Long-term solar PV planning in High-Density Urban Systems

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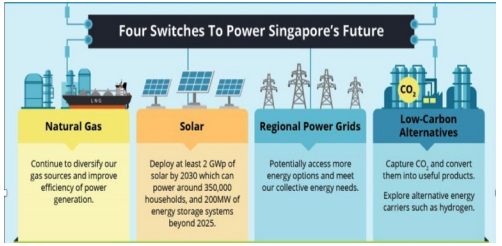
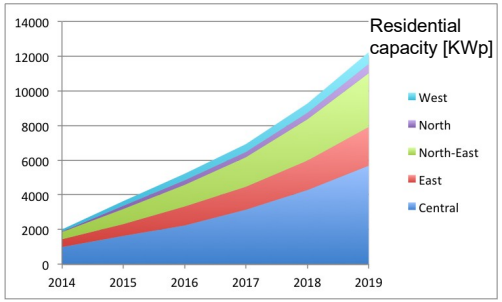
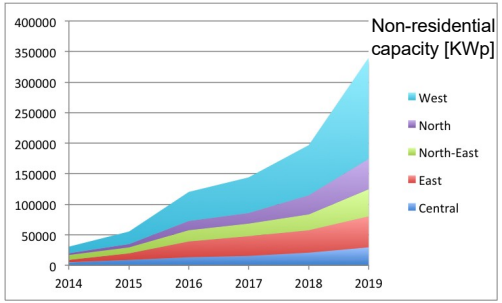
Solar planning model: overview and motivation

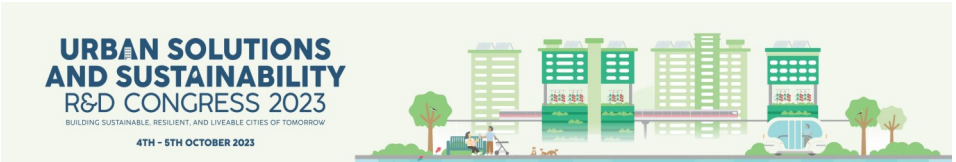
- Singapore has very ambitious solar capacity targets
- The main sources of solar energy are rooftop/façade panels, but space is scarce and consumers may be risk averse
- How can government/agencies achieve targets?

- Our approach: robust optimization to estimate solar adoption
- Idea: after calibrating our model with past data, determine the incentives necessary to achieve the targets
- Space availability is considered as a constraint.



