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Defining density and land uses under energy performance targets at the early stage of urban planning processes

Shanshan Hsieh[a,b,c,*,†], Nils Schüler[c,†], Zhongming Shi[a,b], Jimeno A. Fonseca[a,b], François Maréchal[a,c], Arno Schlueter[a,b]

[a]Future Cities Laboratory, Singapore-ETH Centre, 1 Create Way, Singapore 13892, Singapore

[b]Architecture and Building Systems, ETH Zurich, John-von-Neumann-Weg 9, Zurich 8093, Switzerland

[c]Industrial Process and Energy Systems Engineering Group, Ecole Polytechnique Fédérale de Lausanne, Sion 1950, Switzerland

Abstract

The energy demand of cities is highly influenced by urban planning parameters such as urban density and land use. These parameters are mostly determined during early stages of planning. However, the relationships between urban planning parameters and energy systems of districts are rarely incorporated. This paper aims to identify trade-offs between urban density, land use and share of renewable energy sources (RES). For this, we used a Mixed Integer Linear Programming formulation. The model is applied to a real case study of urban planning in Singapore. The results show that when the required share of RES increases from 20% to 70%, the maximum achievable density (floor area ratio) decreases from 32.2 to 2.9 with purely residential land use. While maximizing the self-consumption of electricity produced by PV panels, the resulting land uses are more diverse. These results provide urban planners with constraints from the perspective of energy performance of a district.

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Keywords: urban planning; urban energy system; land use; self consumption; optimization; MILP; district cooling network

* Corresponding author.
† These authors contributed equally to this work.
E-mail address: hsieh@arch.ethz.ch

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1. Introduction

The immediate importance of environmental targets and urbanization pose serious challenges for designing future cities. Energy system designers need to set limitations to attend a growing energy demand while addressing aspects of sustainability [1]. In this context, the renewable energy potential and the efficiency of energy systems may define the maximum energy that could be supplied to urban areas.

Extensive research has been focusing on establishing the links between urban planning and design parameters and building energy demand reduction at the district scale [2]–[4]. The urban form not only influences the energy demand of buildings but also the performance of energy supply systems. For instance, tall buildings could increase shading on other building surfaces for solar energy harnessing. Furthermore, the photovoltaic (PV) electricity production determines the amount of renewable energy supplied to districts in cities, and this would constrain the population density and distribution of buildings if certain environmental targets are imposed. Some studies have tested such constraints on land uses [5] and density [6] imposed by urban energy supply systems. In a densely populated city like Singapore, space availability is one of the key drivers for conversion technology selection. Rooftop areas are limited due cooling tower installations that could otherwise be used to install solar panels. In this context, district cooling with centralized cooling plants has the advantage of increasing chiller conversion efficiencies and rooftop areas for solar panels. In the Master Plan of Singapore, land uses and urban density (floor area ratio (FAR)), are the two main parameters that could restrict the performance of energy systems.

This paper identifies the relationship between urban planning parameters and energy and environmental targets. This entails setting up thresholds of urban density and land use that attain a maximum penetration of renewable energy sources (RES). Section 2.1 describes the case study and inputs of the MILP formulation. Section 2.2 describes the MILP formulation. Section 3 compares the different optimization objectives and metrics. Section 4 concludes with highlights, shortcomings, and potential future work.

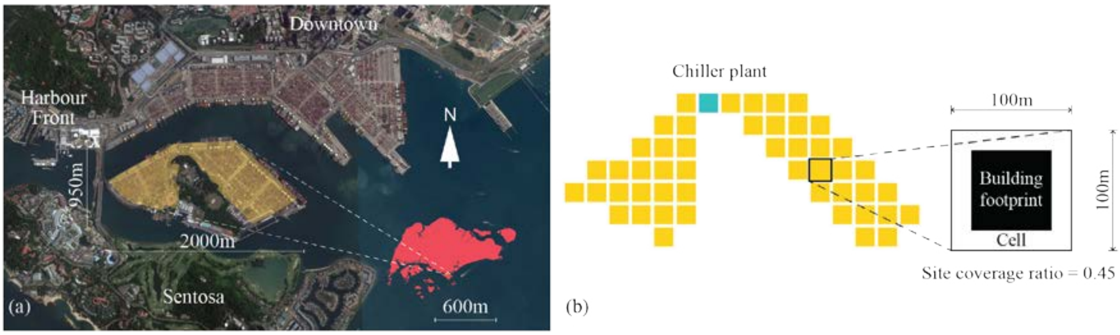

Fig. 1 (a) Real map of the case study site and (b) abstracted map with layout of the cells and the building footprint (podium pattern) in each cell.

