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1 Introduction

Solar and Storage Industries Institute (SSII) has recognized that the high costs of distribution system infrastructure upgrades often required to interconnect distributed energy resources (DER) are at times a barrier to widespread DER deployment. Community Solar projects are uniquely designed to bring the benefits of renewable energy to multiple customers who would otherwise not have access due to lack of proper space or adequate capital. Because Community Solar is essentially an aggregation of many would be smaller, distributed solar projects, the deployment challenge is compounded because of their larger aggregate capacities. SSII has identified an opportunity for technical assistance from the Department of Energy's Interconnection Innovation e-Xchange (i2X) initiative to explore the potential for Flexible Interconnection (FIX) solutions. FIX is relatively nascent in its application and the implications are not yet well understood. However, the tenets of FIX to facilitate faster interconnections and allow greater energy exports without the immediate need for upgrades could offer opportunities to solar developers. The trade-off is occasional curtailments, of which are underexplained at present.

SSII-the principal partner in this technical assistance project-requested assistance in conducting a set of power systems modeling exercises to predict the degree to which a theoretical Community Solar project could be curtailed over a representative year based on traditional power system constraints such as voltage requirements. The curtailments would then be expressed in economic impacts. Other partners in this project are Coalition for Community Solar Access (CCSA), National Grid, nexamp, and Smarter Grid Solutions.

SSII also intends to explore how flexible interconnection could increase the grid's ability to interconnect DER projects. Potential outcomes of this exploration may also be concretely identifying where targeted utility upgrades are most needed to aid in distribution system planning.

For the purpose of clarifying the merits of flexible interconnection, PNNL utilized a feeder model previously developed at PNNL under a prior DOE project. The 9500 Node Test Feeder has its foundation as an authentic feeder taken and modified from an electric utility's distribution system who participated in the earlier project. PNNL has since modified the feeder by adding DER and other attributes to be more focused on a distributed energy grid. Additional detail on the test feeder is provided in Section 3.

PNNL carried out the same analytical process (described in Section 2) at three locations on the 9500 Node Test Feeder. This was done to better simulate results with very different physical conditions and their respective hosting capacity and economic results. While the three locations are intrinsically related as parts of a localized power system in this work, this will likely not be the case in reality. Instead, every point on the physical grid carries with it a very different set of physical and electrical qualities. Therefore, the reader should be advised to consider the hosting capacity and economics results exclusive to the point of analysis and avoid casting comparisons between results at different locations. Simply stated, flexible interconnection is meant to provide options to the conventional capped output method at a particular point of interconnection and not necessarily a means to compare the merits between various points on the grid.

1.1 Readers Guide

This report is intended for a diverse audience and as such, some sections may not be as compelling for all readers. The general structure is as follows:

- Section 2 describes the dispatch, economic modelling methodology, and sets up the theoretical foundation of the study.
- Sections 3.1 and 3.2 describe the input data used in the analyses.
- Section 3.3 presents the results.
- Sections 4 and 5 provides general discussion, key takeaways, and concluding remarks.

Table 1 presents recommendations to the reader on where to focus attention, depending on the desired balance between theory versus results or detail versus analysis.

Table 1 Recommendations for Readers

Reader Preferences	**Recommended Sections**
Interested in key-takeaways and/or policy/programmatic implications	Recommended: Review Section 3.3, which presents the data leading to the key takeaways Must Read: Section 4
Interested in understanding the modeling and its potential limitations	Section 3.3, Section 4, and Section 2
Interested in replicating the work	All previous listed plus Sections 3.1 and 3.2

1.2 Notation

The following provides a listing of variables and description of how they are used in the analyses.

Symbol	**Description**	**Symbol**	**Description**
t	Time instance	$lpg[t]$	Limited generation value at time t
Δt	Simulation time interval (1 hr)	$pv[t]$	Unitized solar generation at time t
y	Year instance	V	System voltage
n	Number of years of analysis (project lifetime)	R_{sc}, X_{sc}	Short-circuit resistance, reactance
$hc[t]$	Hosting capacity value at time t		

Symbol	Description
S_r	Plant apparent power nameplate rating
S_{exp}	Plant apparent power export rating
$\Delta P, \Delta Q$	Active and reactive difference between S_r and S_{exp}.
PF	Power factor
$P_{\text{conventional}}$	Nameplate capacity under conventional interconnection.
P_{flexible}	Nameplate capacity under flexible interconnection
$P_{\text{flexible}}^{\text{max}}$	Maximum nameplate capacity under flexible interconnection
$P_{\text{export}}[t]$	Exported power from plant at time t
$P_{\text{curtailment}}[t]$	Curtailed power at time t
g_{over}	Potential over generation at time t
$b_{\text{charging}}[t]$	BESS charging at time t
$b_{\text{no curtailment charge}}[t]$	Charging power with opportunity cost, i.e., that could alternatively be exported
$b_{\text{discharge}}[t]$	BESS discharge at time t
$E[t]$	BESS state of charge at time t
$r_{\text{kW}}, r_{\text{kWh}}$	BESS power and energy rating

Symbol	Description
$u[t]$	BESS indicator variable (0=charge, 1=discharge)
$c_{\text{energy}}[t]$	Price of energy (combination of all value streams) at time t.
$c_{\$}[t]$	Price of energy (all value streams except DRV) at time t.
$c_{\text{DRV}}[t]$	Demand reduction value at time t.
$f_{\text{DRV}}[y]$	Scaling factor for DRV benefit in year y.
d	Degradation factor
s	Escalation factor
r	Discount rate
$R[y]$	Revenue in year y
$R_{\text{curtailment}}[y]$	Opportunity cost of curtailment in year y
C_{total}	Total capital costs in today's dollars
$C_{\text{annualized}}$	Annualized cost
$O\&M$	Operations and maintenance cost.
$C[y]$	Capital cost in year y.
$P[y]$	Profit in year y.
NPV	Net present value
$NPV_{\text{curtailment}}$	Net present value of the curtailment opportunity cost.

2 Methodology

This section will layout the methodology that Pacific Northwest National Laboratory (PNNL) developed to carry out the scope by first describing the metrics under which utilities commonly gauge system impacts by DER, then describing hosting capacity and the technical approach to determining it, and then finally the methodology used to predict the economic impacts of flexible interconnection when compared to the traditional capped output interconnection approach.

2.1 Hosting Capacity

The methodology used to investigate the benefits of flexible interconnection (FIX) is based on the concept of time series hosting capacity, which determines the power injection limit at a particular location of a distribution feeder at any given time. The limits considered are shown in Table 2. There are several other metrics not considered in this analysis, such as reverse power flow, which is the flow of energy in the reverse direction along the distribution feeder. Another is the contribution to total short-circuit at any protective device. The reason for excluding other metrics is that utility concerns over them are subjective and frequently exclusive to the feeder in question. For example, some utilities are taking action to contend with reverse power flow and increases in short-circuit levels even when exporting energy from the distribution system through the substation and onto the transmission system. Such is the case with National Grid, the utility partner on this project. National Grid and Smarter Grid Solutions provided several examples of system impact studies that had already been performed stemming from interconnection applications submitted under Community Solar projects. The New York State Public Utilities Commission has standardized DER interconnection practices under the New York State Standardized Interconnection Requirements (NYSSIR) with DER interconnection screening criteria elucidated in the Coordinated Electric System Interconnect Review (CESIR) document. The CESIR is a collection of DER screens that utilities apply when predicting the degree to which a DER could impact the power grid.

Table 2 Hosting Capacity Metrics

Limit	**Explanation**
Equipment thermal limits	Normal and Emergency limits cannot be violated
Static voltage limits	Maximum: 1.05 pu Minimum: 0.95 pu
Rapid Voltage Change (RVC)	When determining the maximum nameplate capacity *beyond* the hosting capacity the 3% RVC limit from IEEE 1547-2018 [1] is used[1].

The time series hosting capacity takes a feeder model, load profile, solar PV resource profile, and control operations (such as voltage regulators or capacitor banks) as inputs. Then, the maximum power injection for each time interval is calculated at a location of interest on the feeder that does not cause violations based on the metrics and limits specified in Table 2. The process is illustrated in Figure 1. Note that control operations, such as voltage regulator changes, are not modified during the hosting capacity calculation. Similarly, existing battery storage operation, or the operation of any other resources are assumed unaltered compared to the baseline scenario. The output of this process is an hourly curve indicating the hosting capacity at the point of interest. Conventional interconnection requires sizing the plant inverter

[1] The RVC definition comes from IEEE Std. 1453 [2], but the selection of 3% as the limit is from IEEE Std. 1547. There are differing opinions on the appropriate use of RVC in hosting capacity, Table 2 represents the decision for this analysis, which could be modified in other circumstances.

nameplate below the minimum hosting capacity of the total time interval in the simulation, in this case, one year:

$$P_{\text{Conventional}} \leq \min_{t} hc[t] \quad (1)$$

where $P_{\text{Conventional}}$ is the size of the plant and $hc[t]$ is the hosting capacity calculated at time t.

Flexible interconnection allows interconnecting a greater nameplate capacity by allowing the DER power injection to follow the available hosting capacity on the feeder at any time, t. If the available DER output exceeds the injection that the feeder can accept, then the output of the DER is curtailed or diverted to storage, if a storage device is available.

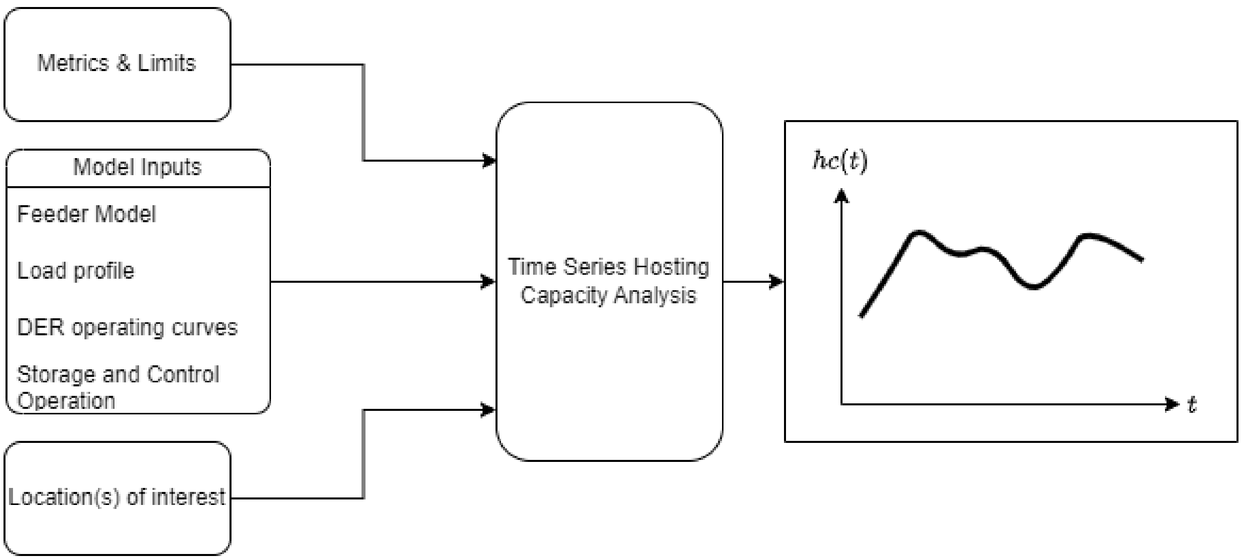

Figure 1 Concept of time-series hosting capacity analysis.

2.2 Limited Generation Profiles

The hosting capacity described in the previous section has a unique value for each hour. In practice, developing such detailed time series data may be computationally demanding for a utility. For example, the hosting capacity profiles in California consist of 576 (2x24x12) hours[2] compared to a full year 8760. One compromise that has emerged is the use of limited generation profiles (LGPs) that use a limited set of unique values to create a “blockier” profile. California resolution E-5296, from March 2024, adopts the use of LGPs with 24 unique values per year. Table 3 in resolution E-5296 details the three adopted profile options, which are reproduced in Table 3.

[2] See definitions pg. 16: https://www.pge.com/tariffs/assets/pdf/tariffbook/ELEC_RULES_21.pdf

Table 3 Definition of Limited Generation Profiles

Name	Monthly blocks	Hourly blocks	Description
Daily		**24**	One value per hour of day, repeated throughout the year
Block	**4**: Jan-Mar, Apr-Jun, July-Sep, Oct-Dec	**6**:1am-5am, 5am-9am, 9am-1pm, 1pm-5pm, 5pm-9pm, 9pm-1am	One value for each pairing of seasonal block and hourly block.
18-23-fixed	12 (monthly)	**2**: 12am-6pm, 6pm-12am	One value for each pairing of month and hourly block.

The hourly hosting capacity, $hc[t]$, can be converted to one of the LGPs, $lgp[t]$, which is shown in Figure 2. Since the LGPs still represent time series data that returns a hosting capacity value for any given hour, all the subsequent analyses are equally as applicable if $hc[t]$ is simply replaced with $lgp[t]$.

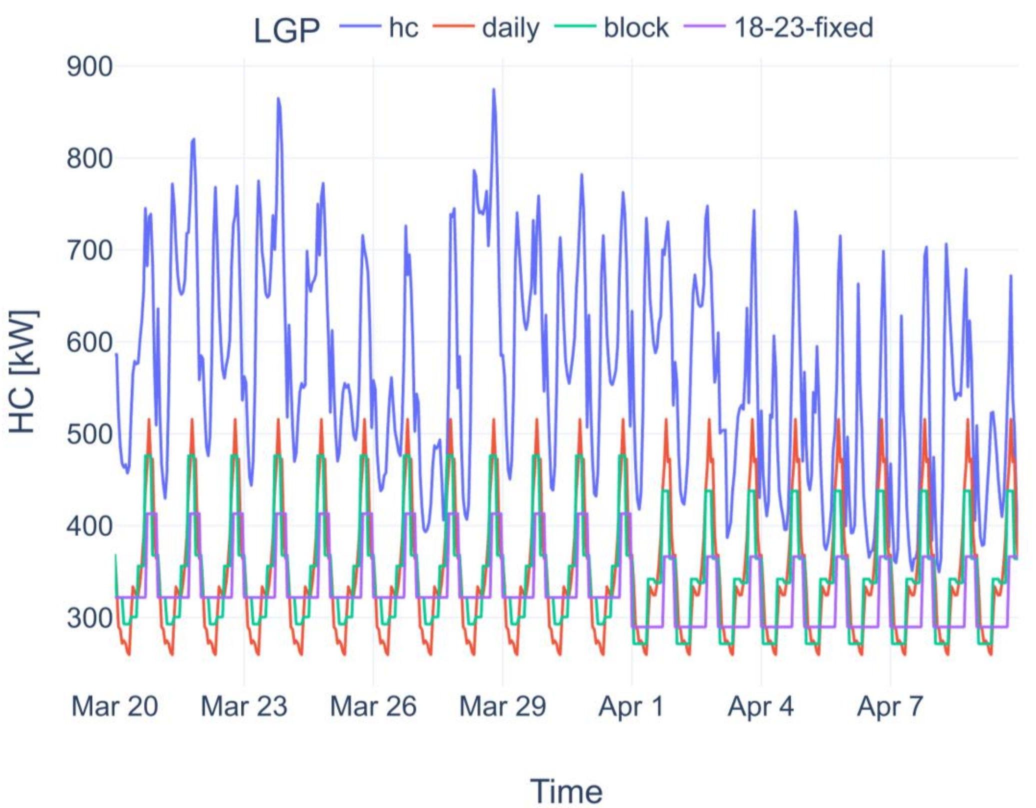

Figure 2 Comparison between $hc[t]$ and derived limited generation profiles. Note the reduced and compressed values of the LGPs compared to the 8760 profile.