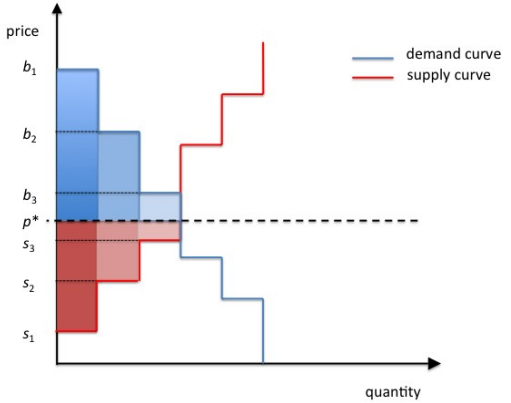




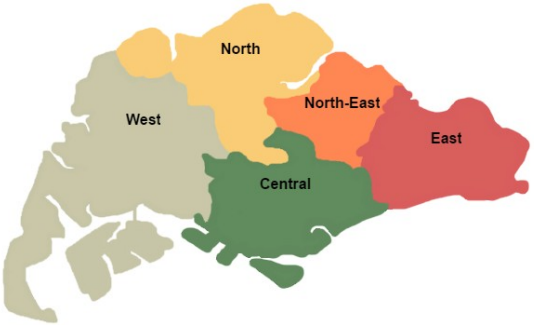


Assumptions

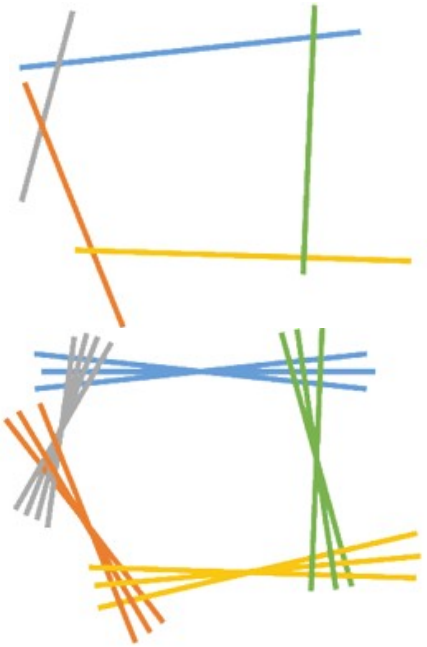
- Decision of installing capacity depends on the economic surplus principle involving producers and consumers of solar PV (PhotoVoltaic) systems



- Test case: Singapore, 2020-2050
- Limited rooftop and façade space
- Risk-averse behaviour of consumers (robust optimization)
- Parameters to be calibrated: net space used, maximum buying price from consumers, budget of uncertainty.
- Requirement: meet capacity targets from government/agencies.



Methodology: main idea



1. Robust optimization model:
   - Objective: maximization of the total economic surplus of buyers/sellers of solar PV systems
   - Constraints: space availability, equilibrium of capacity bought/sold
   - Uncertainty: maximum buying price; risk-averse consumers

2. Derivation and solution of the Robust Counterpart (linear program) to forecast capacity installed (2020-2050)

3. Analysis of the solution to derive incentives necessary to achieve capacity targets.

Methodology: formulations

uncertainty (risk-averse consumers)

$$\max \left(\sum_{t\in T} -\beta_t \sum_{q\in Q}\sum_{k\in K_q} r_{t,k,q} w_{t,k,q} + \min_{\epsilon\in U(\Gamma)} \sum_{t\in T} \beta_t \sum_{l\in L}\sum_{c\in C}\sum_{k\in K} y_{l,t,k,c}\bar{p}_{l,t,k,c}(1-\epsilon_{l,t,k,c}) \right)$$

$$\text{s.t.} \quad \forall t \in T, \forall k \in K \quad \sum_{l\in L}\sum_{c\in C} y_{l,t,k,c} = \sum_{q\in Q:k\in K_q} w_{t,k,q}$$

$$\forall l \in L, \forall t \in T, \forall c \in C, \forall j \in J \quad s_{l,t,c,j} = \sum_{k\in K_j} \frac{y_{l,t,k,c}}{\eta_{k,t}}$$

$$\forall l \in L, \forall t \in T, \forall c \in C, \forall j \in J \quad \sum_{t'\in T:t'\le t} s_{l,t',c,j} \le \sum_{t'\in T:t'\le t} a_{l,t',c,j}$$

$$\boldsymbol{y}, \boldsymbol{w}, \boldsymbol{s} \ge \mathbf{0}.$$

Robust optimization model

$$\max \sum_{t\in T} \beta_t \left(\sum_{l\in L}\sum_{c\in C}\sum_{k\in K} \bar{p}_{l,t,k,c} y_{l,t,k,c} - \sum_{q\in Q}\sum_{k\in K_q} r_{t,k,q} w_{t,k,q} \right) + \sum_{l\in L}\sum_{c\in C} \rho_{l,c}\Gamma_{l,c} + \sum_{l\in L}\sum_{t\in T}\sum_{k\in K}\sum_{c\in C} \mu_{l,t,k,c}$$

$$\text{s.t.} \quad \forall t \in T, \forall k \in K \quad \sum_{l\in L}\sum_{c\in C} y_{l,t,k,c} = \sum_{q\in Q:k\in K_q} w_{t,k,q}$$

$$\forall l \in L, \forall t \in T, \forall c \in C, \forall j \in J \quad s_{l,t,c,j} = \sum_{k\in K_j} \frac{y_{l,t,k,c}}{\eta_{k,t}}$$

$$\forall l \in L, \forall t \in T, \forall c \in C, \forall j \in J \quad \sum_{t'\in T:t'\le t} s_{l,t',c,j} \le \sum_{t'\in T:t'\le t} a_{l,t',c,j}$$

$$\forall l \in L, \forall t \in T, \forall k \in K, \forall c \in C \; \rho_{l,c} + \mu_{l,t,k,c} + \beta_t y_{l,t,k,c}\bar{p}_{l,t,k,c} \le 0$$