2. Material and method

2.1 Description of case study

The authority of Singapore is planning to relocate the Tanjong Pagar container terminal (Fig. 1a) leaving a greenfield of 200 hectares for development. The site is located right off the gateway of the central business district. The project will become part of the major access point to the sea from the center of the city. In this study, a part of the buildable area of the site was divided into 49 homogenous cells (squares) with a size of 100 meters by 100 meters (Fig. 1b). Based on a survey to 602 blocks in six mixed-use Singapore regional centers, we gave the blocks a podium building pattern, which is referred in Fig. 1b. We further assumed all the blocks in the case study site adopt this building pattern with a site coverage ratio of 0.45. For land uses, we adopted the most common ones of the Singapore Master Plan in this research, which are residential, office, and commercial. Industrial use is less likely to appear on this site, therefore, was not included. The respective hourly energy demand profiles for weekdays and weekend days in Singapore are depicted in Fig. 2 [7]–[10]. Since Singapore is located in the tropics, it is assumed that the space cooling load and the domestic hot water heating load is identical through the year. Currently, the RES share of the national electricity supply of Singapore is almost negligible [11].

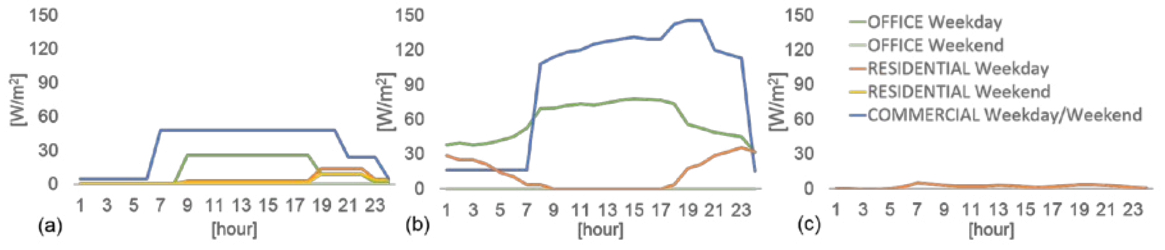

Fig. 2 Daily profiles of (a) electricity consumption for appliances and lighting (b) cooling load (c) domestic hot water (DHW) load depending on day types and occupancy types.

2.2 Optimization model

For this work the MILP model behind URB^{io}, an interactive optimization framework for early-stage urban planning was employed [6,16]. Core decision variables of this model are the number and type of floors and the type, size, and temporal usage of energy conversion technologies per cell. To account for the tropical conditions encountered in the case study, it is extended by the energy conversion systems depicted in Fig. 3.

The cooling load in Singapore comprises a high latent heat ratio (40%). This opens up the opportunity for a more efficient energy supply by using building cooling systems applying the low-exergy concept instead of conventional all-air systems. In these systems, the sensible and latent heat removal processes are respectively performed by radiant panels and condensing cooling coils with ventilation systems. The radiant panels can utilize chilled water at 19°C instead of 8°C, which could be supplied with high-temperature chillers at a better efficiency [12]. The high- and low-temperature chillers can be either installed at individual buildings or at centralized locations at the district level. The first has the drawback that cooling towers are installed on the rooftops, which will limit the available area for PV panels to 60% of the building's footprint [13]. We further assume buildings with centralized cooling can install PV panels on 100% of the roof top area. However, using centralized chillers implies transport losses in the distribution network. The excess electricity produced from the PV panels can be shifted to other time steps by exchanging with the low-voltage grid or on-site storage [14][15]. In this case study, the excess electricity produced from PV is exported to the low-voltage grid.

2.3 Optimization strategy

The research questions stated in section 1 are synthesized to formulate two distinct optimization problems:

1. What is the maximum achievable density under given environmental targets? Specifying the FAR as objective, the ε–constraint method is used via varying minimum RES shares.
2. What are the optimal land use strategies under a given density, environmental, and technological constraints? In addition to achieving the environmental and societal targets of problem 1, the goal is now to identify a combination of land uses which additionally increases the grid stability. This is done by maximizing the self-consumption of electricity produced by PV panels, therefore, less surplus electricity will be exported to the low-voltage grid. The objective function is therefore maximizing the difference between PV electricity production and surplus electricity accumulated over all time steps. Which equals to the maximization of the electricity produced from PV, while minimizing the surplus electricity produced from PV that is shifted to other time steps (PV shift). The ε–constraint method is used to define inequality constraints for FAR and RES shares within the boundaries of these two parameters.