2.3 Limits on Nameplate Capacity Under Flexible Interconnection

The benefits of flexible interconnection come with the need for a degree of power export control to limit the exported power at times when power exports exceed $hc[t]$. Inadvertent exports that exceed the desired limit for a short time can occasionally occur before the power control system (PCS) can react to the change. The BATRIES Toolkit [3] develops an inadvertent export screen based on the 3% rapid voltage change (RVC) limit from IEEE Std. 1547-2018 [1]. The rapid voltage change is estimated using IEEE Std 1453-2022 [2], as:

$$\frac{(R_{\text{sc}} \times \Delta P) - (X_{\text{sc}} \times \Delta Q)}{V^2}. \tag{2}$$

R_{sc} and X_{sc} in (2) are the system short-circuit resistance and reactance, respectively, at the point of interconnection on the primary conductors (3-phase), and V is the system nominal voltage.

The changes in active, ΔP, and reactive, ΔQ, power are determined based on the difference between the nameplate capacity, S_r, and the export limited capacity, S_{exp}, as:

$$\begin{aligned} \Delta P &= \left(S_r - S_{\text{exp}}\right) \times \text{PF} \\ \Delta Q &= \left(S_r - S_{\text{exp}}\right) \times \sqrt{1 - \text{PF}^2} \end{aligned} \tag{3}$$

where PF is the power factor. This relationship can be used to bound the nameplate rating, as to not violate the inadvertent export screen as:

$$S_r \leq \min_t hc[t] \; + 0.03 \times \frac{V^2}{R_{\text{sc}} \cdot \text{PF} - X_{\text{sc}} \cdot \sqrt{1 - \text{PF}^2}}. \tag{4}$$

In this way, the hosting capacity still provides a limit on the maximum capacity that can be interconnected, even under flexible interconnection. In the subsequent analysis $P_{\text{flexible}}^{\text{max}}$ is used to denote the value of Equation (4) at equality and with a power factor of 1.

2.4 Evaluating Operations under Flexible Interconnection

To evaluate the benefits of flexible interconnection three different scenarios are considered.

1) A *conventional* interconnection scenario, where the capacity of the plant is chosen as the minimum of the hosting capacity: $P_{\text{conventional}} = \min_t hc[t]$.

2) A *solar-only* interconnection scenario, where the solar plant is sized greater than the minimum hosting capacity: $P_{\text{flexible}} > P_{\text{conventional}}$. As a rule of thumb, a value around the 90th percentile from the hosting capacity values is used[3].

3) A *solar-plus-storage* scenario, where the same capacity, P_{flexible}, as the solar-only scenario is used with an added battery energy storage system (BESS). As a rule of

[3] Sizing components is out of scope for this project and should be considered in subsequent work. The logic behind the 90th percentile is to pick a relatively large plant, but not one that would have to always curtail (i.e. greater than 100% of all hosting capacity values).

thumb, the BESS is sized as the difference between the solar capacity and the minimum hosting capacity in terms of power, and a two-hour duration.

A yearly, unitized, solar profile, $pv[t]$, is selected and scaled by the respective plant size for each scenario. The determination of yearly operations in each scenario is described in the following.

2.4.1 Conventional Scenario

Under the conventional scenario, no curtailment occurs, and the output always varies below the minimum hosting capacity. The exported power at any given time is:

$$P_{\text{export}}[t] = P_{\text{conventional}} \cdot pv[t], \tag{5}$$

which simply scales the unitized solar profile, $pv[t]$, by the plant capacity, $P_{\text{conventional}}$ for every hour, t. Curtailment, $P_{\text{curtailment}}[t]$, in the conventional scenario is, by definition, always.

2.4.2 Solar-Only Scenario

Unlike the conventional scenario above where the PV plant's exported power will never exceed the minimum hosting capacity as determined by the utility, the solar-only scenario employs flexible interconnection principles, and the solar exported power will be allowed to modulate with the real-time hosting capacity at any time t. The virtual plant will export the minimum power between the solar production, $P_{\text{flexible}} \cdot pv[t]$, and the real-time hosting capacity, $hc[t]$, as captured by (6). This means that the PV plant may produce more power than the grid can accept at a given time, and therefore, the plant will be curtailed, $P_{\text{curtailment}}[t]$, by the difference between the possible production, $P_{\text{flexible}} \cdot pv[t]$ and the actual export, as depicted in (7).

$$P_{\text{export}}[t] = \min\{P_{\text{flexible}} \cdot pv[t], hc[t]\} \tag{6}$$

$$P_{\text{curtailment}}[t] = P_{\text{flexible}} \cdot pv[t] - P_{\text{export}}[t]. \tag{7}$$

2.4.3 Solar-Plus-Storage Scenario

The solar-plus-storage is more complex as the operation of the BESS needs to be considered. There are more complex aspects to consider since the battery can not only mitigate curtailment losses, but also help hedge between different times of the day where energy prices may differ[4]. To solve this, an optimization is set up to maximize the profit from the BESS output, while minimizing the opportunity cost of charging the battery from the solar plant, during times when there are no capacity constraints:

$$\text{maximize} \quad \sum_t c_{\text{energy}}[t]\left(b_{\text{discharge}}[t] - b_{\text{no curtailment charge}}[t]\right) \cdot \Delta t. \tag{8}$$

In (8) $c_{\text{energy}}[t]$ is the price of energy at time t in \$/kWh, $b_{\text{discharge}}[t]$ is the discharge of the BESS at time t in kW, $b_{\text{no curtailment charge}}[t]$ is the BESS charging at time t in kW that is *not* coming from

[4] BESS can also be operated as a backup reserve. This operating mode, however, is not considered in this analysis.

generation that would otherwise be curtailed, and $\Delta t = 1\text{hr}$ is the simulation time step. Note that the battery is not allowed to charge from the grid[5].

The relationship between curtailment, $P_{\text{curtailment}}[t]$, curtailable generation, i.e., generation that exceeds the hosting capacity, $g_{\text{over}}[t]$, total charging, b_{charging}, and the portion of charging that is not attributable to curtailable power, $b_{\text{no curtailment charge}}[t]$, is handled through two constraints.

$$0 \leq P_{\text{curtailment}}[t] \leq g_{\text{over}}[t] \quad \forall t \tag{9}$$

$$b_{\text{charging}}[t] - b_{\text{no curtailment charge}}[t] + P_{\text{curtailment}}[t] = g_{\text{over}}[t] \;\; \forall t. \tag{10}$$

Where over generation, g_{over} is defined and precomputed for all t as:

$$g_{\text{over}}[t] = \; P_{\text{flexible}} \cdot pv[t] - \min\{P_{\text{flexible}} \cdot pv[t], hc[t]\}. \tag{11}$$

Constraint (9) forces curtailment to be no greater than over-generation, that is, the plant should not curtail more than the difference between possible production and hosting capacity. Constraint (10) builds on (9) to distinguish between charging power supplied by curtailable generation and that supplied by generation that could otherwise be exported, $b_{\text{no curtailment charge}}$.The reason for the distinction is that the opportunity cost for the former is effectively zero, while the opportunity cost for the latter is the energy price at time t.

To Illustrate how these definitions work together, consider the following cases:

1. *No over generation*: $g_{\text{over}}[t] = 0$ in (11).
   - Constraint (9) requires $P_{\text{curtailment}} = 0$ and Constraint (10) becomes $b_{\text{charging}}[t] = b_{\text{no curtailment charge}}[t]$. In words, when there is no over generation *all* charging is from energy that could otherwise be exported.
2. *Over generation with no curtailment*: $g_{\text{over}}[t] > 0$ in (11) but $P_{\text{curtailment}}[t] = 0$ in (9).
   - In this case, Constraint (10) becomes $b_{\text{no curtailment charge}}[t] = b_{\text{charging}}[t] - g_{\text{over}}[t]$. In words, when there is no curtailment, only charging beyond the available over-generation will be counted as a *cost* in (8).
3. *Over generation and curtailment*: $g_{\text{over}}[t] > 0$, in (11) and $P_{\text{curtailment}}[t] > 0$ in (9).
   - In this case, Constraint (10) becomes: $b_{\text{no curtailment charge}}[t] = b_{\text{charging}}[t] - (g_{\text{over}}[t] - P_{\text{curtailment}}[t])$. In words, the amount of curtailment is subtracted from the total over-generation, and the only charging counted as *cost* in (8) is the difference between this quantity, and total charging, b_{charging}.

Considering these cases, Case 2 is a limit of Case 3 in terms of minimizing curtailment. This helps to illustrate why the objective stated in (8) also helps reduce curtailment overall.

The total output of the plant is controlled by the following two constraints:

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[5] This is a fairly common assumption, as allowing the BESS to charge from the grid complicates the attribution of its discharge to the solar energy produced on site.

$$b_{\text{discharge}}[t] - b_{\text{charging}}[t] - P_{\text{curtailment}}[t] \leq hc[t] - P_{\text{flexible}} \cdot pv[t] \quad \forall t \tag{12}$$

$$b_{\text{charging}}[t] \leq P_{\text{flexible}} \cdot pv[t] \;\; \forall t \tag{13}$$

Constraint (12) states that solar generation, $P_{\text{flexible}} \cdot pv[t]$, BESS output ($b_{\text{discharge}}[t] - b_{\text{charging}}[t]$), and curtailment must be below the hosting capacity. Constraint (13) forces the BESS charging to never exceed the solar generation at any given time, and in this way prevents grid charging.

Finally, the BESS dynamics are captured in the following constraints:

$$0 \leq b_{\text{charging}}[t] \leq r_{\text{kW}}(1 - u[t]) \;\; \forall t \tag{14}$$

$$0 \leq b_{\text{discharge}}[t] \leq r_{\text{kW}} \cdot u[t] \; \forall t \tag{15}$$

$$E[t] = E[t-1] - (b_{\text{discharge}}[t] + b_{\text{charging}}[t])\Delta t \;\; \forall t \tag{16}$$

$$0 \leq E[t] \leq r_{\text{kWh}} \quad \forall t, \tag{17}$$

where r_{kW} and r_{kWh} are the power and energy ratings of the BESS, respectively, $E[t]$ is the BESS state of charge in kWh, and $u[t] \in \{0,1\}$, is a binary variable that indicates charging ($u = 0$) or discharging ($u = 1$). Constraints (14) and (15) provide the limits on the BESS charging and discharging power, respectively. Constraint (16) describes the change in state of charge from one time instant to the next. Note that no self-discharge or efficiency is modeled currently, but these could be easily incorporated into constraint (16). Finally, Constraint (17) describes the limits on the state of charge.

As a post-processing step after the optimization solves, total exported power can be calculated as:

$$P_{\text{export}}[t] = P_{\text{flexible}} \cdot pv[t] + b_{\text{discharge}}[t] - \left(b_{\text{charging}}[t] + P_{\text{curtailment}}[t]\right). \tag{18}$$

In words, Equation (18) states that the net export power is the difference between solar and battery exports ($P_{\text{flexible}} \cdot pv[t] + b_{\text{discharge}}[t]$) minus battery charging and curtailment $\left(b_{\text{charging}}[t] + P_{\text{curtailment}}[t]\right)$.

2.5 Economic Analysis

The economic analysis is based on the hourly export, $P_{\text{export}}[t]$, for each scenario and is based loosely on the New York State Energy Research and Development Authority (NYSERDA) Value Stack Calculator[6]. The main use of the calculator is to extract hourly prices in $/kWh. The value stack is comprised of the following components:

- DRV (demand reduction value)
- LSRV (locational system relief value)

[6] https://www.nyserda.ny.gov/All-Programs/NY-Sun/Contractors/Value-of-Distributed-Energy-Resources/Solar-Value-Stack-Calculator

- Community Credit
- System Capacity
- Energy
- Environmental value

For the following analysis all value streams except for DRV are lumped together as one price, $c_{\$}[t]$, while DRV is indicated separately as $c_{\mathrm{DRV}}[t]$. The reason is that there is an additional yearly scaling factor, $f_{\mathrm{DRV}}[y]$, for the DRV benefit that needs to be accounted for.

A yearly degradation factor d is applied to the production of the plant, an escalation factor s is applied to account for inflation, and a discount rate r is applied for the cost of capital in the CAPEX calculation.

2.5.1 Revenue

Yearly revenue for the initial year, $y = 0$, is based on the exported power and calculated as:

$$R_0 = \sum_t P_{\mathrm{export}}[t][\mathrm{kWh}] \times c_{\$}[t][\$/\mathrm{kWh}]$$
$$R_{0,\mathrm{DRV}} = \sum_t P_{\mathrm{export}}[t][\mathrm{kWh}] \times c_{\mathrm{DRV}}[t][\$/\mathrm{kWh}]. \quad (19)$$

The total yearly revenue for year y (in that year's dollars) for the duration of the project is then estimated as:

$$R[y][\$] = \left(R_0 + R_{0,\mathrm{DRV}} \cdot f_{\mathrm{DRV}}[y]\right) \times (1-d)^y \times (1+s)^y. \quad (20)$$

2.5.2 Capital Costs

Capital costs are considered on an annualized basis, plus a yearly operation and maintenance cost, $O\&M[y]$, that is escalated to inflation. For a project lifetime of n years, the annualized cost is calculated as:

$$C_{\mathrm{annualized}} = C_{\mathrm{total}} \times \frac{r}{1-(1+r)^{-n}}, \quad (21)$$

where C_{total} is the total CAPEX in today's dollars. The total yearly cost, for year y, in that year's dollars is then calculated as:

$$C[y] = C_{\mathrm{annualized}} + O\&M \times (1+s)^y. \quad (22)$$

2.5.3 Profit

The profit for any given year is:

$$P[y] = R[y] - C[y], \quad (23)$$

and can be considered over the lifetime of the project on a net present value (NPV) basis:

$$NPV = \sum_{y=0}^{n-1} \frac{P[y]}{(1+r)^y}. \tag{24}$$

A key comparison between the scenarios is how their NPV compares; the larger the NPV, the better. The NPV can also be seen as the maximum upgrade cost the project can tolerate before it begins to lose money.

2.5.4 Upgrade Equivalent Cost

One of the challenges of flexible interconnection is to grasp the impact of curtailment, which can be viewed as an opportunity cost. One of the questions that may face a potential interconnection customer is what it is preferable: pay for a system upgrade to allow for a higher capacity project, or accept some curtailment?

Since the logic behind what upgrades might be required for a given interconnection may be dependent on many factors, not to mention the design concept of the system in question, weighing flexible interconnection against a concrete upgrade is challenging in a hypothetical situation. Instead, this report uses the opportunity cost of curtailment as an upper bound for desirable upgrades. The idea is that any upgrade that is cheaper than the opportunity cost incurred through curtailment is preferable to flexible interconnection. Conversely, the financial impact of curtailment is preferable over that of any upgrade whose cost exceeds the opportunity cost of curtailment.

The opportunity cost of curtailment is calculated much the same way as the revenue in Section 2.5.1 (19)-(20), except that instead of accounting for $P_{\text{export}}[t]$, the curtailment power, $P_{\text{curtailment}}[t]$, is used:

$$\begin{aligned}
R_{0,\text{curtailment}} &= \sum_t P_{\text{curtailment}}[t][\text{kWh}] \times c_{\$}[t][\$/\text{kWh}] \\
R_{0,\text{DRV, curtailment}} &= \sum_t P_{\text{curtailment}}[t][\text{kWh}] \times c_{\text{DRV}}[t][\$/\text{kWh}]. \\
R_{\text{curtailment}}[y][\$] &= \left(R_{0,\text{curtailment}} + R_{0,\text{DRV,curtailment}} \cdot f_{\text{DRV}}[y]\right) \times (1-d)^y \times (1+s)^y.
\end{aligned} \tag{25}$$

The opportunity cost over the lifetime of the project can be calculated like (24) as:

$$NPV_{\text{curtailment}} = \sum_{y=0}^{n-1} \frac{R_{\text{curtailment}}[y]}{(1+r)^y}, \tag{26}$$

where $NPV_{\text{curtailment}}$ is the net present value of curtailment, which represent its opportunity cost in present day dollars. This analysis suggests that flexible interconnection is financially sound for any project where the upgrade costs is *greater* than $NPV_{\text{curtailment}}$.

