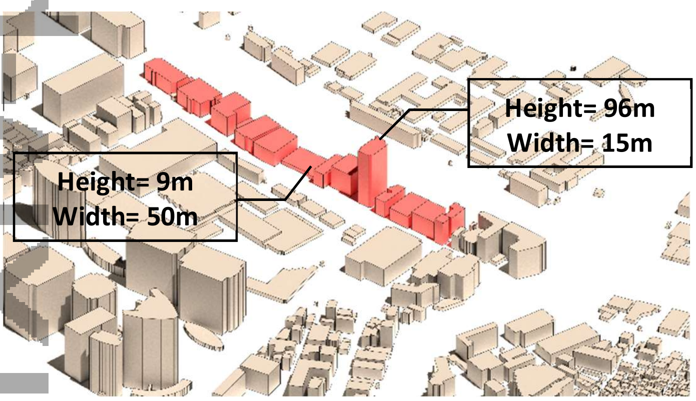
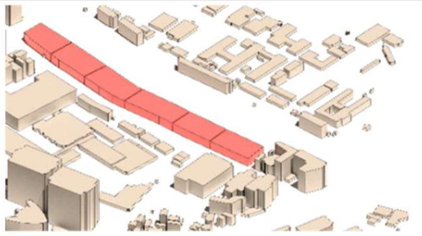
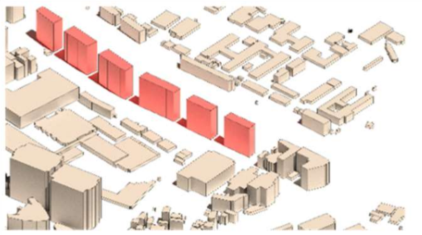
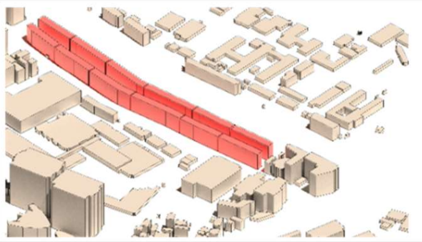


Fig 3 3D model of the target area in red. The lowest building height is 6m, and the heighest building height is 75m. The widest building width is 50m, and the narrowest building width is 15m.

Table 1 Scenarios 1-3. Scenario 1= low-rise, Scenario 2= high-rise, Scenario 3= Center corrior

Scenario 1	
Building height= 6m	
Scenario 2	
Building height= 96m	
Scenario 3	
Building height= 60m	

3. RESULTS FOR ENERGY DEMANDS AND PV GENERATION

Although FARs are set constant for all the scenarios, annual energy demands are variable owing to energy balance of buildings and shading from other buildings. Existing buildings, Scenario 1 and 3 have similar demands (Table 2). On the other hand, energy demand of Scenario 2 is smaller (63% of the existing buildings) than other scenarios due to smaller surface area of the buildings (Table 1). Due to the largest and smallest rooftop area, Scenario 1 and 2 has the biggest and smallest annual PV generations, respectively (Table 2).

PV panels can produce enough energy for annual energy consumption for buildings (energy sufficiency) for all the Scenarios except Scenario 2 (Table 2). However, if we consider hourly demand-supply balance, PV panels can supply only 35-55% of demands (self-sufficiency), indicating the need for energy storage. We also noted that without storage a large amount of PV generated electricity needs to be exported or curtailed as self-consumption is low (31-44%) (Table 2).

Heating is the largest demand component of buildings in all the scenarios. The order of other demand components are variable depending on the shapes of the buildings (Table 2). Fig 4 shows monthly energy demands and PV generation for scenarios. In winter, heating demands produce the largest peak in a year. Summer cooling also produce a peak, but it is smaller than the peak in winter. PV generation is high from spring to summer. The seasonal variations of demand and PV generation are opposite, which makes difficult renewable energy 100%. In the case of Scenario 1, PV generation is larger than demand for most of the month, indicating building shapes are important for the renewable 100% (Fig. 4).

Table 2 Annual energy demand and PV generation of existing building and each scenario. Self-sufficiency is calculated as [PV to load (GWh/y)]/ total energy demand (GWh/y) × 100 [10]. Self-consumption is calculated as [PV to load(GWh/y)]/ total PV generation (GWh/y) [10].

