Solar and Storage Industries Institute

Modeling the Revenue Impacts of “Flexible Interconnection” on Community Solar Projects

December 10, 2024

Presenters

David Gahl, Solar & Storage Industries Institute

Todd Wall, Pacific Northwest National Laboratory

Eran Schweitzer, Pacific Northwest National Laboratory

Samantha Weaver, Coalition for Community Solar Access

INTERCONNECTION INNOVATION e-XCHANGE
U.S. DEPARTMENT OF ENERGY

Flexible Interconnection Webinar
SSII Technical Assistance Outcomes

December 10th, 2024

An initiative spearheaded by the Solar Energy Technologies Office and the Wind Energy Technologies Office

Eran.Schweitzer@pnnl.gov

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Motivation & Objective

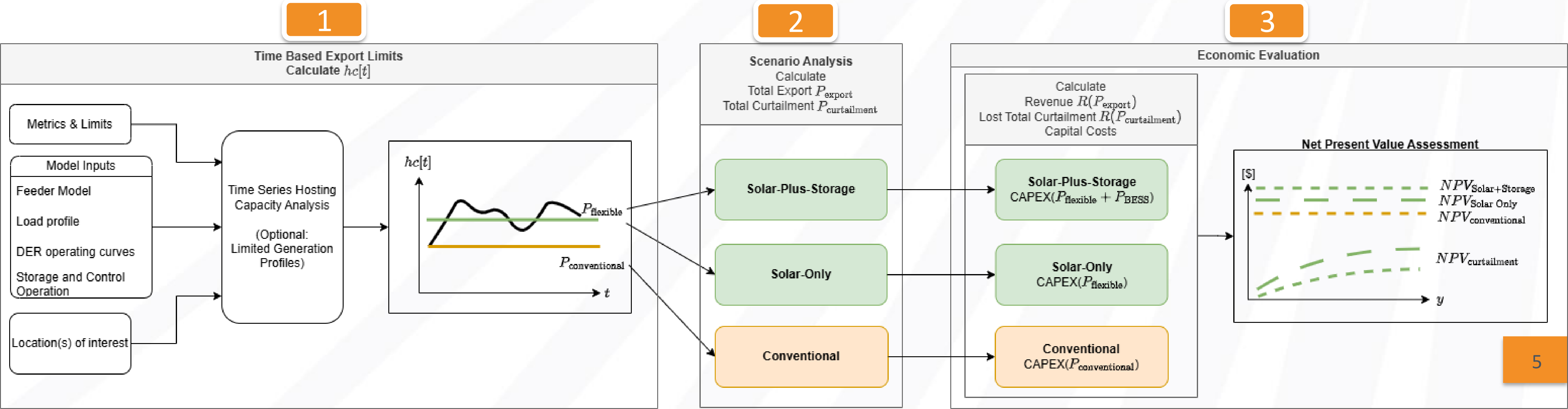
- Interconnection is a complex process that
  - Can run into time delays
  - Accrue high costs to upgrade the system
- Flexible Interconnection (FIX) accepts some curtailment to:
  - Speed up interconnection by not waiting for upgrades to complete
  - Avoid cost of an upgrade altogether

Objective

Conduct an economic costs and benefit evaluation of the interconnection option – curtailment – upgrade tradeoff

Methodology

1. Use Hosting Capacity Analysis (HCA) to develop hourly export limits
2. Evaluate net export and curtailment by scenario
3. Perform economic evaluation



Analysis Scope

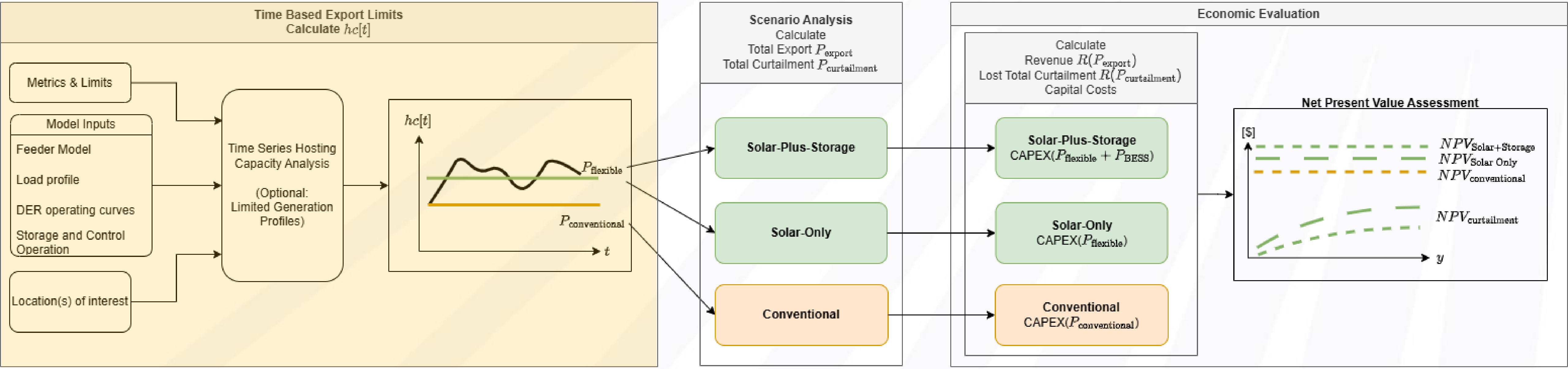
This Analysis Does…

- Evaluate the economics of *specific* designs at a *single* location
- Evaluate how decisions between interconnection choices *vary* by location
- Keep the *logic* between interconnection scenarios constant
- Evaluate a threshold for upgrade costs