2.5.5 Deferred Upgrade

While the previous analysis considers flexible interconnection as avoiding an upgrade entirely, there are potentially issues with such a paradigm, that have to do with what happens in subsequent years when upgrades are eventually performed on the feeder. An alternative or additional application for flexible interconnection is as a trade of time for money, due to the delay in completing construction on upgrades. Rather than wait, a project could choose to interconnect early under a flexible interconnection agreement, until the upgrade is completed.

In this sort of situation, the upgrade cost needs to be factored into the capital cost calculation of the project. In addition, however, a question arises whether it makes sense to interconnect quickly or wait and produce with guaranteed zero curtailment from day one.

Once again, the curtailment NPV can be used, but this time, as a function of time until the upgrade is complete:

$$NPV_{\text{curtailment}}[y] = \sum_{y'<y} \frac{R_{\text{curtailment}}[y']}{(1+r)^{y'}}, \tag{27}$$

where y in this case represents the year in which the upgrade is completed[7]. This is illustrated as a curve in Figure 3. Upgrades, whose cost lie below this curve are cheaper than the opportunity cost of curtailment and therefore, it is worth waiting for them rather than taking a flexible interconnection. For all upgrades with costs above this curve, but below the project NPV, it is preferable to interconnect quickly as the opportunity cost of curtailment is cheaper than waiting.

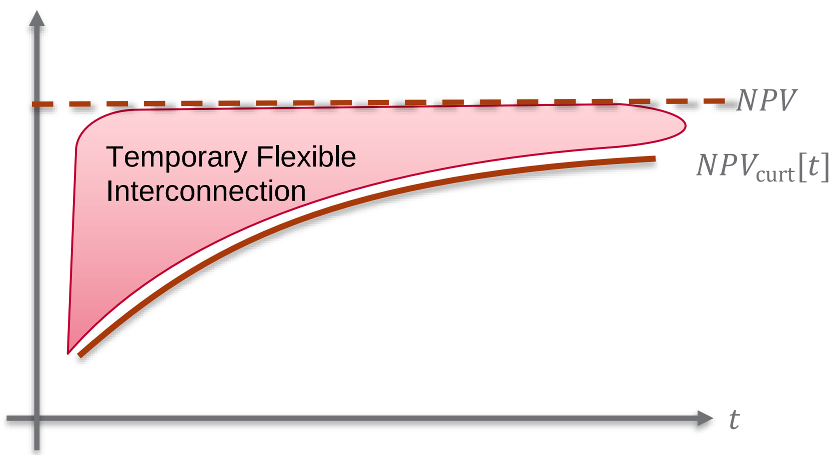


Figure 3 Viable region for temporary flexible interconnection lying between the opportunity cost of curtailment and the project lifetime net present value.

[7] Note that if $y = n$, the lifetime of the project, this just becomes the single $NPV_{\text{curtailment}}$ from (26).

3 Case Studies

The code to run all the case studies presented is available on the PNNL i2x GitHub: https://github.com/pnnl/i2x/.

3.1 Base Model

The model chosen for the simulation is the 9500 Node Test System developed by PNNL. This model is an extension of the widely used IEEE 8500 Node Test Feeder and is currently being validated to become an IEEE test case to help increase adoption and widespread usage among both academia and industry. It is a full-size model representative of a section of a utility's distribution system with multiple feeders fed from different substations. The model includes multiple distribution circuits, a sub-transmission system, multiple substations, behind the meter customer rooftop photovoltaics (PV), and multiple utility-scale distributed energy resources. To enable accurate simulations of operational scenarios, the 9500 Node Test System is designed to support procedure-based operations, with the ability to realistically demonstrate switching operations, feeder reconfiguration, adjustment of volt-var control equipment, dispatch of distributed generation, and response to planned and unplanned outages. This system is depicted in Figure 4. A full description of the system and other details can be found in [4].

Figure 4: System Overview

The 9500 Node System was originally developed for static or 'snapshot' analysis. For this work several modifications were made to the system in order to create a baseline for time-series analysis. The modifications are now summarized.

3.1.1 Load Profile

A time series consisting of 8760 entries, corresponding to hourly values over a full year, is used as the load profile. This profile was developed by EPRI, and it is referred to as LoadShape4. It can be found as an example load profile in OpenDSS. Simulation time steps are set to one hour. The time series is shown in Figure 5.

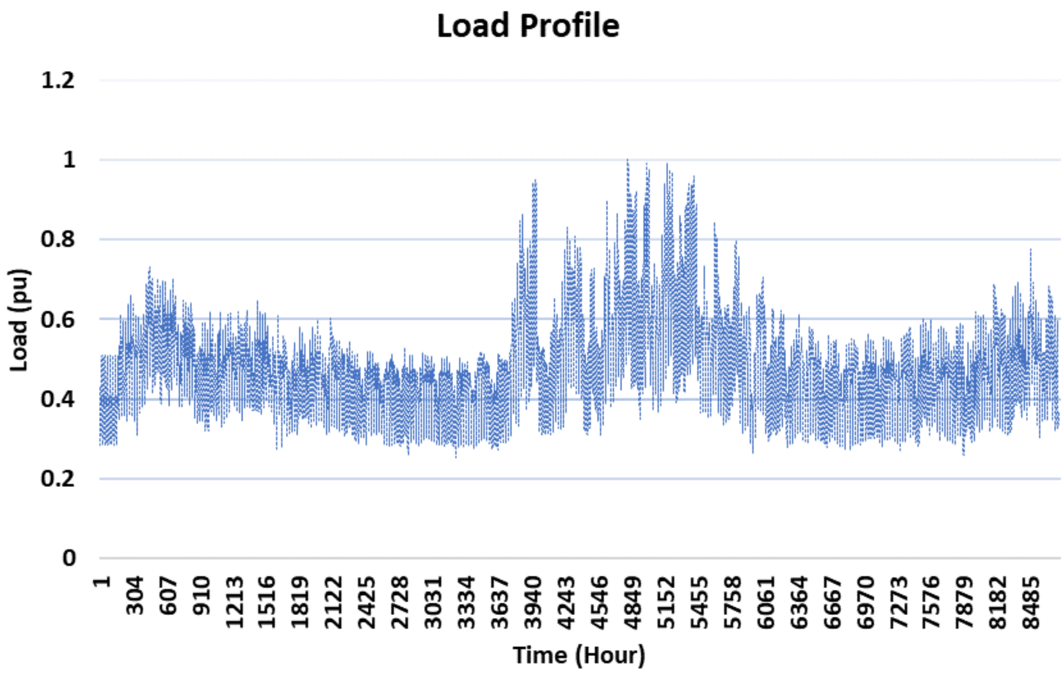


Figure 5 Hourly Load Profile

3.1.2 PV System Profile

In order to generate results that emulate real PV systems, an irradiance profile was applied so the PV profile would be more authentic. This irradiance profile changes over time and is based on the intensity of the sun during a day with clear weather conditions. This is a 24-hour profile that is repeated 365 times. The irradiance profile can be easily disabled or modified to approximate a wide range of operating conditions. In this work all PV systems follow the same profile[8], however this can be modified as needed. Figure 6 illustrates the irradiance profile over a 48-hour period. This profile drives the power output of PV systems such as the one shown in Figure 7. It can be observed that times of high irradiance correspond to peaks in power production. In OpenDSS, a negative power flow at a source indicates that the source is providing (injecting) power into the gird, since the meter object that is measuring assume a load sign convention.

[8] Note that this refers to all the *existing* systems in the system. Consideration for *new* installations as described in Section 3.3, considers a different profile that varies over the year. The choice of a sunny day profile for the existing systems can be seen as a conservative assumption to make sure that none of the capacity reserved for these resources might be overlooked.

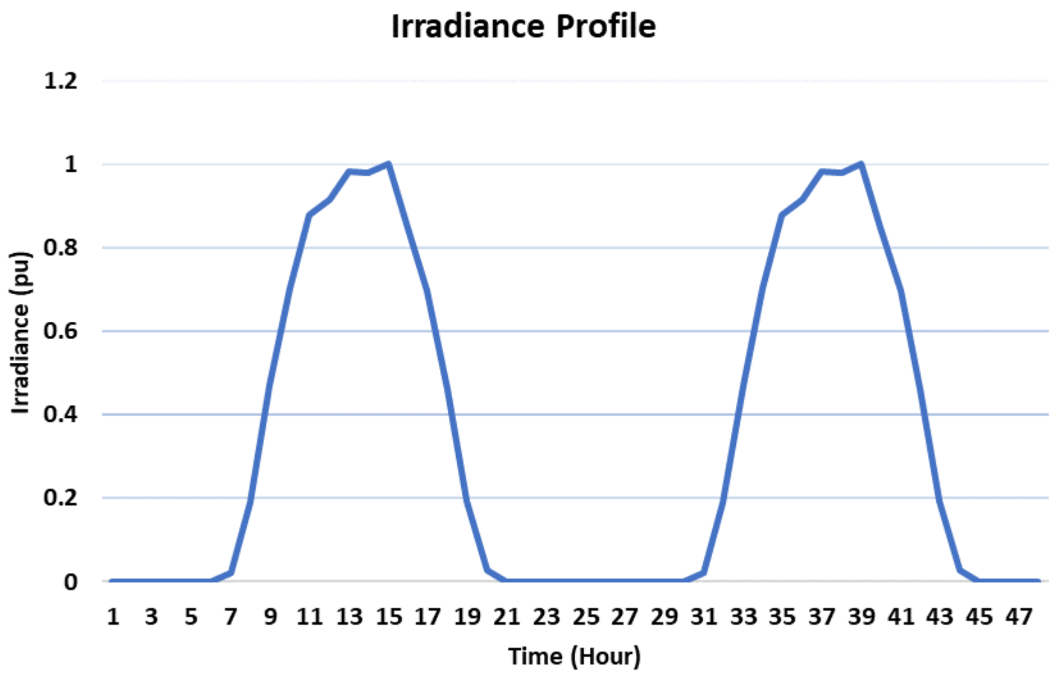


Figure 6 Irradiance Profile

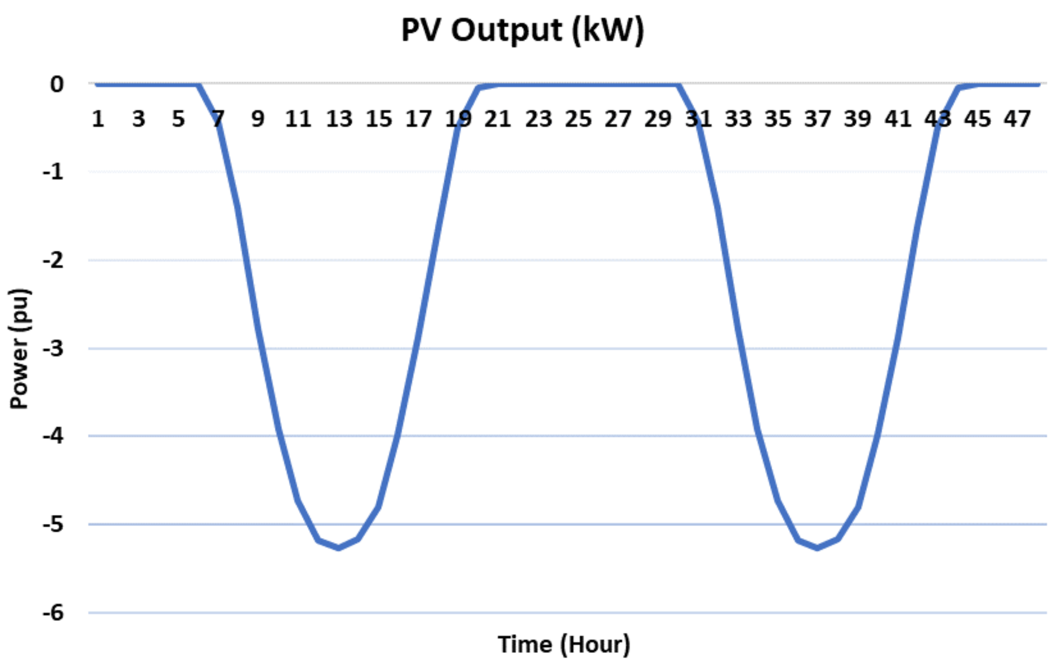


Figure 7 PV Output

3.1.3 Battery Operation

The existing BESS in the feeder was simulated to cycle between charging and discharging as illustrated in Figure 8. The BESS charges during periods of high PV power output, and discharges during the late afternoon/early evening hours in response to load peaks; the discharge cycle continues throughout the night under lower power injection. In Figure 8, BESS cycles are presented in terms of kWh stored with respect to nameplate capacity. This is consistent with the power output of the system as depicted in Figure 9.

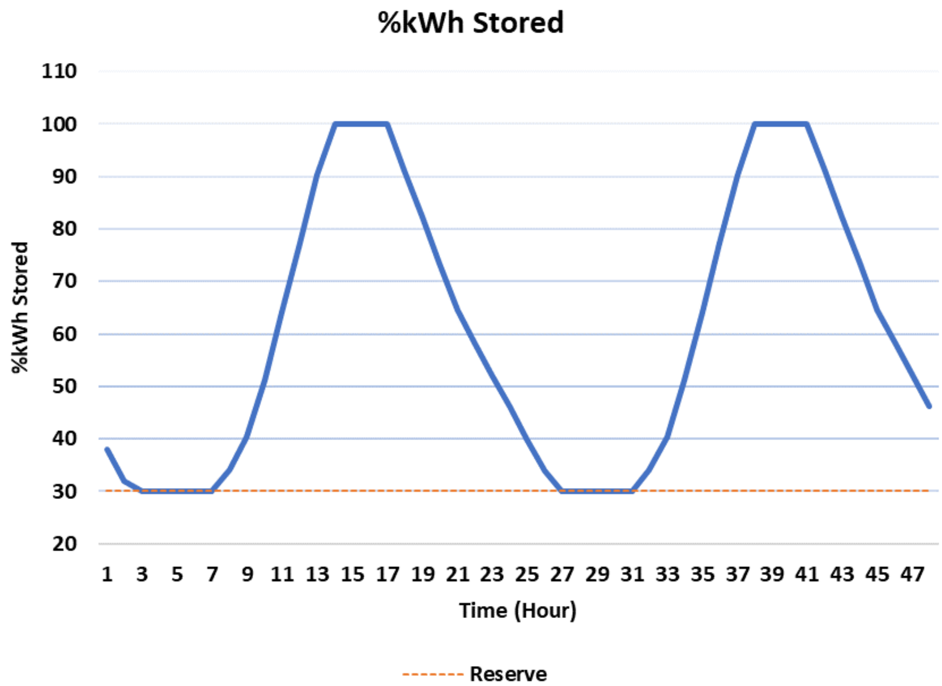


Figure 8: %kWh Stored

Figure 9 shows that the BESS charges during the morning and early afternoon hours and then begins discharging in the early evening hours and reaches reserve thresholds in the early hours of the following day. In this work, the reserve capacity was set to 30% of the rated capacity, meaning that batteries will stop discharging once they reach this value, except during emergencies. As previously mentioned, negative power indicates power injections to the grid. In this case during hours 16 to 26, the BESS injects power and then charges during hours 26 to 41.