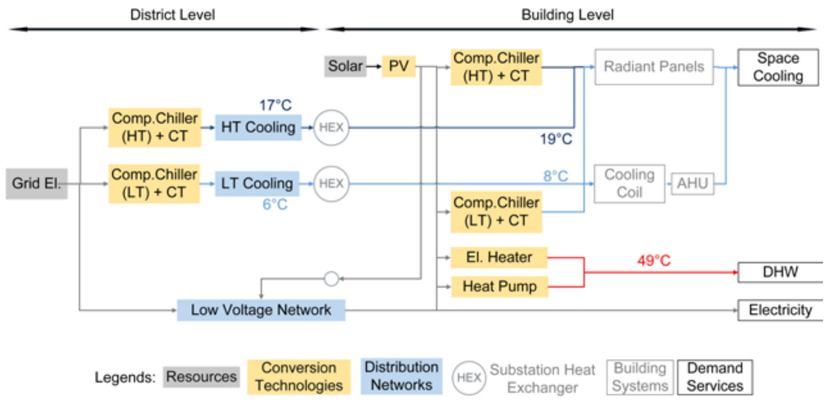

Fig. 3. Energy conversion pathways (HT: High Temperature, LT: Low Temperature, CT: Cooling Tower, HEX: Heat Exchanger, DHW: Domestic Hot Water. The district level chillers at the centralized location are connected to cooling networks with two supply lines.

3. Results

3.1 Maximize FAR

Figure 4a shows the maximum achievable densities with respect to the constraints on RES shares. Since residential floors have the overall lowest energy demand per area, the maximum densities are achieved for purely residential use.

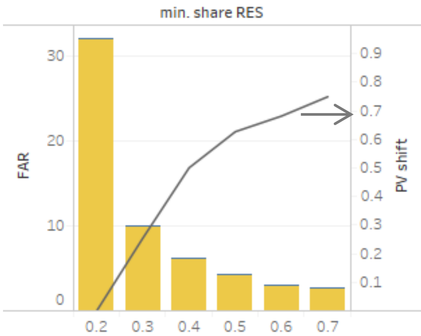

Fig. 4. Maximum achievable densities (bars), and the share of shifted electricity from PV (line) with respect to minimum shares of RES

3.2 Minimize electricity shift

Figure 5 shows the effect of varying constraints on environmental and societal targets on the selection of land use and the share of shifted PV electricity. The histograms are in ascending order of the calculated FARs, which might slightly differ from the minimum FARs. Note that beside electricity produced from PV, the heat from the ambient air used in heat pumps to satisfy hot water demand is also accounted as RES. Furthermore, when the objective function is at zero, i.e. amount of surplus electricity from PV which is shifted, one cannot conclude that the identified land use strategy is the unique solution that minimizes the objective while respecting the given combination of constraints.

Figure 6 displays the electricity consumed by different technologies to supply the energy demand services and the electricity exported, which is the surplus of the PV production that is not instantly required to satisfy local demands.

