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STOCHASTIC INTEGRATED GRID PLANNING MODEL: CASE STUDY IN MALAYSIA

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ABSTRACT

We do not know the impact of distribution network constraints on grid expansion planning and how uncertainty may influence the transmission and distribution level investment decisions. This paper presents a novel stochastic integrated grid planning approach considering distribution network constraints, combining a two-stage optimization grid expansion model with a distribution network hosting capacity (HC) assessment for a stylized representation of the Malaysian grid. Our result shows that omitting distribution constraints and ignoring uncertainty in grid investment planning has a significant impact on the optimal solution and quantifiable economic consequences. We also evaluate the benefit of integrating solar PV and battery storage, which, as we show can lead to potential savings of 0.86% ($2.37billion) of the expected cost.

Keywords: stochastic, integrated grid planning, solar PV, battery storage, Malaysia, renewable

NONMENCLATURE

Set and indices

L	Corridors l
N	Nodes, n
K	Generator types, k
E	Model stages e
T	Years, t
P	Intra-annual time blocks, p
S	Scenarios, s
B	Energy storage (ESS) facilities, b

Parameters

CY_{esk}	Capital cost of new generation k ($/MW)
CX_{es}	Transmission investment cost e=1,2 ($/MW/km)
CV_{esk}	Generation cost type k, stage e=1,2 (USD/MWH)
CZ_{esb}	Capital cost of new ESS b, e=1,2 ($/MW)
CD_{esb}	ESS discharge cost type b, stage e=1,2 (USD/MWH)
E_{sk}	Carbon emission by plant type k (t/MWH)
CP_{es}	Carbon price per year stage e=2,3 scenario s $/t)
i	Discount rate per year (1/yr)
N	Sample size (hours)
ρ_s	Probability of scenario s

Variables

tc_{se}	Total cost at stage e ($)
x_{sel}	New transmission investment e=1,2 (MW)
y_{senk}	Capacity of new plant stage e=1,2 (MW)
z_{esnb}	Capacity of new ESS stage e=1,2 (MW)
g_{esnpk}	Generation of plant stage e=2,3, period p (MW)
g^S_{esnpk}	Generation of Solar plant stage e=2,3
r^d_{esnpb}	Discharging of ESS stage e=2,3 at bus n
r^c_{esnpb}	Charging of ESS stage e=2,3 at bus n

1. INTRODUCTION

Large solar photovoltaic (LPV) plants may be connected to transmission networks, as other types of renewable capacity, including wind, tends to be. However, in most markets, a large fraction of solar PV capacity is connected to distribution networks (distributed solar photovoltaic, DPV), beyond the transmission system operator's control.

Energy storage presents a similar challenge. Storage can play a vital role in accommodating variable renewable generation into the electricity system, but, like solar PV, a large amount of storage capacity is connected to distribution networks, and therefore invisible to transmission system operators.

Electrical infrastructure will need to be expanded or rearranged to accommodate variable renewable generation. However, the current approach for transmission and generation expansion planning does not generally account for distribution network constraints. Also, separately, risk and uncertainty are not always properly accounted for, as many planning models are deterministic.

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As a consequence, we do not know the impact of distribution network constraints on grid expansion planning and how uncertainty may influence transmission and distribution level investment decisions.

In light of these issues, we combine a two-stage stochastic optimization transmission and generation expansion model with a detailed distribution network hosting capacity (HC) assessment, solving these two models iteratively to heuristically find a fixed point. We apply this model to a stylized representation of the Malaysian grid, which is expected to have to integrate a large amount of DPV capacity over the coming decade

2. MATERIAL AND METHODS

2.1 Model overview

First, the transmission and generation expansion model calculates an optimal solution considering only transmission grid constraints. Then, at the distribution level, the proposed capacity of distributed solar PV (DPV) energy mix is assessed subject to distribution network hosting capacity (HC) limits that consider reverse power flow and voltage constraints. This cycle iterates until the proposed optimal solution satisfies the transmission level constraints and distribution network constraints as depicted in figure 1.