$$\forall \tau \in \Omega \quad \sum_{l\in L}\sum_{k\in K}\sum_{c\in C}\sum_{t\in T:t\le\tau} y_{l,t,k,c} \ge \psi_\tau$$

$$\boldsymbol{y}, \boldsymbol{w}, \boldsymbol{s} \ge \mathbf{0}$$

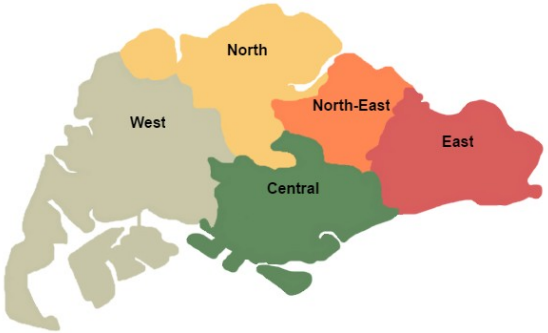
$$\boldsymbol{\rho}, \boldsymbol{\mu} \le \mathbf{0}.$$

target constraints

Robust counterpart (Linear Program)

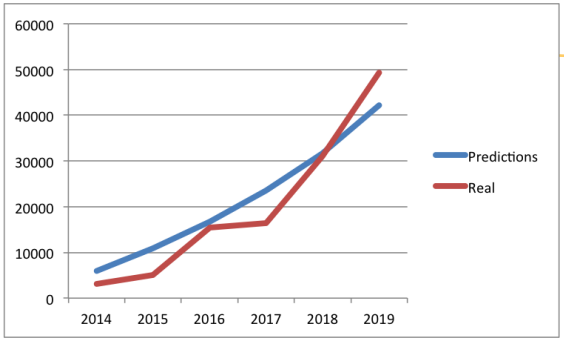
Test case: background

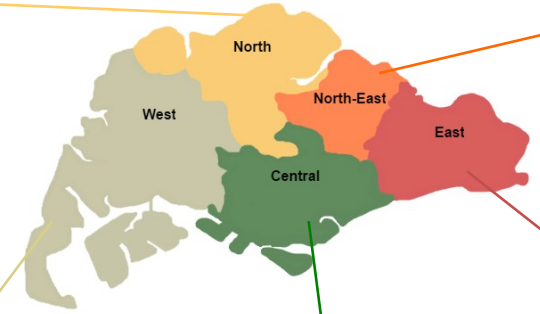
- Singapore used as a case study for its potential in terms of solar energy
- Rooftop: for each region, 3 consumers: Residential, Commercial, Industrial
- Façade: single profile, no past data available
- Data sources: EMA, SERIS reports 2014/2020. Calibration for the other parameters of interest (net space used, maximum buying price from consumers, budget of uncertainty).