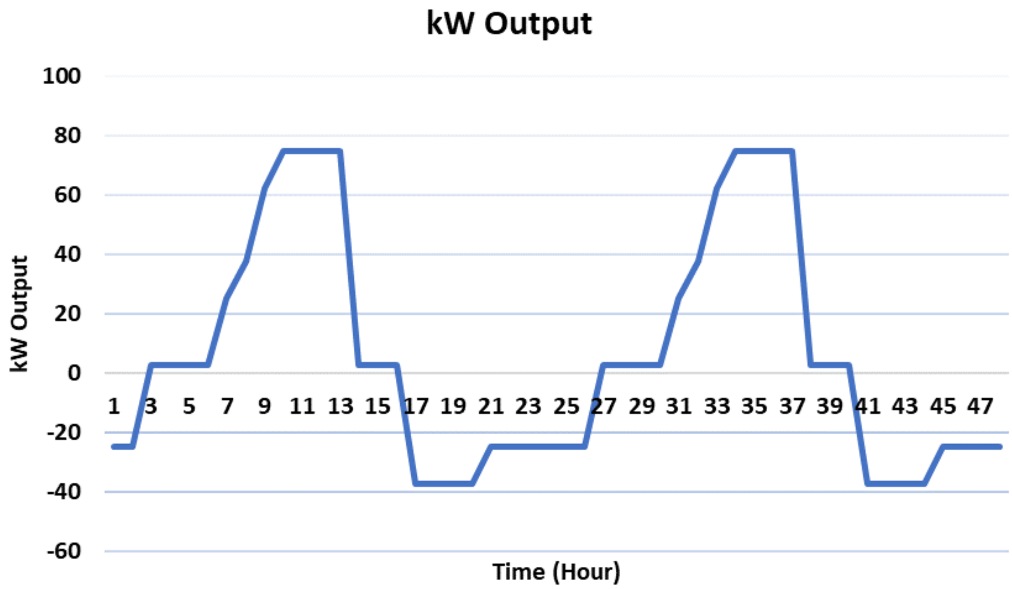


Figure 9: kW Output

3.1.4 Generator Dispatch

As mentioned earlier, the simulations for this project were carried out using the 9500 Node Test Feeder, and several DER were already present in the model before adding the solar PV community projects for this project. The largest generator in the system (SteamGen1, 4000 kVA, 3000kW), was found to be operating as a reactive power sink, which led to a relatively low power factor (0.68) and undervoltage issues brought on by the high degree of reactive power being absorbed by the generator. The issues were initially rectified in the model by setting voltage regulation systems to unusually high values. To provide more common operating conditions, dispatch curves were provided for SteamGen1. This produces the power output illustrated in Figure 10.

It can be observed that StemGen1 now operates as a source for both real and reactive power, with an equivalent power factor of 0.8 leading. The total power injection is around 940 kVA, which corresponds to roughly 24% of its nameplate capacity.

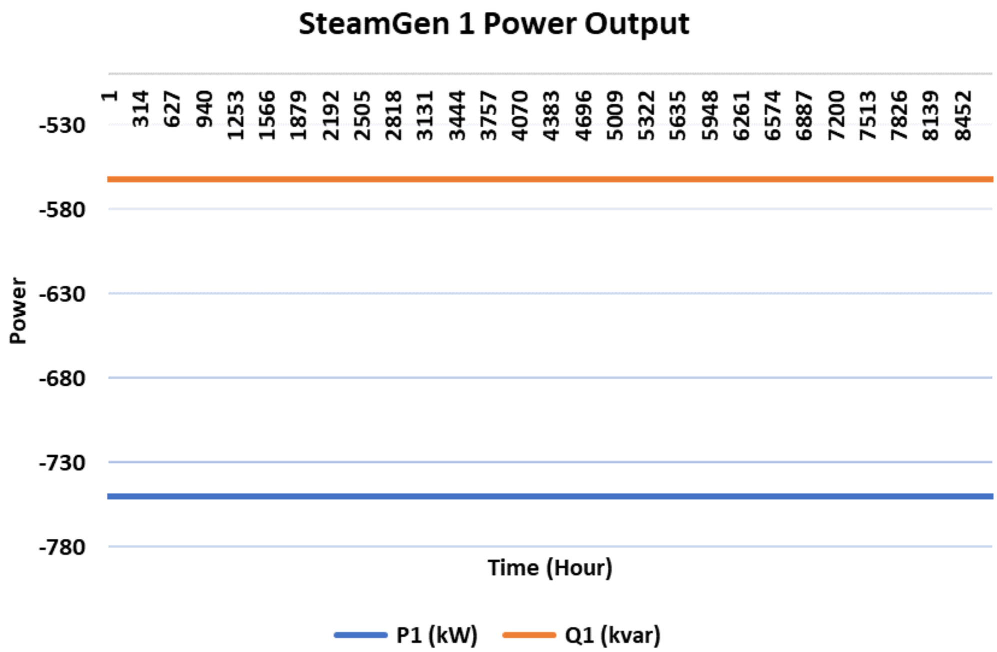


Figure 10: SteamGen1 Power Output

3.1.5 Voltage Control Settings

Modifying the operating condition of SteamGen1 increased the reactive power in the system, which made it possible to lower all voltage regulator set points. Figure 11 shows the tap positions of Transformer.VREG2_A during 48 hours of operation. This is a 32-step regulator with 16 raise taps and 16 lower taps. The changes in tap position in Figure 11 produce the voltage profile in Figure 12.The result is a system that can support a time-varying load with acceptable levels of robustness as illustrated in Figure 13, which shows the minimum and maximum voltage values in the system during each time step. The assumed limits, 0.95 and 1.05, are never reached in this base case.

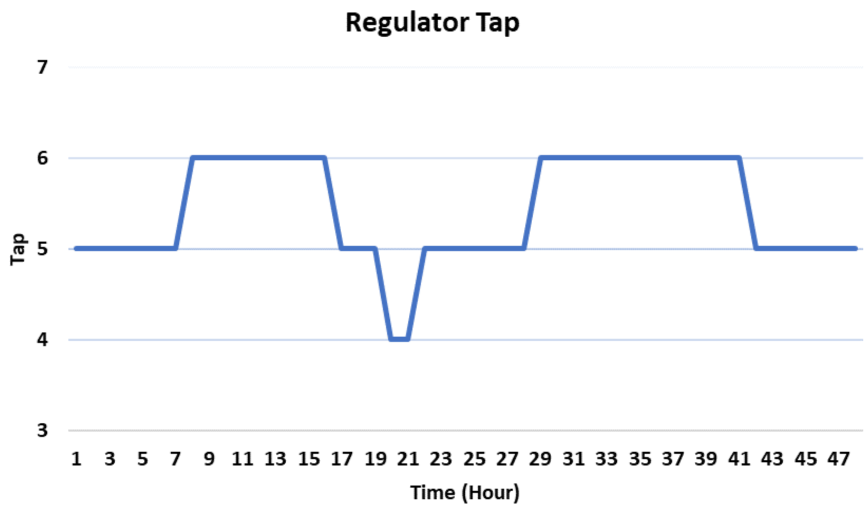


Figure 11: Regulator Tap Position

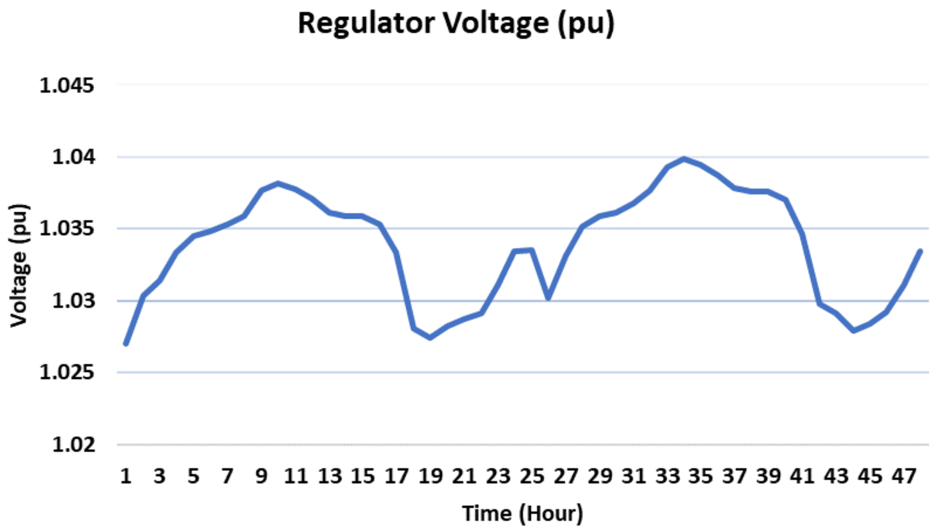


Figure 12: Voltage Profile at Regulator

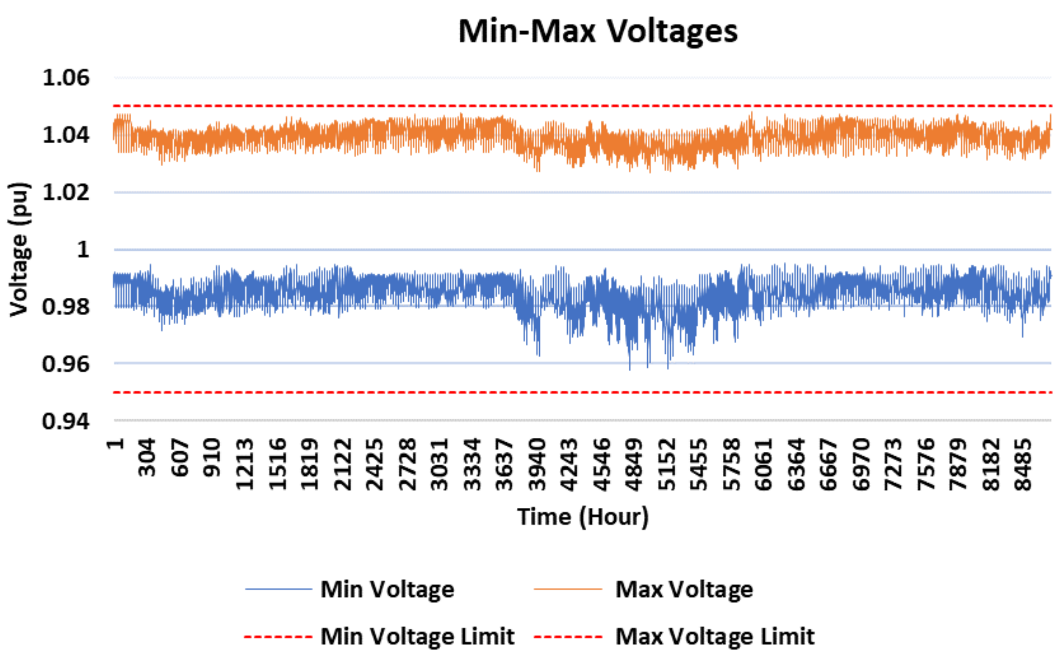


Figure 13: Min and Max voltages per time step

3.1.6 Modifications from Base Case

The modifications made from the original model are summarized in Table 4. The changes were necessary to produce a realistic operating feeder as a baseline that would result in valid results for the flexible interconnection studies. Settings and parameters not listed in Table 4 were left as found per Table 6 in [4].

Table 4: Modifications

Device	Description	Previous Setting	New Setting
Source Bus	Lowered voltage	1.05 p.u.	1.01 p.u.
SteamGen1	Updated set points using dispatch curves	1000 kW -1049.5 kVA (consuming VARs)	750 kW 560 kVA
PV Systems	Added variable solar irradiance	Fixed at 100% irradiation	Time varying irradiance profile
Battery Systems	Enabled time varying operation	Fixed at Off (Idling)	Time varying charge/discharge cycles
Feeder Regulator 1A-1C	Lowered voltage and band settings	Vreg/revreg = 123 Band = 2	Vreg/revreg = 120 Band = 1
Feeder Regulator 2A-2C	Lowered voltage and band settings	Vreg/revreg = 123 Band = 2	Vreg/revreg = 120 Band = 1
Feeder Regulator 3A-3C	Lowered voltage and band settings	Vreg/revreg = 126 Band = 2	Vreg/revreg = 123 Band = 1
Regulator VREG2_A-C	Lowered voltage and band settings	Vreg/revreg = 125 Band = 2	Vreg/revreg = 120 Band = 1
Regulator VREG3_A-C	Lowered voltage and band settings	Vreg/revreg = 125 Band = 2	Vreg/revreg = 120 Band = 1
Regulator VREG4_A-C	Lowered voltage and band settings	Vreg/revreg = 125 Band = 2	Vreg/revreg = 120 Band = 1
Transformer.T2001014B	Increased size (kVA) to avoid overload	KVA=25	KVA=50
Transformer.T2001015B	Increased size (kVA) to avoid overload	KVA=25	KVA=50
Transformer.T225571845B	Increased size (kVA) to avoid overload	KVA=15	KVA=25
Line.TPX2001400C0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex
Line.TPX21396815C0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex
Line.TPX21399326C0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex
Line.TPX2221108404B0	Increased	4/0 Triplex	750 Triplex

Device	Description	Previous Setting	New Setting
	conductor size to avoid overload		
Line.TPX2221108405C0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex
Line.TPX2221108407B0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex
Line.TPX2226061820B0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex
Line.TPX338899C0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex
Line.TPX338915C0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex
Line.TPX338924C0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex
Line.TPX338943C0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex
Line.TPX338968C0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex
Line.TPX338978C0	Increased conductor size to avoid overload	4/0 Triplex	750 Triplex

3.2 Data Inputs

3.2.1 Time Series Hosting Capacity

The time series hosting capacity is calculated as described in Section 2.1. The energy storage setpoints and voltage regulation set points for the entire year of the base model are saved and played in during the hosting capacity calculation. This ensures that at each hour of the hosting capacity analysis, the system looks as it did in the base model, with the new DER addition being the only difference. There are other methodologies for performing hosting capacity, that allow for more response from the rest of the system. However, keeping the base system static is the current industry standard and is a conservative estimate.

3.2.2 Solar Profile

The solar profile in Figure 14, comes from NREL's ReVX tool[9]. The data are based on 2009 weather data with location coordinates $42.803° \text{ N}, 73.375° \text{ W}$, which is in the Hoosick area of New York state. The location was selected because several of the examples provided by National Grid sought interconnection at the Hoosick substation.

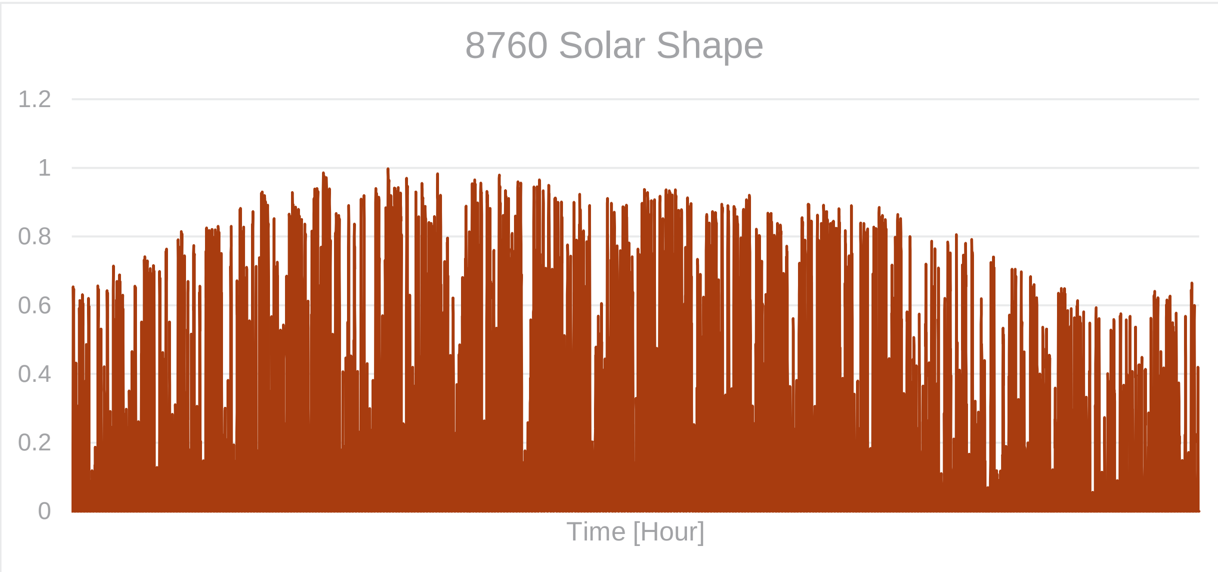


Figure 14 Unitized solar shape used for the interconnection evaluations.