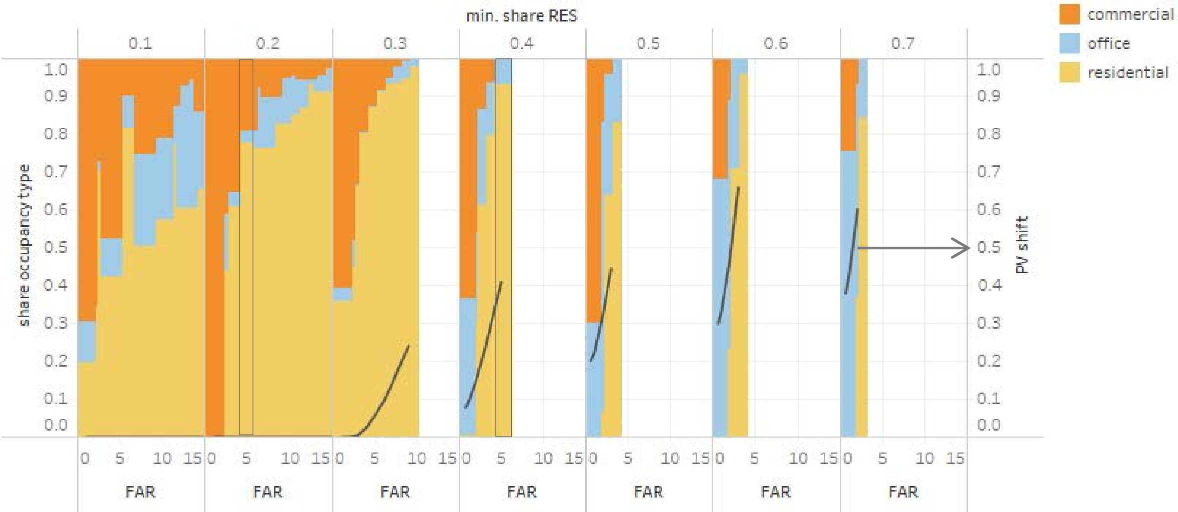

Fig. 5. Land uses and shares of PV shift in dependence on minimum share of RES and minimum FAR (the two outlined scenarios with the same FAR are presented in Fig. 6 with more detail for comparison).

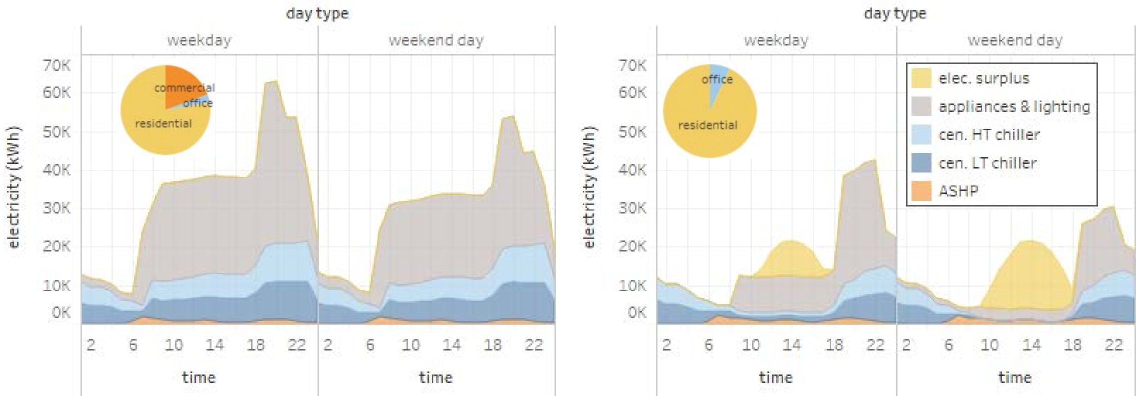

Fig. 6. Electricity consumption profiles and surplus electricity produced from PV that is shifted of the two selected scenarios with minimum shares of RES: (a) 20% (b) 40% for weekday and weekend days.

3.3 Interpretation and comparison

Table 1 lists one selected result for the maximization of FAR and two for the minimization of PV shift. From these and the above figures, one can make several observations: In the first optimization, maximizing the FAR, the maximum achievable FAR decreases from 11.6 to 2.9 as the share of RES constraint increases from 20% to 70%. Meanwhile, the optimal results only contain residential use since the total demand for residential uses is the lowest. Therefore, higher FARs can be obtained in comparison to other land uses (office and commercial). However, the demand profiles of residential use do not coincide with the profile of solar potential availability. Thus a high percentage of electricity generated from PV is shifted to later time-steps (see Fig. 4). When minimizing PV shift in the second optimization, the diversity of land uses increases (see Fig. 5). As the targeted share of RES increases, three trends are observed: Firstly, more efficient energy conversion pathways are chosen to reduce the non-RES usage, for example, the usage of centralized high-temperature chiller increase. Secondly, with the same FAR, land uses with less demand are chosen. Thirdly, when the share of RES constraint is higher than 20%, PV shift is necessary since a fixed portion of the energy demand does not coincide with PV electricity production.