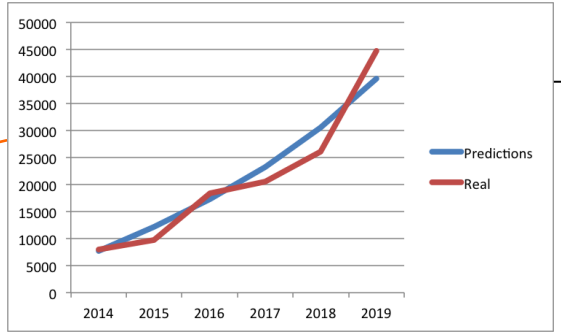


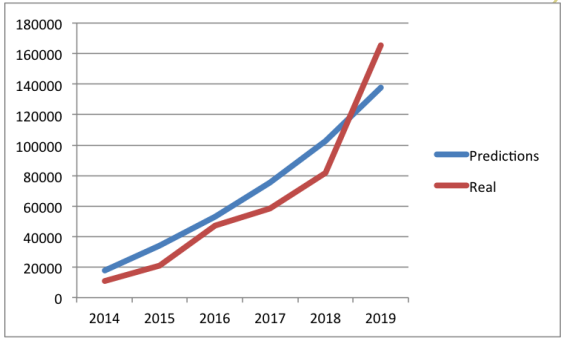
Test case: calibration

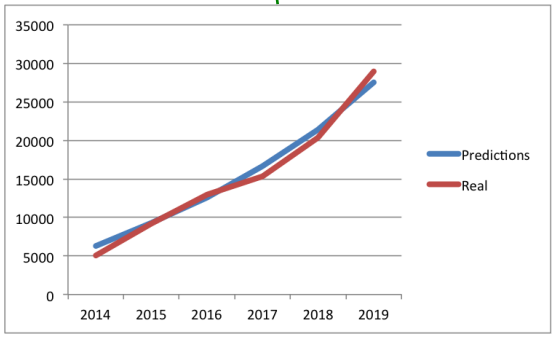
- Singapore, 5 regions, residential/non-residential consumers
- Calibration: 2014-2018 capacity [KWp]. Validation: 2019

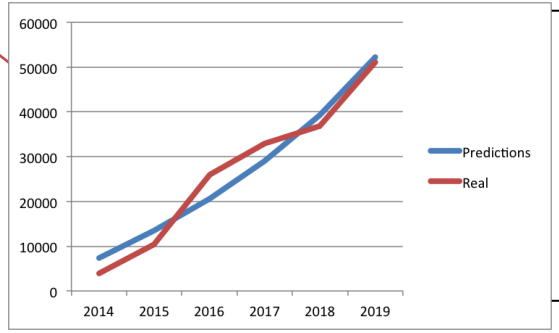






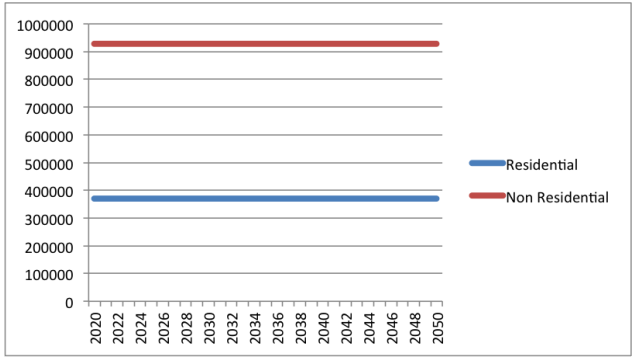




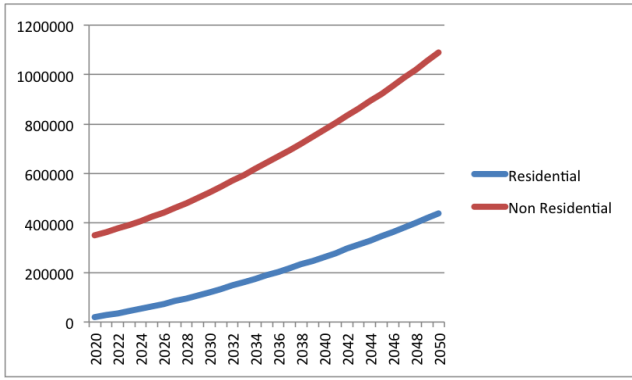


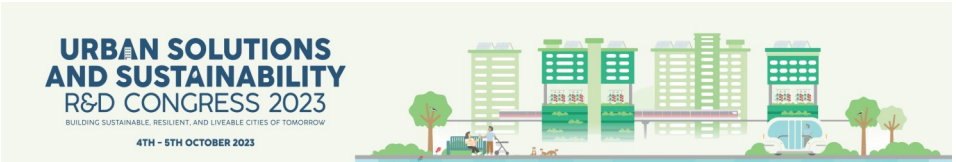
Test case: the importance of uncertainty

- Without including risk-aversion of buyers, results of the deterministic model show that rooftop capacity [KWp] is installed at the first time period (unrealistic)



- The robust model including risk-aversion of buyers produces more meaningful results.