3.2.3 Energy Price

The energy price is extracted from the NYSERDA value stack calculator[10] for one of the National Grid nodes. The 8760 element time-series used for the analyses is illustrated in Figure 15.

[9] https://github.com/NREL/reVX

[10] https://www.nyserda.ny.gov/All-Programs/NY-Sun/Contractors/Value-of-Distributed-Energy-Resources/Solar-Value-Stack-Calculator

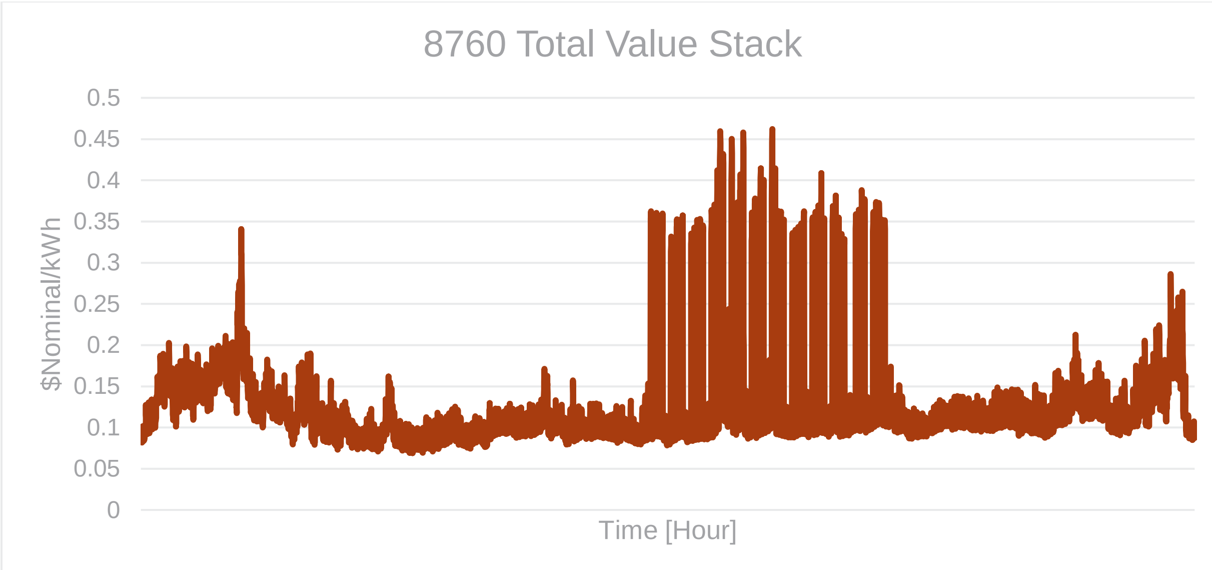


Figure 15 Time series energy price used for the interconnection evaluations.

3.2.4 Capital Costs

Capital costs are based on NREL's 2023 Annual Technology Baseline (ATB)[11]. The PV costs are based on the utility-scale data shown in Figure 16, and the BESS costs are based on the 2-hour utility-scale battery storage data shown in Figure 17. The ATB has a combination of solar and storage option[12], however, this forces the use of 4-hour batteries. A key assumption in the cost calculation of the hybrid plant, is that the PV and BESS share an inverter (are DC linked), and therefore, there are some inverter cost savings. To replicate this assumption, the cost of the central inverter in $/kW is compared to the complete costs as shown in Figure 18. This shows that the central inverter makes up around 5.5% of the $/kW cost of the batter. In the solar and storage scenarios, this savings is applied to the BESS CAPEX. In addition, the values for escalation, degradation, and discount are defaults form the NYSERDA value stack. The quantities used to calculate capital costs are based on 2024 values and summarized in Table 5.

Table 5 Capital Costs

	PV	BESS	Source
CAPEX [$/kW]	1289.51	979.97	2023 ATB
CAPEX Inverter Savings [%]	0	5.5	2023 ATB
Fixed O&M [$/kW-a]	20.99	24.50	2023 ATB
Escalation [%/a]	2	2	NYSERDA Value Stack Calculator

[11] https://atb.nrel.gov/electricity/2023/index
[12] https://atb.nrel.gov/electricity/2023/utility-scale_pv-plus-battery

	PV	BESS	Source
Degradation [%/a]	0.5	0.5	NYSERDA Value Stack Calculator
Discount Rate [%/a]	8	8	NYSERDA Value Stack Calculator

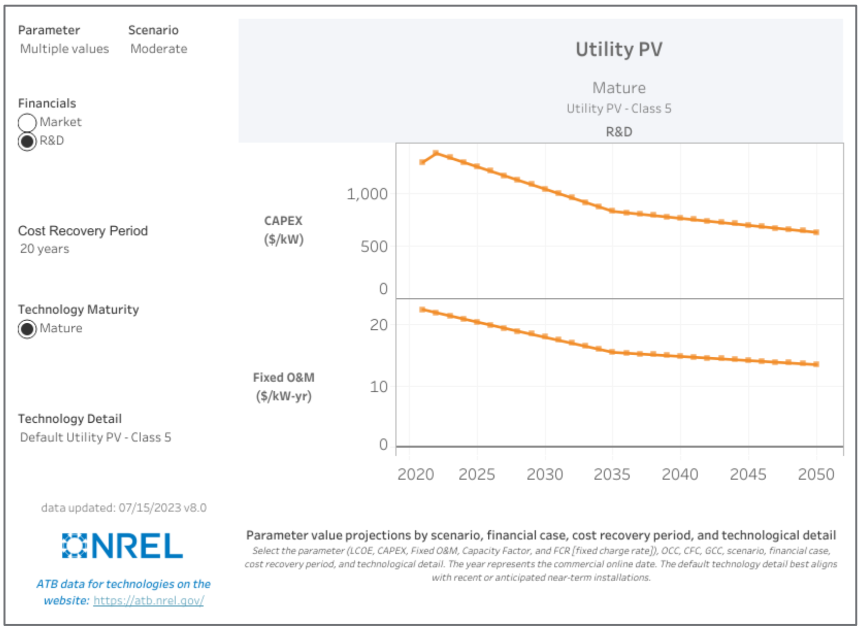


Figure 16 Capital cost configuration for solar PV.
Source: https://atb.nrel.gov/electricity/2023/utility-scale_pv

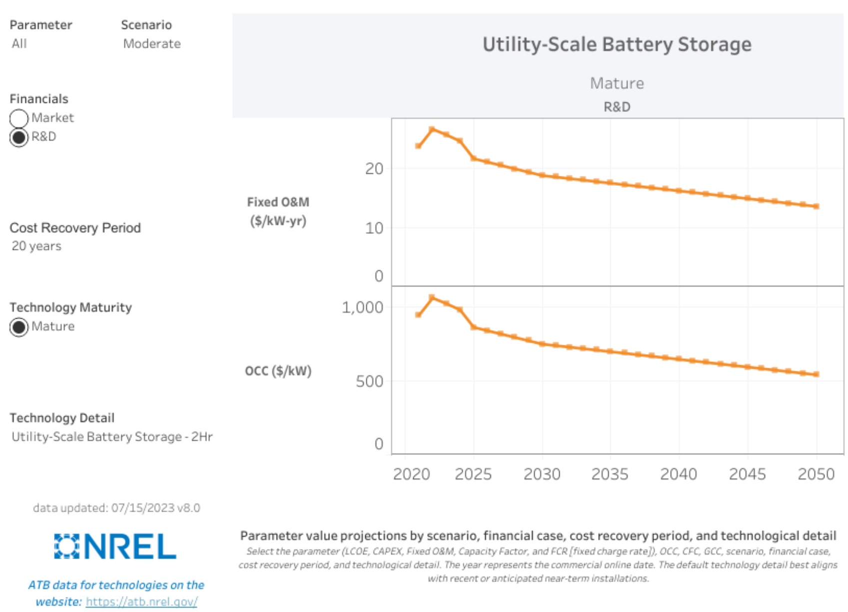


Figure 17 Capital cost configuration for BESS.
Source: https://atb.nrel.gov/electricity/2023/utility-scale_battery_storage

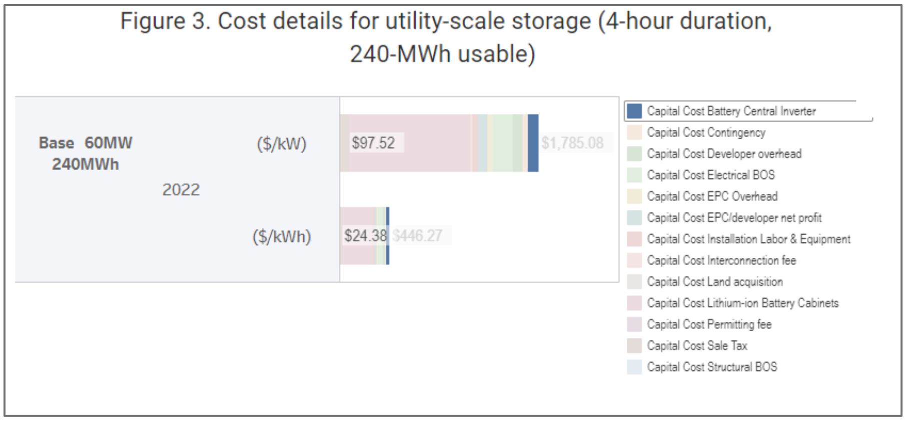


Figure 18 Makeup of central inverter as part of BESS cost.
Source: https://atb.nrel.gov/electricity/2023/utility-scale_battery_storage

3.3 Location Specific Results

The following section presents results for three different node locations on the 9500 Node Test Feeder. Figure 19 illustrates their relative locations on the feeder, in addition to relevant details of the equipment directly around them. Note that all locations considered are 12.47 kV, 3-phase buses.

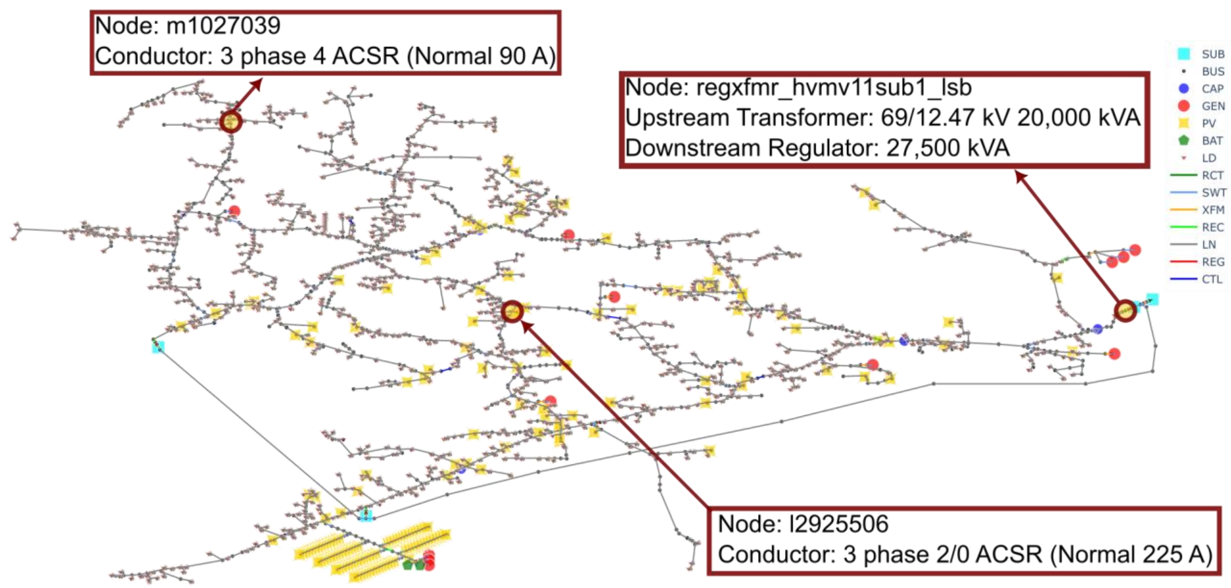


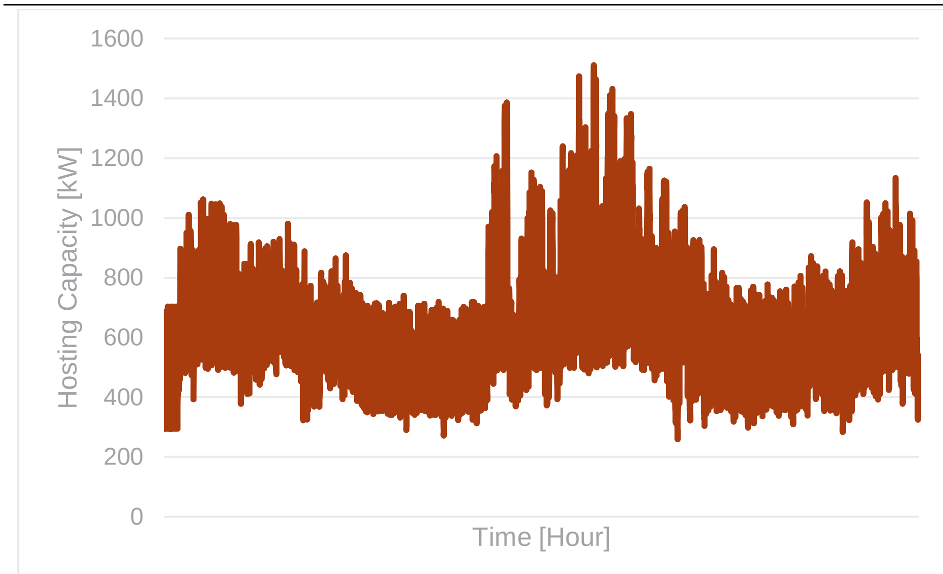
Figure 19 Locations under investigation on the 9500-node feeder. The substations are light blue squares in the figure.

The physical location of the point of interconnection can have a significant impact on the overall capacity of a DER that may be interconnected. For this reason, the PNNL team selected nodes that could be considered closer to the substation with larger conductors (2/0 ACSR) and another located farther from the substation with #4 ACSR. ACSR stands for Aluminum Conductor Steel Reinforced and is a class of overhead conductors. Conductors are available in an array of sizes and designs ranging from larger gauge (Example 795 ACSR) to very small (#4 ACSR). Typically, conductors diminish in size and rated capacity with distance from the substation, as electrical load concentration follows the same pattern. The team chose the location with #4 ACSR to assess to what extent the rated DER capacity was affected by the conductor size and to see how flexible interconnection could mitigate the limitations of the smaller conductors.

Raw results, such as NPV or total energy produced are *not* intended to be compared between locations, because the systems modeled at the different locations differ by orders of magnitude. Instead, the question being asked is: *Given* a point-of-interconnection, what is the most that can be achieved and under which interconnection concept?

3.3.1 Node m1027039 with 8760 Hosting Capacity

Of the three nodes, this location is the farthest away from a source and has the lowest rated conductor. Figure 20 shows the 8760 hosting capacity along with its order statistics and maximum flexible capacity based on the RVC analysis from Section 2.3. The chosen capacities and yearly operational results, based on the description in Section 2.4, are presented in Table 6.



Percentile	HC [kW]
Min	259.6
10	405.4
25	498.1
50	594
75	71739
90	875
Max	1511.1
RVC Analysis	
R_{sc} [Ω]	4.8744
X_{sc} [Ω]	4.9036
$P_{\text{flexible}}^{\text{max}}$ [kW]	1217

Figure 20 8760 hosting capacity result for node m1027039.

Table 6 Operational Results for node m1027039

	Conventional	**Solar Only**	**Solar and Storage**
$P_{\text{conventional}}$ [kW]	259		
P_{flexible} [kW]		875	875
$r_{\text{kW}}/r_{\text{kWh}}$ [kW/kWh]			620/1240
$\sum_t P_{\text{export}}[t]$ [MWh]	454	1387 (205% of conventional)	1489 (228% of conventional
$\sum_t P_{\text{curtailment}}[t]$ [MWh]		143 (10% of export)	41 (2.8% of export)

The profitability of each configuration, according to Section 2.5.3, in terms of NPV, and the ratio of NPV to the conventional scenario is shown in Figure 21. The NPV underscores that flexible interconnection achieves preferable outcomes to the conventional case, while also indicating that the BESS capital costs do not necessarily justify the curtailment savings.