The optimization model is established based on linearized DC power flows, while the distribution network hosting capacity is assessed using non-linear steady state power flow analysis. To evaluate the effects

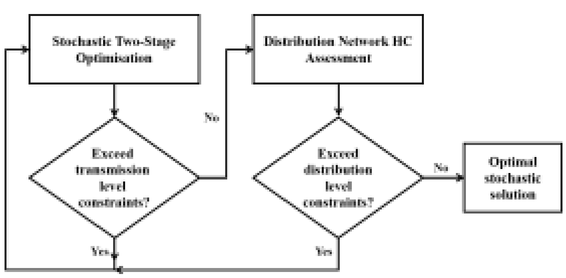

Fig 1 Stochastic integrated grid planning model flowchart

of distributed solar PV (DPV) in lower level network, we introduce a distribution corridor that connects the transmission and distribution nodes. Also, we consider two distinct types of solar PV in the case study; dispatchable large-scale solar (LPV), which is connected to the transmission network, non-distpatchable distributed solar (DPV) which is connected to the distribution network. In addition, we include three battery storage types in this model; grid scale, controllable Distribution Service Operator (DSO) operated storage, and uncontrollable distribution-connected domestic storage.

2.2 Timeline and model objective

There are two decision points for investment and three periods of energy market operations as depicted in [fig:Model-timeline]. In 2015, the planner decides on transmission investment and the generators commit to building new plants which are assumed to be fully commissioned starting 2025. The second point of investment decisions occur in the year 2025 and the built assets will come into operation in year 2035. Note that, after the second stage decision in 2025, only dispatch decisions are made for the next 25 years until 2050, so the model has combined planning horizon of 35 years.

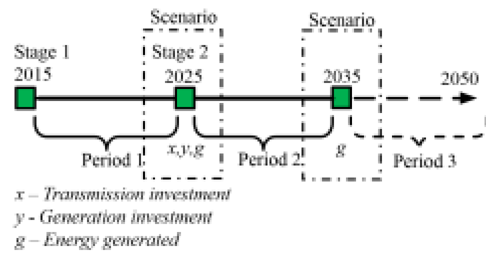

Fig 2 Model timeline on decision stages

The model minimizes the total expected cost of grid investment and operations taking into account grid network constraints, build constraints, resource limitations, and solar generation target. The total expected cost includes capital expenses for new transmission, generation, and battery storage investment and also grid operation cost including generation margin, battery discharge cost and carbon tax. The overall model objective function is formulated in [1] consist of total cost for each stage, e, defined in [2], [3] and [4].

$$min\{tc_1 + \sum_s \rho_s \, [(\frac{1}{1+i})^{10} tc_{2s} + (\frac{1}{1+i})^{10} tc_{3s}]\} \quad [1]$$

$$tc_1 = \sum CX_1 x_1 + \sum_{nk} CY_{1k} y_{1nk} + \sum_{nb} CZ_{1b} z_{1nb} \quad [2]$$

$$tc_2 = \sum CX_{2s} x_{2s} + \sum_{nk} CY_{2sk} x_{2snk} + \sum_{nb} CZ_{2sb} z_{1snb} + \frac{8760}{N} \sum_{t=1}^{10} \left(\frac{1}{1+i}\right)^{t-1} \sum_{npk} (CV_{2sk} + E_{sk} CP_{2s}) g_{2snpk} + \sum_{nkp} CD_{2sb} r^d_{2snpb} \quad [3]$$

$$tc_3 = \frac{8760}{N} \sum_{t=1}^{15} (\frac{1}{1+i})^{t-1} \sum_{npk} (CV_{3sk} + E_{sk} CP_{3s}) g_{3npk} + \sum_{nkp} CD_{3sb} r^d_{3snpb} \quad [4]$$

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Scenario	Description
Status Quo	No major changes in any parameter and solar targets are unambitious with no carbon prices
Off-grid	Network decentralization strategy
Decarbonization	Favors renewable generation and high carbon price being imposed
No storage	Investment in any type of energy storage system (ESS) is uneconomical
Technology	Favors of new technologies including biomass, solar PV and battery storage.
Low cost conventional	Higher demand growth, low renewable targets and an unchanged cost for renewable

Table 2 Planning scenario

2.3 Scenario

We establish six scenarios s, defined by the cost parameters, demand growth, renewable targets and carbon prices to represent regulatory, technological, and economic uncertainty are summarized in Table 2.