	Existing Buildings	Scenario 1(low-rise)	Scenario 2(high-rise)	Scenario 3(center corridor)
Building Height(m)	6~102(m)	6(m)	96(m)	60(m)
Number of Buildings	14	6	6	12
BCR	54%	87%	28%	53%
FAR	400%	400%	400%	400%
Landuse	Office	Office	Office	Office
PV Generation	3.68(GWh)	5.91(GWh)	1.88(GWh)	3.57(GWh)
Energy Sufficiency	102%	178%	82%	105%
Self-sufficiency	45%	55%	35%	41%
Self-consumption	44%	31%	42%	39%
Total Energy Demand(Year)	3.61(GWh)	3.31(GWh)	2.29(GWh)	3.41(GWh)
Lighting Demand	0.63 (GWh)	1.13(GWh)	0.35(GWh)	0.67(GWh)
Cooling Demand	0.41 (GWh)	0.52 (GWh)	0.53(GWh)	0.70(GWh)
Heating Demand	2.06(GWh)	1.13(GWh)	1.46(GWh)	0.73(GWh)
Other Demand	0.87 (GWh)	0.32(GWh)	0.45(GWh)	0.11(GWh)
CO2 Emission	1,262 (ton)	1,137 (ton)	828 (ton)	1,205 (ton)

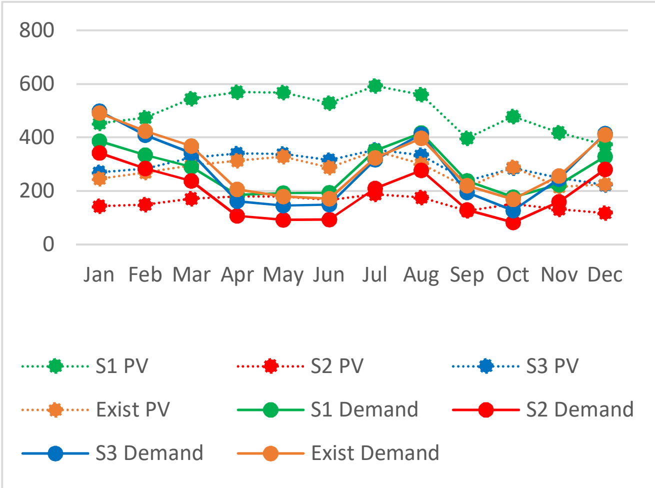


Fig 4 Monthly energy demands and PV generation of each scenario (GWh).

CO_2 emissions from imported grid electricity can be estimated by the following equation (Fig 5) [11].

$$\text{CO2emission (kg)} = 0.455 * (\text{imported electricity from grid; kWh}) \qquad (c)$$

where 0.455 ($kgCO_2/kWh$) is an emission coefficient for TEPCO in 2018.

Scenario 2 with high-rise buildings has the least emission because energy demands are the smallest. Other scenarios have higher PV generations, but they cannot offset larger energy demand that created by building shapes. This result emphasizes the fact that variable energy demands owing to variable building shapes cannot be offset by *in-situ* PV generation. Therefore, consideration on CO_2 emission during building planning is critical.

Fig. 5 shows monthly CO_2 emissions for scenarios. Emissions in winter cannot be reduced by PV generation because of the smaller insolation in winter and large heating demands. We also note that if heating and cooling efficiency or building insulation are improved, other scenarios can be better option as the differences in heating and cooling between scenarios dominate the difference in CO_2 emissions (Fig 5).

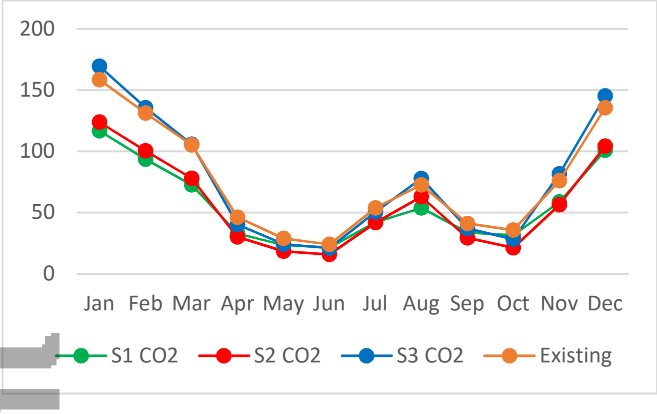


Fig 5 Monthly CO_2 emission for Scenarios (ton).

4. DISCUSSION AND CONCLUSION

We analyzed energy demand and PV generation of Shinagwa waterfront in Tokyo. To find an optimal design in terms of energy demand and CO_2 emission, we made three scenarios with low-rise, high-rise buildings, and buildings with a central corridor in addition to existing buildings (base scenario).

ArcGIS is used to map building information, and Rhinoceros 3D and its plugin, Grasshopper are used to model PV potentials and building energy balances in 3D to estimate energy demands.

Results show that each scenario has different advantages and disadvantages. Existing buildings have more buildings with smaller sizes than the scenarios, resulting in the highest energy demands. Scenario 1 (low-rise buildings) has higher energy demand but also the highest PV generation. Scenario 2 (high-rise buildings) consumes the least energy, but due to the small roof-top area PV generation is the lowest. Scenario 3 of the center corridor type have larger energy demand with medium PV generation. As a result, Scenario 2 has the smallest CO_2 emission, emphasizing that the size of demand is more critical factor for CO_2 emission than PV generation in the scenarios we considered.

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