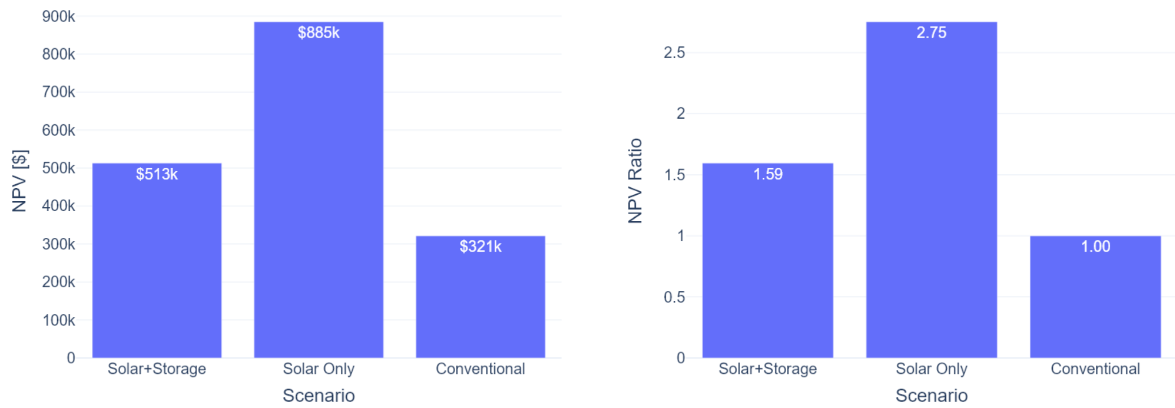


Figure 21 Net present value for the three different scenarios at node m1027039 showing advantage for flexible interconnection. The right panel shows the NPV ratio with respect to conventional interconnection.

Finally, Figure 22 shows the evaluation of the curtailment opportunity cost for the flexible interconnection scenarios with respect to potential upgrade costs. Panel A presents the analysis described in Section 2.5.4, showing that flexible interconnection with BESS is preferable to any upgrade above around $50,000. This stands in contrast to the solar only result, that is only preferable to performing an upgrade if it is below almost $200,000. Panel B illustrates the analysis with respect to deferred upgrades from Section 2.5.5. Focusing on the lower end, the solar and storage option suggests that except for very cheap upgrades (below the blue dotted line) it is worthwhile to interconnect quickly, rather than wait for the upgrade to be complete. For solar only, the curve is a bit steeper, crossing $100,000 around year seven of delays/deferment. These results are discussed further in Section 4.

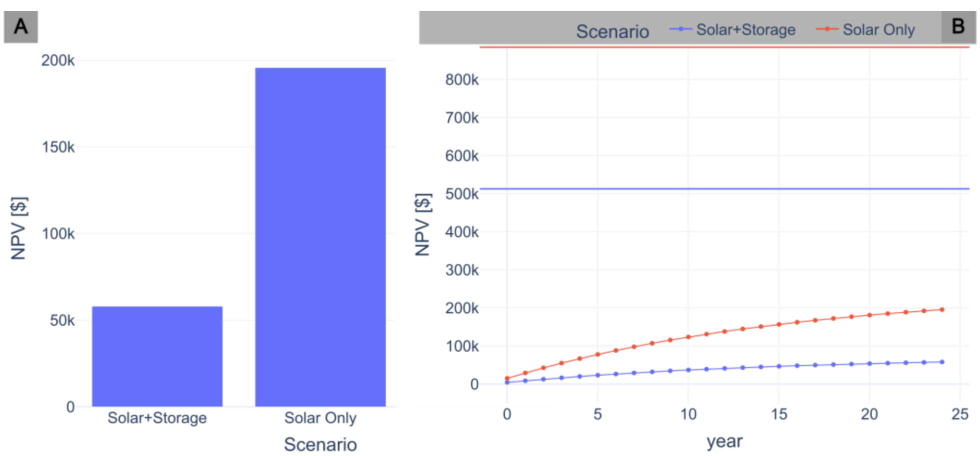
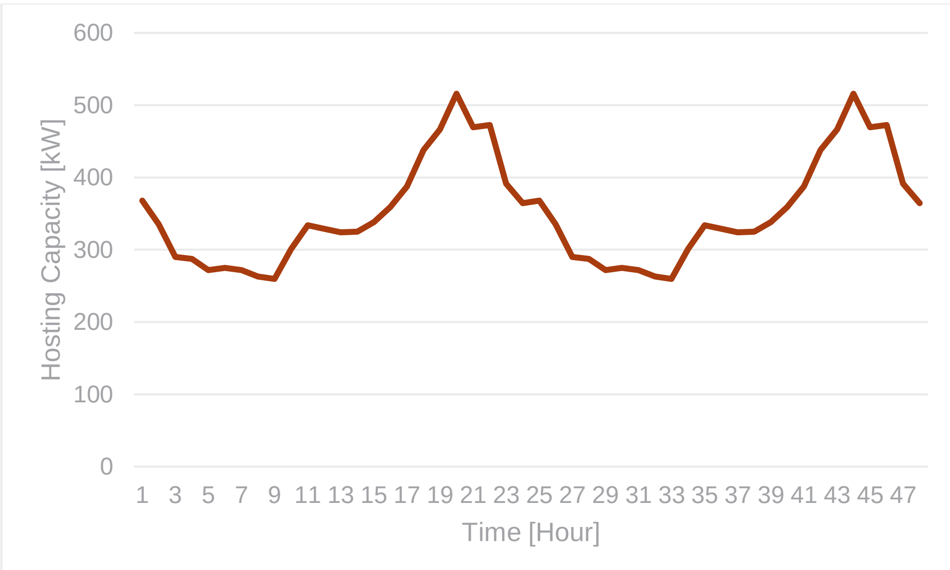


Figure 22 Panel A: Upgrade NPV based on opportunity cost of curtailment. Panel B: Deferred upgrade evaluation. Deferring upgrades for y years with a cost between each set of lines makes sense, as opposed to waiting for the upgrades to complete.

3.3.2 Node m1027039 with Limited Generation Profiles

As described in Section 2.2, an 8760-hour hosting capacity profile may be a challenging assumption. The limited generation profiles are created based on the hourly hosting capacity, and the analysis from Section 3.3.1 is repeated, only based on the daily limited generation profile curve. The resulting time-series hosting capacity, is shown this time for only 48 hours in Figure 23. Note that the maximum hosting capacity is significantly reduced compared to that illustrated in Figure 20, leading to different P_{flexible}, BESS ratings, and therefore, smaller magnitude operational results, as documented in Table 7.



Percentile	HC [kW]
Min	259.6
10	271.9
25	289.5
50	334.4
75	388.3
90	469.4
Max	515.8
RVC Analysis	
R_{sc} [Ω]	4.8744
X_{sc} [Ω]	4.9036
$P_{\text{flexible}}^{\max}$[kW]	1217

Figure 23 Hosting capacity results for node m1027039 based on the daily limited generation profile.

Table 7 Operational results for node m1027039 using the daily limited generation profile.

	Conventional	Solar Only	Solar and Storage
$P_{\text{conventional}}$ [kW]	259		
P_{flexible} [kW]		470	470
$r_{\text{kW}}/r_{\text{kWh}}$ [kW/kWh]			210/420
$\sum_t P_{\text{export}}[t]$ [MWh]	454	756 (167% of conventional)	803 (177% of conventional
$\sum_t P_{\text{curtailment}}[t]$ [MWh]		66 (8.7% of export)	18 (2.2% of export)

The project NPVs still show the same trend in Figure 24, but the margin is decreased. It is worth noting that while the solar only NPV decreased to about 54% of its value with the 8760 $hc[t]$, the solar-and-storage NPV decreased to only 72% of the value with 8760 $hc[t]$. In other words, the solar and storage configuration is more resilient to changes in the underlying hosting capacity profile.

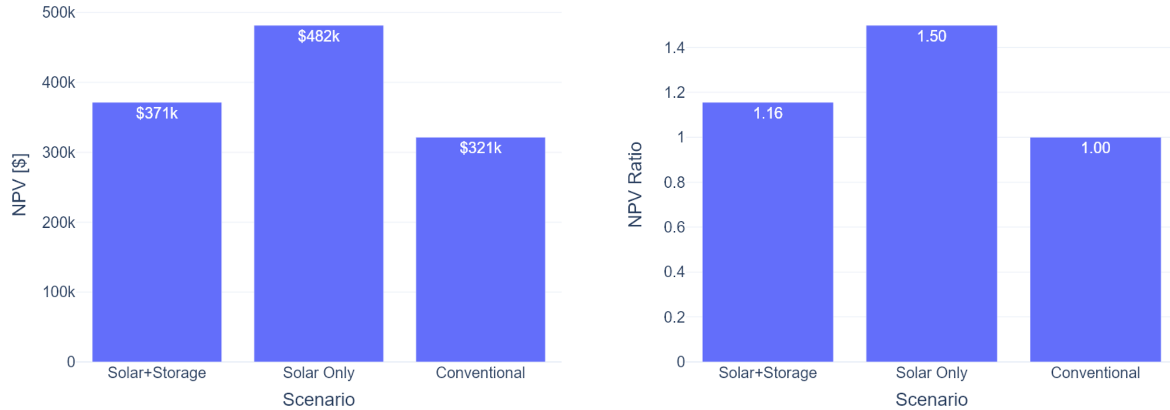


Figure 24 Net present value for the three different scenarios based on the daily limited generation profile. Flexible interconnection options are still preferable to conventional, but with less margin, as also seen in the ratio with respect to the conventional option in the right panel.

The curtailment opportunity cost roughly halves compared to the 8760 hosting capacity profile, as shown in panel A of Figure 25. This is consistent with the shrinking margin of flexible interconnection, as it suggests that simply implementing upgrades is worthwhile at a lower threshold. Finally, panel B of Figure 25, tells a similar story to the 8760 case, where for all but very cheap upgrades, it is preferable to connect and operate flexibly, rather than wait for an upgrade to complete before interconnection.

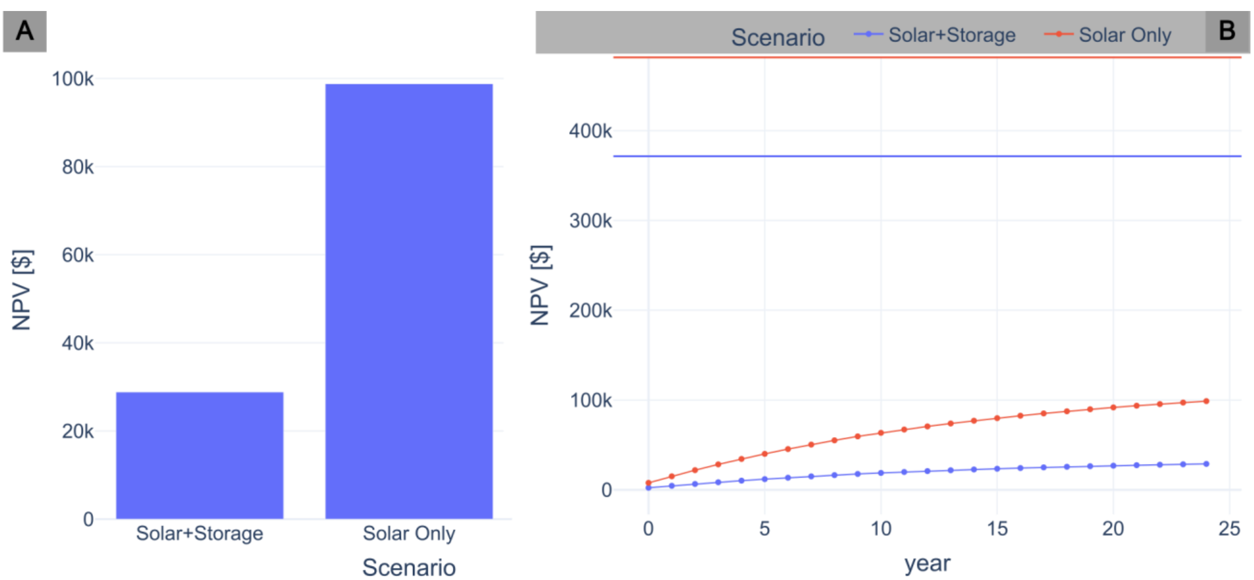
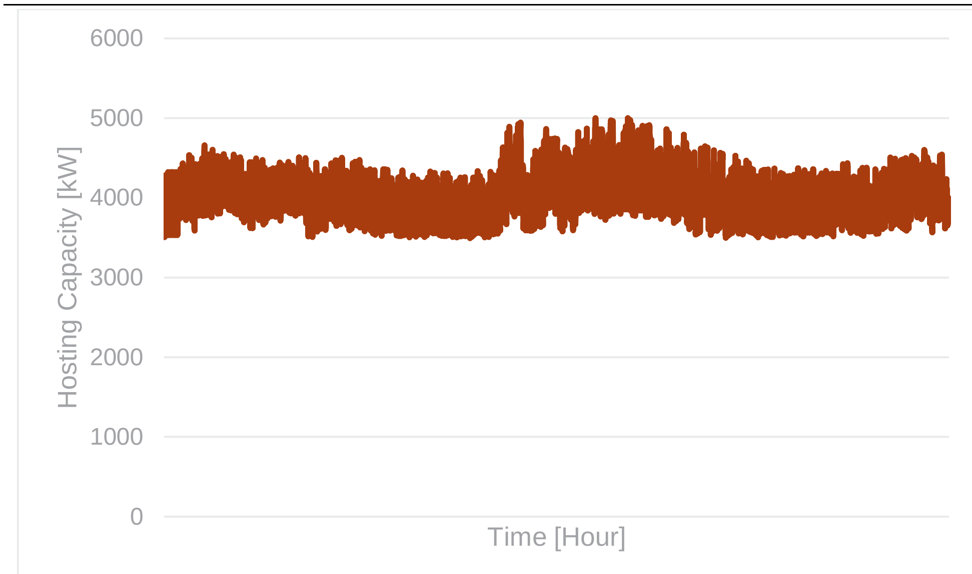


Figure 25 Reproduction of Figure 22 based on results using the daily limited generation profile.

3.3.3 Node l2925506 with 8760 Hosting Capacity

This location is closer to the substation, is connected via a higher capacity conductor (2/0 ACSR versus #4 ACSR in the first case) and is a stronger connection (lower short-circuit impedance) in general. As a result, the hosting capacity, in Figure 26 is not as variable as for node m1027039. The maximum hosting capacity is around 43% greater than the minimum, compared to around 482% for node m1027039. The chosen capacities and yearly operation results, based on the description in Section 2.4, are presented in Table 8.



Percentile	HC [kW]
Min	3493.4
10	3678.2
25	3864.3
50	4040.1
75	4214.2
90	4393.8
Max	4999.9
RVC Analysis	
R_{sc} [Ω]	2.2674
X_{sc} [Ω]	3.5366
$P_{flexible}^{max}$ [kW]	5550

Figure 26 8760 hosting capacity results for node l2925506

Table 8 Operational results for node l2925506

	Conventional	Solar Only	Solar and Storage
$P_{conventional}$ [kW]	3493		
$P_{flexible}$ [kW]		4395	4395
r_{kW}/r_{kWh} [kW/kWh]			900/1800
$\sum_t P_{export}[t]$ [MWh]	6119	7665 (125% of conventional)	7682 (126% of conventional
$\sum_t P_{curtailment}[t]$ [MWh]		17.6 (0.2% of export)	0 (0% of export)

The lower variability in hosting capacity between the conventional, solar only, and solar plus BESS options, is reflected in the spread of NPVs in Figure 27; this appears to make flexible interconnection appear less appealing. The upgrade NPV and deferred upgrade plots are left out in this case because the low curtailment numbers render them uninformative. The solar and storage scenario has no curtailment and therefore the upgrade NPV is likewise zero. For the Solar only scenario, the upgrade opportunity cost is around $20,000, which is very small compared to the size of the plant.