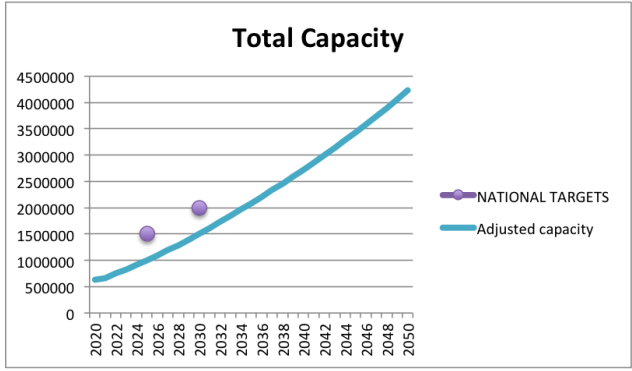


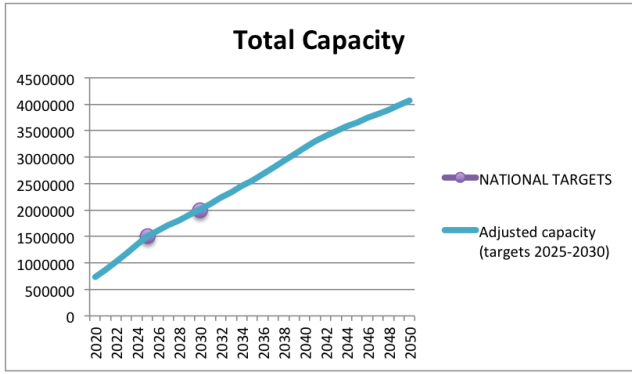
Test case: total capacity and incentives

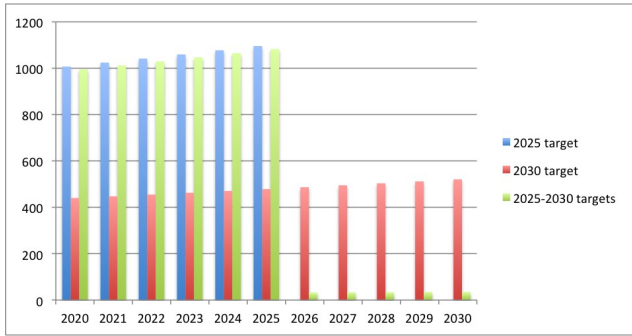
- Model forecasting (rooftop residential + non-residential and façade, all 5 regions capacity [KWp]) compared with national targets

- Without incentives, the targets in 2025 and 2030 may not be achieved

- Incentives to achieve targets [SGD/KWp] can be derived directly (dual variables of the target constraints).







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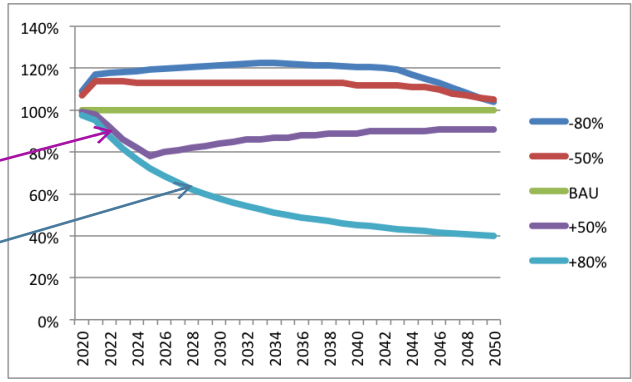
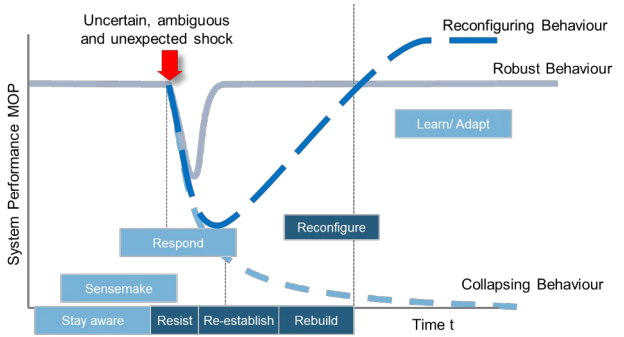
Test case: resilience

- Effect of change of selling prices (shock event) on the capacity installed

- +50%: robust behaviour
- +80%: collapsing behaviour.