Tab. 1. Comparison of urban, energy and environmental parameters for three selected results.

objective	min. share RES (%)	FAR	share PV shift (%)	share residential (%)	share office (%)	share commercial (%)
max. FAR	40	6.12	50.0	100	0.0	0.0
min. PV shift	20	5	0.0	77.6	3.0	19.4
min. PV shift	40	5	41.0	93.0	7.0	0.0

4. Summary and Conclusion

In this paper, two optimization problems are formulated in order to determine two planning parameters, urban density (i.e., FAR) and land uses, which simultaneously ensure a targeted environmental performance and the primary usage of local resources. Furthermore, the second optimization demonstrates how an ideal mixture of land uses could increase self-consumption of local, renewable energy supply. This paper presented a methodology that gives quantified implications on how to coarsely determine the land uses and density under environmental and energy system constraints. However, the generated results should be regarded as extreme solutions, as only energy system related constraints are considered. Other important factors also include the vision of the site in the whole city, the well-being of the residents, urban vitality, and more. The results could serve as reference values in the planning process, for instance, if the share of RES is the main target, they could be used as a seed to fill in other land uses. For example, residential uses may request a certain amount of land uses of hospital and school. The model could be further improved by including PV installation on building façades and energy storage devices.

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References

[1] O. Edenhofer *et al.*, “Special Report on Renewable Energy Sources and Climate Change Mitigation,” Intergovernmental Panel on Climate Change, 2011.
[2] S. Salat and C. Guesne, *Energy and carbon efficiency of urban morphologies. The case of Paris.* Paris: Urban Morphologies Laboratory, CSTB (French Scientific Centre for Building Research) and ENSMP (Ecole Nationale Superieure des Mines de Paris), 2008.
[3] N. Mohajeri, G. Upadhyay, A. Gudmundsson, D. Assouline, J. Kämpf, and J.-L. Scartezzini, “Effects of urban compactness on solar energy potential,” *Renew. Energy*, vol. 93, pp. 469–482, Aug. 2016.
[4] J. J. Sarralde, D. J. Quinn, D. Wiesmann, and K. Steemers, “Solar energy and urban morphology: Scenarios for increasing the renewable energy potential of neighbourhoods in London,” *Renew. Energy*, vol. 73, pp. 10–17, Jan. 2015.
[5] R. E. Best, F. Flager, and M. D. Lepech, “Modeling and optimization of building mix and energy supply technology for urban districts,” *Appl. Energy*, vol. 159, pp. 161–177, Dec. 2015.
[6] S. Cajot, N. Schüler, M. Peter, J. Page, A. Koch, and F. Maréchal, “Establishing Links for the Planning of Sustainable Districts,” in "Expanding Boundaries: Systems Thinking in the Built Environment", presented at the Sustainable Built Environment (SBE) Regional conference, Zurich, Switzerland, 2016, DOI: 10.3218/3774-6_82.
[7] C. Duarte, P. Raftery, and S. Schiavon, “SinBerBEST Technology Energy Assessment Report,” *Build. Effic. Sustain. Trop.*, Apr. 2016.
[8] S. J. Oh, K. C. Ng, K. Thu, W. Chun, and K. J. E. Chua, “Forecasting long-term electricity demand for cooling of Singapore’s buildings incorporating an innovative air-conditioning technology,” *Energy Build.*, vol. 127, pp. 183–193, Sep. 2016.
[9] U. Manandhar, A. Ukil, and D. Wang, “Building HVAC load profiling using EnergyPlus,” in *2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, 2015, pp. 1–6.
[10] “BCA Building Energy Benchmarking Report 2016,” Singapore Building and Construction Authority, Singapore, 2016.
[11] Energy Market Authority, “Singapore energy statistics 2016,” Research and Statistics Unit, Energy Market Authority, Singapore, 2016.
[12] F. Meggers, V. Ritter, P. Goffin, M. Baetschmann, and H. Leibundgut, “Low exergy building systems implementation,” *Energy*, vol. 41, no. 1, pp. 48–55, May 2012.
[13] J. Luther and T. Reindl, “Solar Photovoltaic Roadmap for Singapore,” Solar Energy Research Institute of Singapore, Singapore, 2014.
[14] P. Mancarella and G. Chicco, “Integrated energy and ancillary services provision in multi-energy systems,” in *2013 IREP Symposium Bulk Power System Dynamics and Control - IX Optimization, Security and Control of the Emerging Power Grid*, 2013, pp. 1–19.
[15] R. Luthander, J. Widén, D. Nilsson & J. Palm, “Photovoltaic self-consumption in buildings: A review,” Appl. Energy, 142, 80–94, 2015.
[16] S. Cajot, N. Schüler, M. Peter, A. Koch, and F. Maréchal, “Interactive optimization for the planning of urban systems,” accepted at the CISBAT conference, Lausanne, Switzerland, 2017.