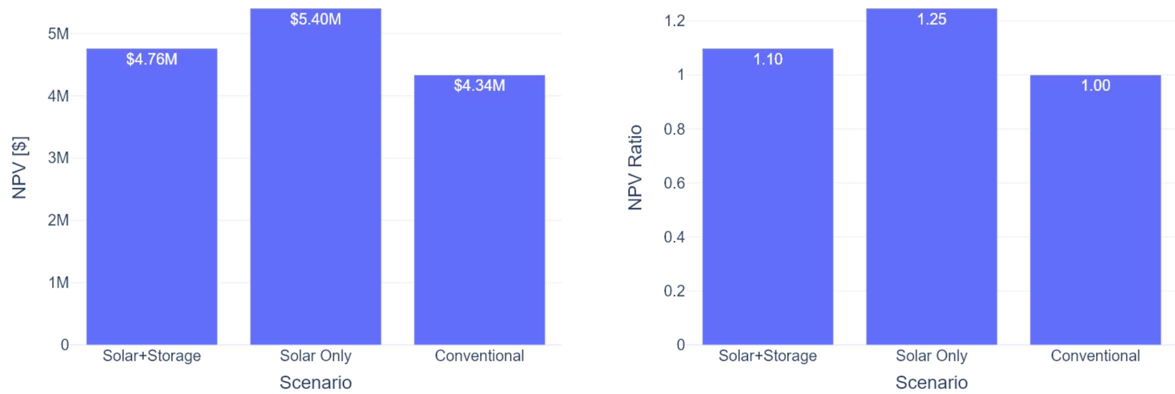
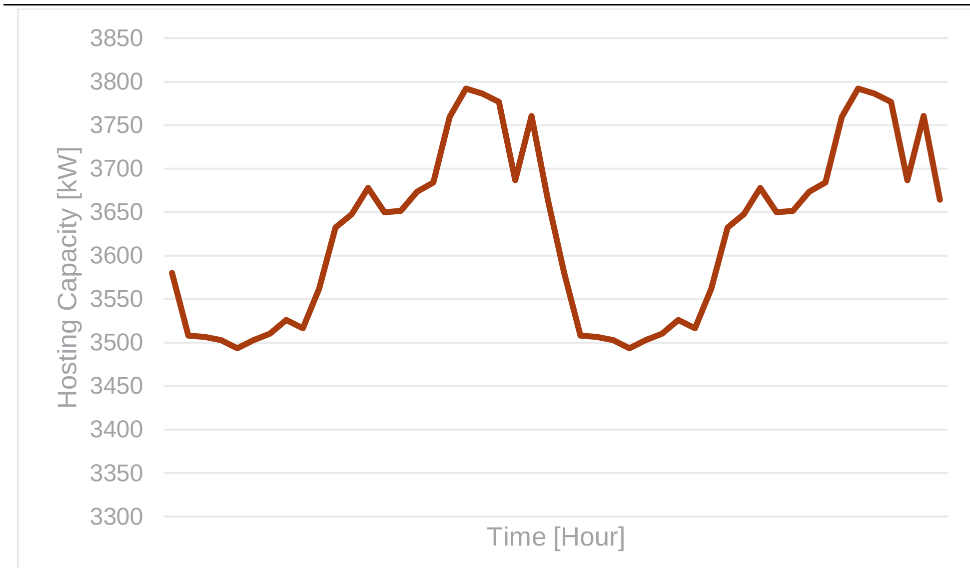


Figure 27 Net present value for three scenarios showing reduced spread due to smaller hosting capacity variability.

3.3.4 Node I2925506 with Limited Generation Profiles

Once again, the analysis is repeated using the daily limited generation profile derived from the 8760 hosting capacity profile. Hosting capacity and operational results are shown Figure 28 and Table 9, respectively.



Percentile	HC [kW]
Min	3493.4
10	3502.8
25	3515.0
50	3648.8
75	3684.7
90	3776.9
Max	3792.1
RVC Analysis	
R_{sc} [Ω]	2.2674
X_{sc} [Ω]	3.5366
$P_{\text{flexible}}^{\text{max}}$[kW]	5550

Figure 28 Hosting capacity results for node I2925506 with the daily limited generation profile.

Table 9 Operation results for node l2925506 with the daily limited generation profile.

	Conventional	Solar Only	Solar and Storage
$P_{\text{conventional}}$ [kW]	3493		
P_{flexible} [kW]		3775	3775
$r_{\text{kW}}/r_{\text{kWh}}$ [kW/kWh]			285/570
$\sum_t P_{\text{export}}[t]$ [MWh]	6119	6597 (108% of conventional)	6599 (108% of conventional
$\sum_t P_{\text{curtailment}}[t]$ [MWh]		1.8 (0.0% of export)	0 (0% of export)

The already relatively flat hosting capacity profile has even less of a range with the limited generation profile, leading to very similar operational results between the scenarios. The result is an even narrower range in NPV between the scenarios, shown in Figure 29. Given such small differences, it is unlikely that flexible interconnection would be desirable over conventional interconnection. The relative upgrade costs are neglected again, for the same reason of near zero curtailment, as in the 8760 profile case.

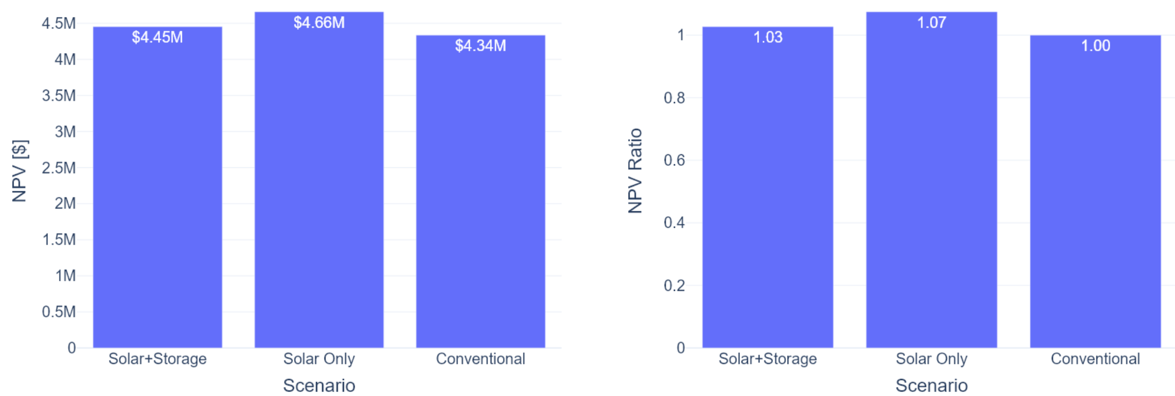
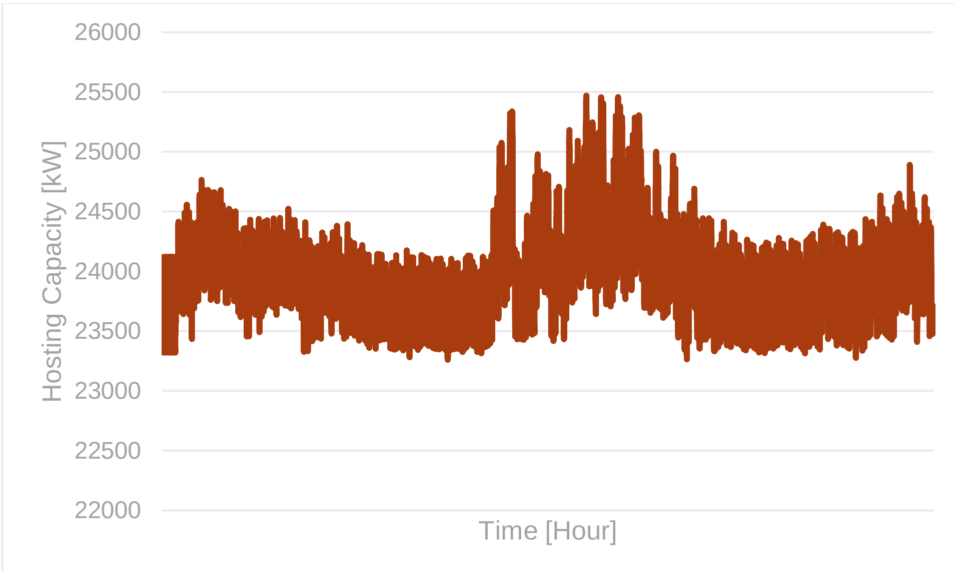


Figure 29 NPV for the three scenarios at node l2925506 using the daily limited generation profile. The spread is reduced further, due to the lower variability in the hosting capacity.

3.3.5 Substation Node with 8760 Hosting Capacity

The final location is right at the substation, at a node called regxfmr_hvmv11sub1_lsb, which for brevity, will simply be referred to as the "substation node." This is a far stronger connection point to a degree such that the active hosting capacity is limited by thermal limits instead of voltage based. It is also far more consistent with only a 9% difference between maximum and minimum hosting capacity, as seen in Figure 30. The operational results presented in Table 10, reveal that the battery brings no added value in this configuration. Given the similarity in capacities, it is not surprising that the NPVs for the three scenarios in Figure 31 are so close to each other. As a result, most upgrades are worthwhile, while interconnecting flexibly while awaiting an upgrade is also always worthwhile, and the plots are not included.



Percentile	HC [kW]
Min	23260.1
10	23490.6
25	23732.2
50	23894.5
75	24127.6
90	24415.9
Max	25468.9
RVC Analysis	
R_{sc} [Ω]	0.1429
X_{sc} [Ω]	0.9387
$P_{\text{flexible}}^{\max}$[kW]	55905

Figure 30 8760 hosting capacity results at the substation node.

Table 10 Operational results for substation node.

	Conventional	**Solar Only**	**Solar and Storage**
$P_{\text{conventional}}$ [kW]	23260		
P_{flexible} [kW]		24400	24400
$r_{\text{kW}}/r_{\text{kWh}}$ [kW/kWh]			1000/2000
$\sum_t P_{\text{export}}[t]$ [MWh]	40747	42650 (105% of conventional)	42650 (105% of conventional)
$\sum_t P_{\text{curtailment}}[t]$ [MWh]		0.8 (0.0% of export)	0 (0% of export)

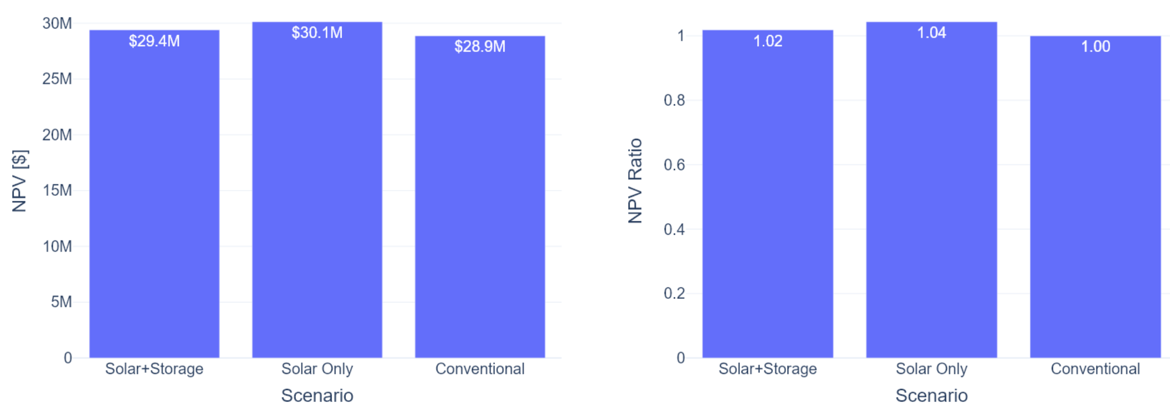
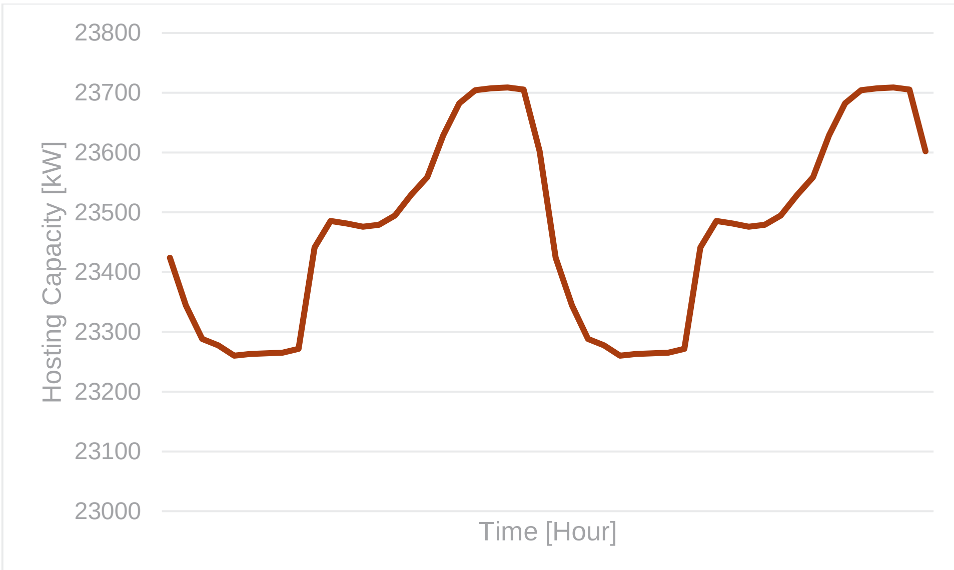


Figure 31 Net present value for the three scenarios at the substation node.

3.3.6 Substation Node with Limited Generation Profiles

Once more, the daily limited generation profile is derived from the hosting capacity hourly series and used for an additional analysis. As already seen in the previous two examples, the use of the limited generation profile reduces the range of the hosting capacity profile leading to reduced operational differences between the scenarios, as seen in Figure 32 and Table 11.



Percentile	HC [kW]
Min	23260.1
10	23264.1
25	23285.6
50	23480.3
75	23608.9
90	23705.3
Max	23708.8
RVC Analysis	
R_{sc} [Ω]	0.1429
X_{sc} [Ω]	0.9387
$P_{flexible}^{max}$ [kW]	55905

Figure 32 Hosting Capacity for the substation node using the daily limited generation profile.

Table 11 Operational results for substation node with the daily limited generation profile.

	Conventional	Solar Only	Solar and Storage
$P_{conventional}$ [kW]	23260		
$P_{flexible}$ [kW]		23700	23700
r_{kW}/r_{kWh} [kW/kWh]			440/880
$\sum_t P_{export}[t]$ [MWh]	40747	41427 (102% of conventional)	41427 (102% of conventional)
$\sum_t P_{curtailment}[t]$ [MWh]		0.2 (0.0% of export)	0 (0% of export)

Since the scenarios already produced similar results in the full hourly scenario, the flattening effect of the limited generation profile results in nearly equal NPVs for the three scenarios as illustrated in Figure 33. In this case, the conventional choice is the clear favorite.

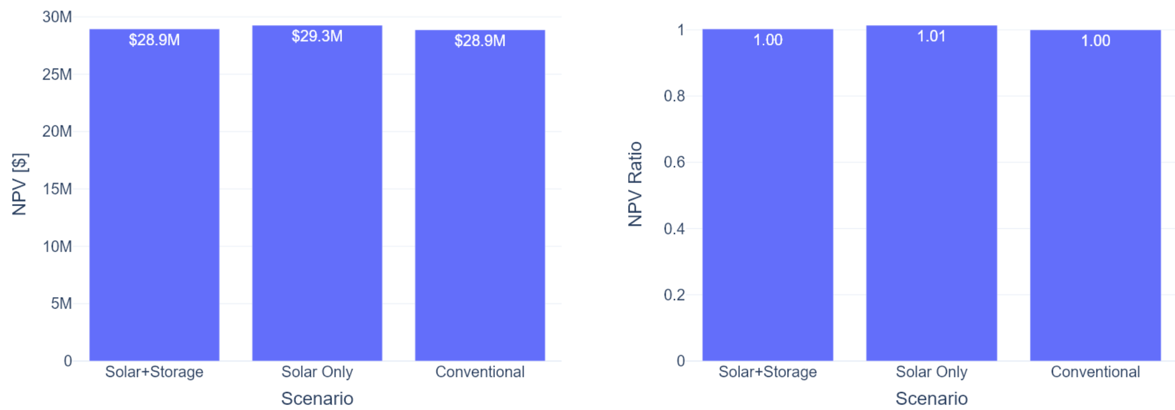


Figure 33 Net present value for the three scenarios at the substation node with the daily limited generation profile.