2.4 Results and discussion

2.4.1 Hosting capacity assessment

First, we consider the added value of including a distribution network HC assessment in a high-level transmission and generation expansion model. Table 1 summarizes the total cost of transmission and generation expansion planning over the modeled time horizon for the upper-level model only (without HC), for the combined model (with HC), and the combined model where we integrate small-scale battery storage. As this table shows, accounting for distribution network constraints has increased the total discounted system cost by 0.91% or $2.47 billion. Note for the first two cases, only grid size battery storage is considered.

Without considering distribution network constraints, the model proposes a significant amount of transmission line investment in the first stage decision to fully utilize the cheaper energy generated by both large solar PV (LPV) and distributed solar PV (DPV) in the second period of operation after the year 2025.

As Fig 3 shows, higher DPV investment is proposed to reduce the net demand at the distribution level so the energy generated from LPV can be utilized within the transmission network. When HC constraints are imposed, the overall amount of DPV is significantly reduced at some distribution nodes where, in otherwise HC limits would be exceeded. However, due to the fixed solar target, some of this DPV investment is shifted to other distribution nodes, including those with lower solar resources.

In our model, integrating distributed storage (HC enhancement) leads to cost reductions of nearly $2.37 billion in NPV terms. Anticipating a higher solar penetration and lower generation costs resulting from higher utilization of small scale battery storage (DSO owned and home storage), 6.98GW of line investment is proposed in the first stage.