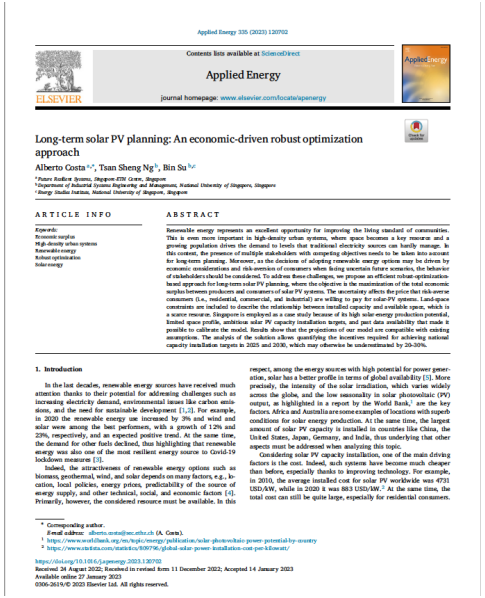
Credit: Hans R. Heinimann, 2019

Conclusions

- Robust solar planning model including space constraints and risk-averse consumers yielding a linear programming problem

- This model can complement the analysis by agencies when deriving effective policies to address the conflicting objectives at a national level

- Reference: A. Costa, T.S. Ng, B. Su. Long-term solar PV planning: An economic-driven robust optimization approach. Applied Energy 335:120702. Elsevier, 2023.



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Long-term solar PV planning: An economic-driven robust optimization approach

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ABSTRACT

Renewable energy represents an excellent opportunity for improving the living standard of communities. This is even more important in high-density urban systems, where space becomes a key resource and a growing population driven the demand to levels that traditional electricity sources can hardly manage. In this context, the presence of multiple stakeholders with competing objectives needs to be taken into account for long-term planning. Moreover, as the decisions of adopting renewable energy options may be driven by economic considerations and risk-aversion of consumers whom facing uncertain future scenarios, the behavior of stakeholders should be considered. To address these challenges, we propose an efficient robust optimization-based approach for long-term solar PV planning, where the objective is the maximization of the total economic surplus between producers and consumers of solar PV systems. The uncertainty affects the price that risk-averse consumers (i.e., residential, commercial, and industrial) are willing to pay for solar PV systems. Land-space constraints are included to describe the relationship between installed capacity and available space, which is a scarce resource. Singapore is employed as a case study because of its high solar energy production potential, limited space profile, ambitious solar PV capacity installation targets, and past data availability that made it possible to calibrate the model. Results show that the projections of our model are compatible with existing assumptions. The analysis of the solution allows quantifying the incentives required for achieving national capacity installation targets in 2025 and 2030, which may otherwise be underestimated by 20-30%.

1. Introduction

In the last decades, renewable energy sources have received much attention thanks to their potential for addressing challenges such as increasing electricity demand, environmental issues like carbon emissions, and the need for sustainable development [1,2]. For example, in 2020 the renewable energy use increased by 3% and wind and solar were among the best performers, with a growth of 12% and 23%, respectively, and an expected positive trend. At the same time, the demand for other fuels declined, thus highlighting that renewable energy was also one of the most resilient energy source to Covid-19 lockdown measures [3].

Indeed, the attractiveness of renewable energy options such as biomass, geothermal, wind, and solar depends on many factors, e.g., location, local policies, energy prices, predictability of the source of energy supply, and other technical, social, and economic factors [4]. Primarily, however, the considered resource must be available. In this respect, among the energy sources with high potential for power generation, solar has a better profile in terms of global availability [5]. More precisely, the intensity of the solar irradiation, which varies widely across the globe, and the low seasonality in solar photovoltaic (PV) output, as highlighted in a report by the World Bank,[1] are the key factors. Africa and Australia are some examples of locations with superb conditions for solar energy production. At the same time, the largest amount of solar PV capacity is installed in countries like China, the United States, Japan, Germany, and India, thus underlying that other aspects must be addressed when analyzing this topic.

Considering solar PV capacity installation, one of the main driving factors is the cost. Indeed, such systems have become much cheaper than before, especially thanks to improving technology. For example, in 2010, the average installed cost for solar PV worldwide was 4731 USD/kW, while in 2020 it was 883 USD/kW.[2] At the same time, the total cost can still be quite large, especially for residential consumers.

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[1] https://www.worldbank.org/en/topic/energy/publication/solar-photovoltaic-power-potential-by-country
[2] https://www.statista.com/statistics/830796/global-solar-power-installation-cost-per-kilowatt/

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