4 Discussion

The results presented in Section 3.3 suggest a set of considerations around flexible interconnection.

Hosting Capacity Variability

Flexible interconnection derives value from the *range* of hosting capacity values. As that range narrows, the value of flexible interconnection diminishes.

Hosting capacity variability can be altered due to numerous factors. Weaker interconnection points, in terms of short-circuit impedance, will have more voltage fluctuations due to the load shape, that could drive a higher variability in the hosting capacity. Locations farther from the substation also aggregate fewer loads and therefore are likely to have more fluctuation, compared to the natural averaging that happens closer to the substation. Finally, as shown in the previous section, the use of limited generation profiles has the impact of flattening the hosting capacity profile.

The corollary to the above argument is that as hosting capacity variability narrows, temporary flexible interconnection becomes more attractive. The lower variability leads to lower curtailment[13] and therefore lower opportunity costs. The losses from interconnecting early on, before an upgrade is realized become increasingly negligeable, encouraging quick flexible interconnection on a temporary basis.

These two views are illustrated in Figure 34, that shows how the benefit of temporary and permanent flexible interconnection varies with the range of the hosting capacity time series. The x-axis is the range of the hosting capacity expressed as a percent with respect to the minimum hosting capacity value. The *permanent FIX benefit* is calculated as the difference between the solar-only NPV and the conventional NPV, expressed as a percent with respect to the conventional NPV. The *temporary FIX benefit* is calculated as the range between the solar-only NPV and the curtailment NPV, expressed as a percentage of the solar-only NPV. This last

[13] Assuming a project is not sized greater than the maximum available capacity.

number is basically stating the percentage of the range from zero to the solar-only NPV that falls in the shaded range at year n in Figure 3.

Figure 34 shows that as hosting capacity variability *increases* the *permanent* FIX benefit increases, while as hosting capacity variability *decreases*, the *temporary* FIX benefit increases.

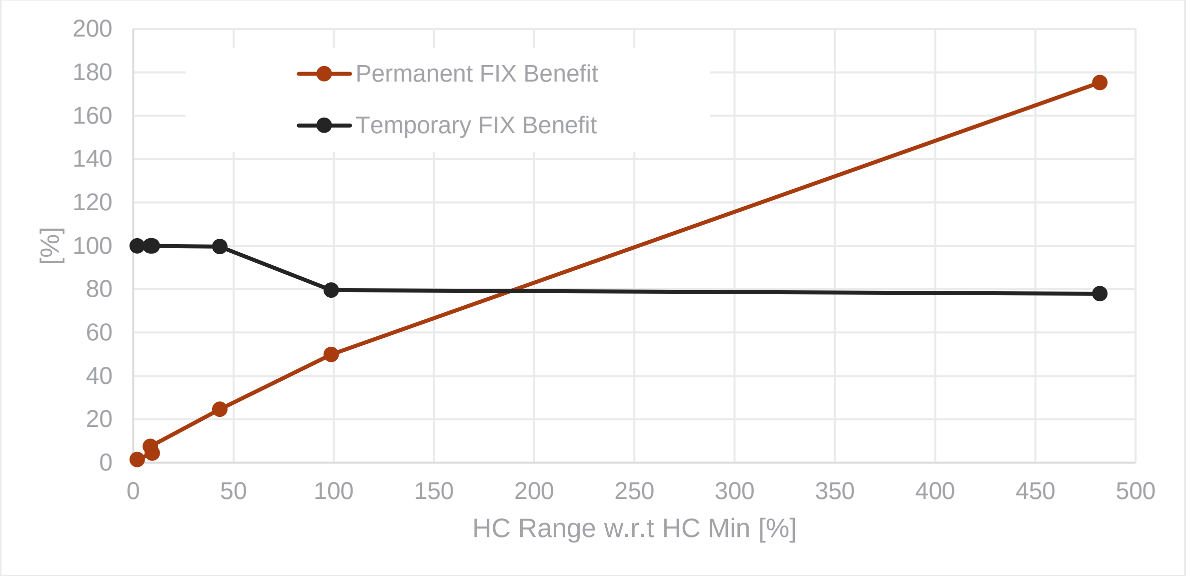


Figure 34 Hosting Capacity variability and its relationship to the benefit of flexible interconnection.

Storage as a hedge against uncertainty

In all cases, the solar only scenario results in a higher NPV, suggesting it is preferable to solar with storage. However, particularly when flexible interconnection is most valuable (Sections 3.3.1 and 3.3.2), curtailment tends to be higher, and storage helps reduce the opportunity cost associated with curtailment. This is most evident in the equivalent upgrade cost that is quite low in all cases for solar and storage, and higher for the solar-only scenario. In some cases, the best choice for solar only might be to opt for an upgrade, while the best choice for solar and storage would be to interconnect flexibly.

Another way to view how storage provides more consistent performance under uncertainty is the comparison between the hourly hosting capacity profile and the limited generation profile results. The project NPV for solar and storage is less affected by the change in hosting capacity profiles. In reality, the solar production is uncertain, and the hosting capacity may dynamically change. The behavior of the solar and storage scenario may be more achievable in the real world compared to the solar only scenario.

Benefit of temporary flexible interconnection

In all cases, the deferred upgrade analysis shows that it is better to interconnect quickly under flexible interconnection than wait for an upgrade to complete construction. This is the one case where flexible interconnection is even *more* valuable for the stronger grid connected locations. Since the curtailment results are so low at these locations, there is little risk in assuming that small amount of curtailment for a limited time.

5 Conclusion

This study evaluates the economic aspects of flexible interconnection through the use of hosting capacity analysis to estimate curtailment. The presented methodology helps quantify the net present value of a project with flexible interconnection, and gives a comparative bound for upgrade costs, below which flexible interconnection might be better replaced by upgrades and conventional interconnection.

The study differentiates between two different kinds of flexible interconnections: those that last indefinitely, and those that are temporary until changes to the system are complete. Weaker locations on the system benefit more from indefinite flexible interconnection, since this is where the hosting capacity range is widest, allowing more opportunity to utilize the capability of the plant beyond the minimum hosting capacity value[14]. Stronger parts of the system, conversely, could clearly benefit from temporary flexible interconnection, as the curtailment levels in these locations, and thus the opportunity cost risk, is very low.

The progression in the presented results from clear differences between flexible and conventional interconnection in the weaker part of the system to very little difference at the substation, highlights the fact that a prerequisite for flexible interconnection are time-varying capacity values. To make this sort of analysis possible by developers, utilities will have to share time series based hosting capacity values. While sharing 8760 hours of hosting capacity values may not be feasible or desirable by the utilities, the analysis shows how the same techniques can be used to evaluate behavior with limited generation profiles as recently approved in CA.

Future work could build on the analysis presented to consider more sophisticated equipment sizing decisions. For example, only 2-Hour batteries were considered in this study, but the impact of different duration storage may be worth studying. Also, all flexible interconnections were sized at around the 90th percentile of the hosting capacity, meaning that as the hosting capacity narrowed, so did the spectrum of project sizes. It may be that sizing PV even beyond the hosting capacity, effectively to just charge the battery in certain hours, might be an attractive proposition in some cases.

[14] These are also locations where system upgrades tend to cost the most.

References

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Appendix A Yearly Cost Benefit Plots

The yearly output, cost, and revenue plots for node m1027039 are shown in Figure 35 and Figure 36. These show the effect of degradation and escalation, as well as the impact of the DRV scaling factor. These curves remain very similar, just progressively closer together, for all the other scenarios, and are therefore not reproduced here.

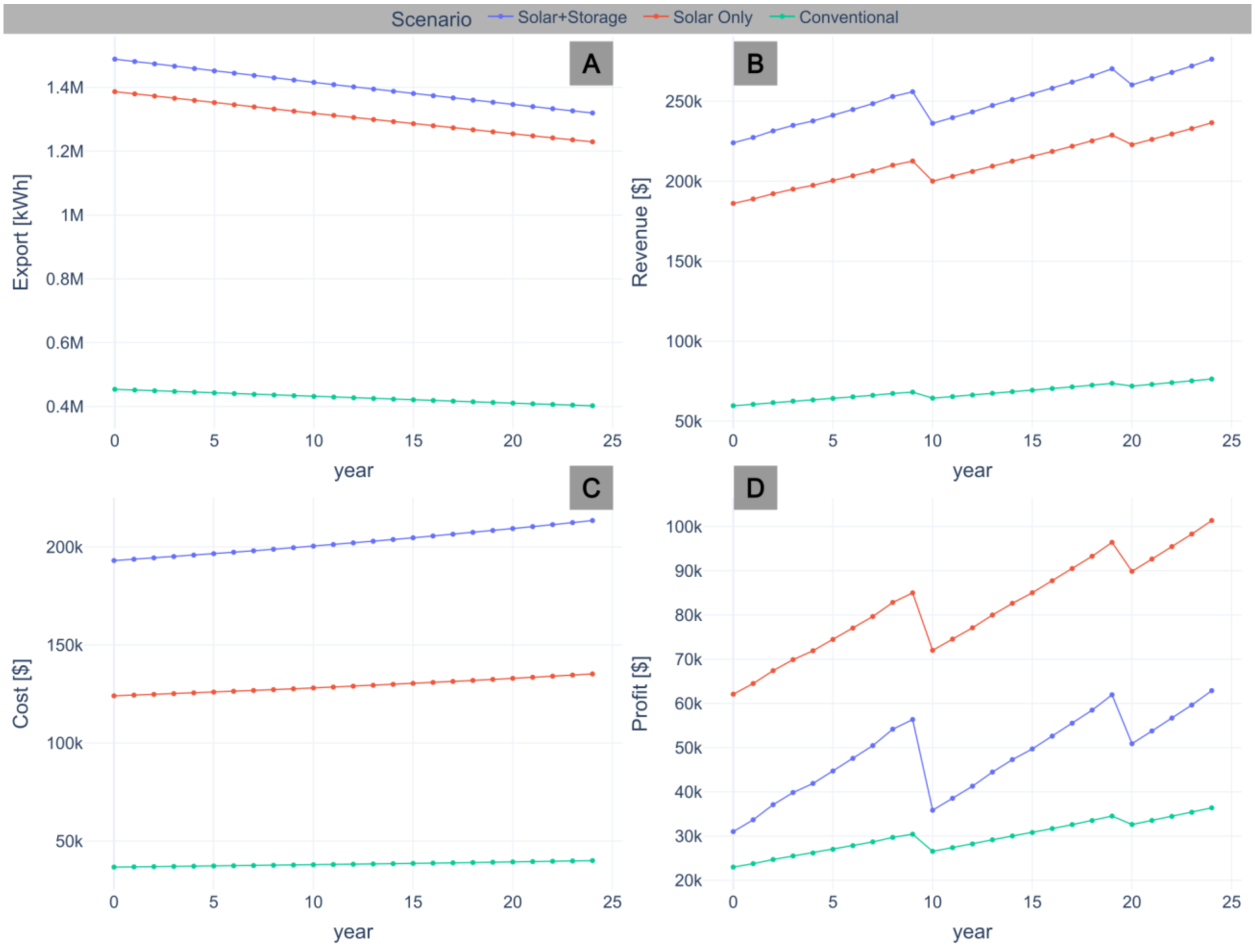

Figure 35 Yearly OPEX and CAPEX results for node m1027039 over the 25-year lifetime of the project based on an 8760 hosting capacity profile.

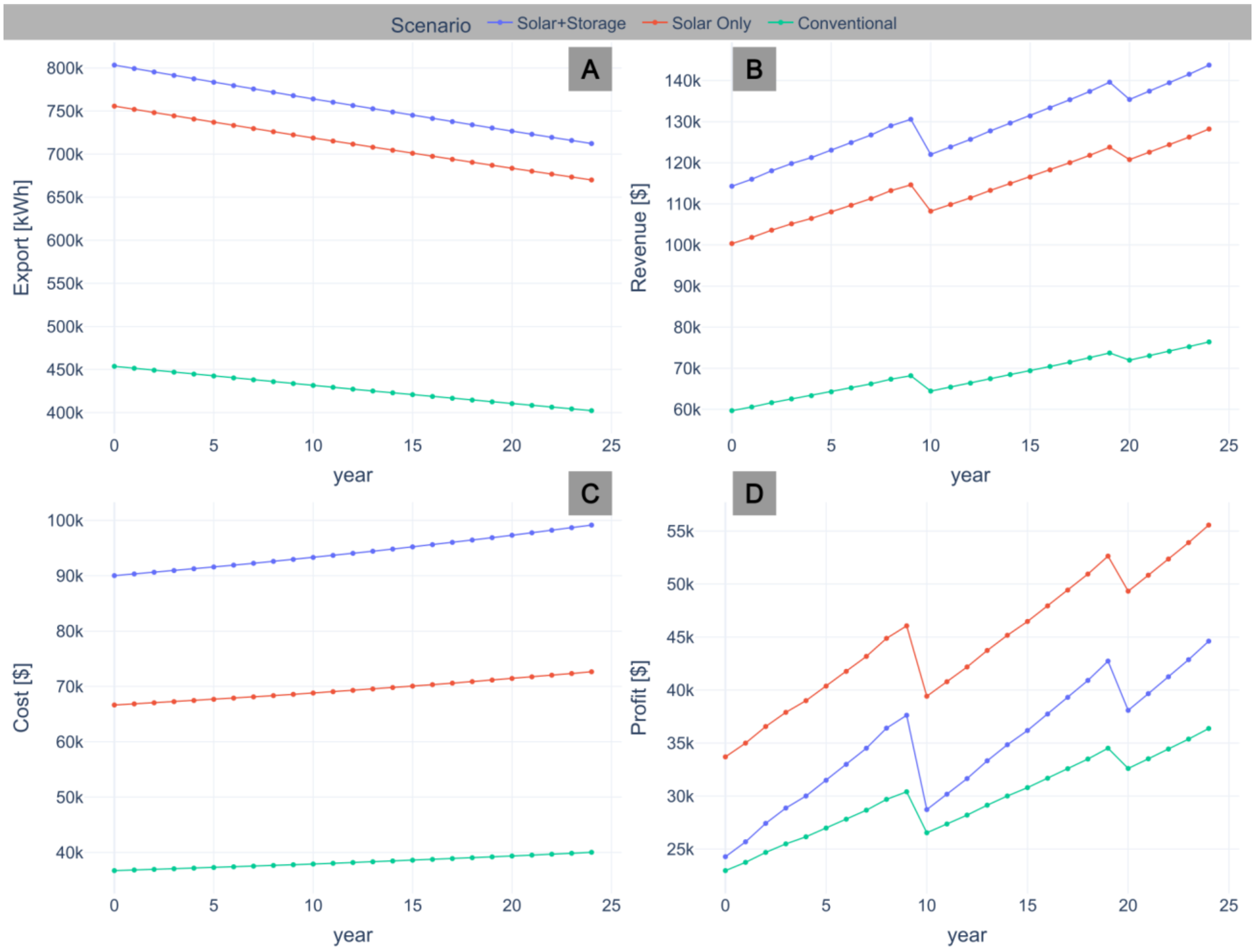

Figure 36 Yearly OPEX and CAPEX results for node m1027039 over the 25-year lifetime of the project, based on the daily limited generation profile.

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