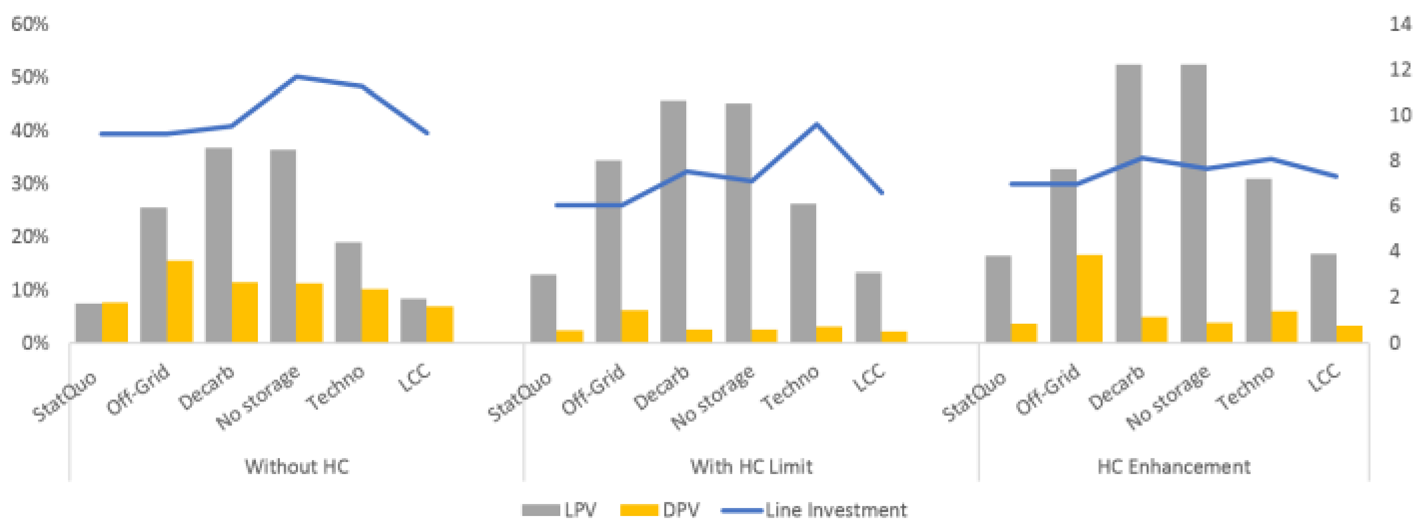

Fig 3 Solar generation mix

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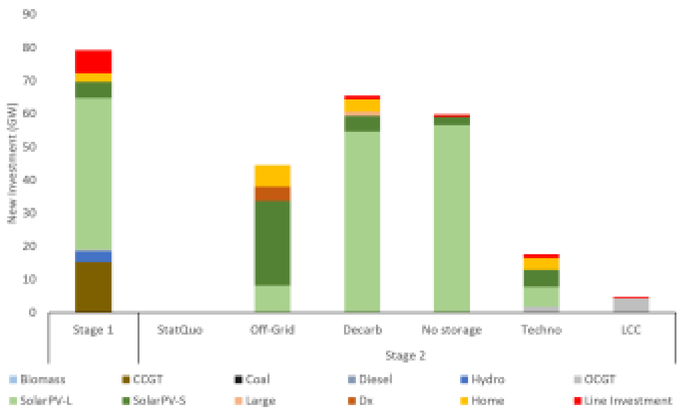

Fig 4 Proposed investment

2.4.2 *Optimal stochastic solution and scenario analysis*

Almost half of the total line investment takes place in the first stage. This can be explained in two ways. First, decisions taken in year 2015 will take into account all possible scenario that could occur in year 2025 due to the 10 year lead time of transmission investment. Due to ambitious solar target and high demand growth in three scenarios, the construction of solar generators must start earlier, in the first stage, if these constraints are to be met. Even a small chance of occurrence will require generators to be built earlier, in the first stage. Hence, transmission investment is chosen to transport the generated power and satisfy all constraints, including in the extreme scenario. This also includes distribution network constraints, which are evaluated using HC assessment. Secondly, it may be optimal to invest earlier, anticipating the needs for future line investment. In this way, the generation cost is be reduced while renewable objectives are met.

Note that in our model, battery storage technology is only used for load shifting and peak shaving. No grid size battery storage and DSO owned battery storage is used in the first stage, because the first-stage solar target is low and can be achieved by integrating LPV, DPV and home storage in the network. As shown in Fig 4, grid battery storage only comes in in the 'Decarbonization' scenario.

Unsurprisingly, we observe the highest DPV mix in the 'Off-grid' scenario, which increases self-consumption and reduces dependency on larger generation facilities. The first stage investment decision provides an indicative transition plan to be implemented accounting for future uncertainty.

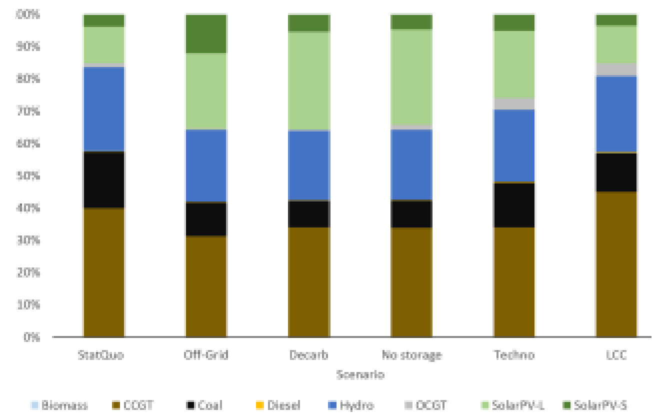

Fig 5 Energy mix

2.5 *Conclusions*

We find that, first of all, distribution network constraints are important and including them changes optimal transmission and generation capacities, not just in distribution networks but also at the transmission level. Distribution network hosting capacity (HC) enhancement techniques, using distribution connected storage, could significantly reduce the overall costs of meeting a renewable target, and increase distributed solar PV (DPV) penetration in the distribution network. However, the correct mix of distribution-connected and transmission-connected storage is crucial. Finally, this paper demonstrates that combined transmission and distribution network modelling is possible practical to assist with transition planning for future grids.

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