This Analysis Does Not…

- Compare the benefit of interconnecting a *specific* plant at one location vs. another
- Propose "optimal" solar-plus-storage design
- Keep the *designs* (i.e. ratings) between interconnection scenarios constant
- Evaluate explicit upgrade costs

Time Based Export Limits



Hosting Capacity Limits

- Focus on steady state thermal and voltage limits
  - Reverse flow and short circuit limits are generally more feeder specific
  - This assumption is easy to change
- At a **given location**, for **each hour**, generation is increased until a limit is reached
  - All other operations (existing DER, Storage, Voltage Regulator Controls, etc.) are held constant with respect to a base run

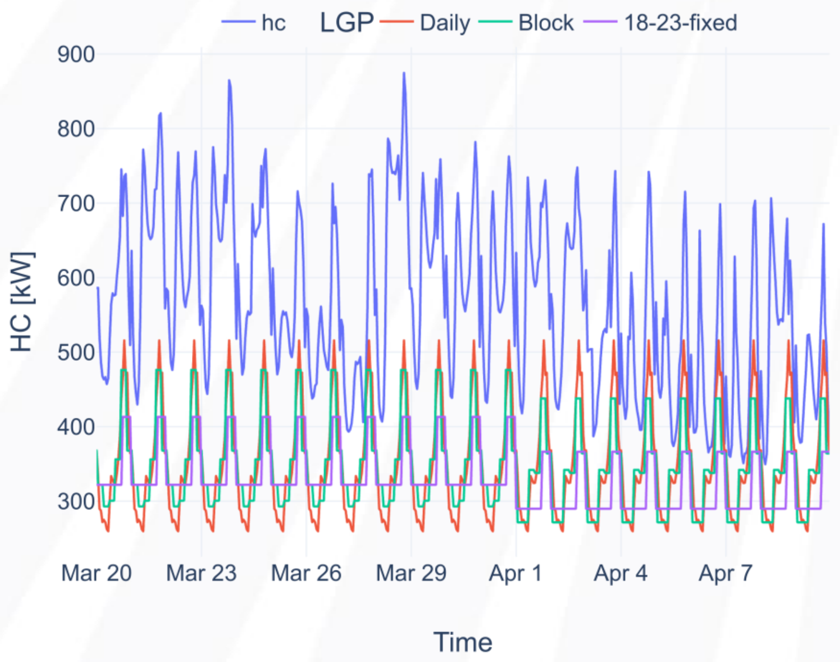
Limit	Explanation
Equipment thermal limits	Normal and Emergency limits cannot be violated
Static voltage limits	Maximum: 105% of nominal (e.g. 13.09 kV for 12.47 kV nominal) Minimum: 95% of nominal (e.g. 11.85 kV for 12.47 kV nominal)
Rapid Voltage Change (RVC)	The maximum nameplate capacity beyond the hosting capacity is based on a 3% RVC limit from IEEE 1547-2018*: $S_r \leq \min_t hc[t] + 0.03 \times \frac{V^2}{R_{\mathrm{SC}} \cdot \mathrm{PF} - X_{\mathrm{SC}} \cdot \sqrt{1 - \mathrm{PF}^2}} = P_{\mathrm{flexible}}^{\max}$

*The RVC definition comes from IEEE Std. 1453, 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.

Limited Generation Profiles

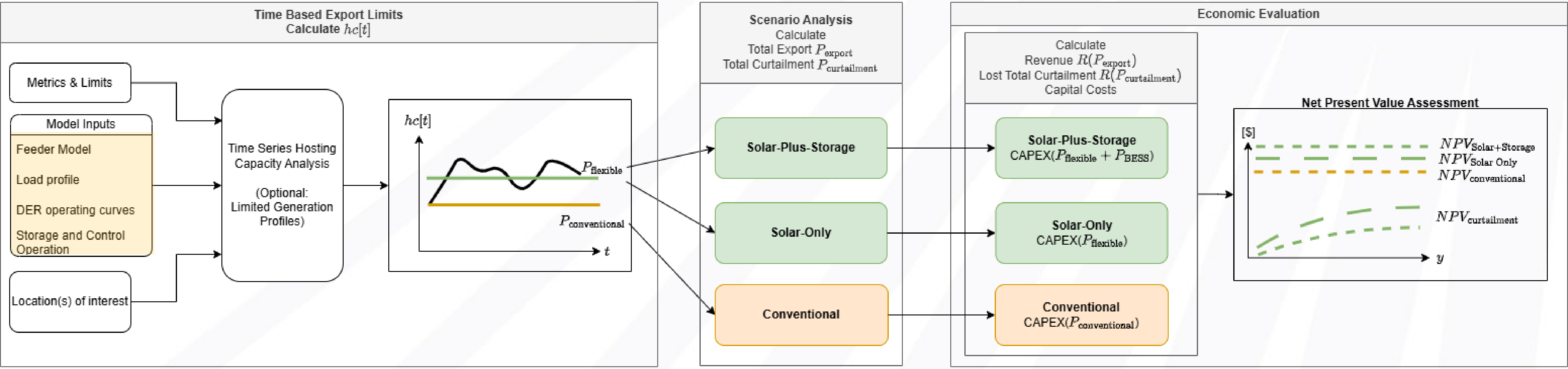
- Changing export limits can pose a communication and control challenge
- One solution is the use of predefined Limited Generation Profiles (LGP) as recently introduced in California*
  - Reduces hosting capacity range

All the presented analysis needs is a limit (any limit) for each hour



*California resolution E-5296, from March 2024

Base Model



Time Based Export Limits
Calculate $hc[t]$
Metrics & Limits
Model Inputs
Feeder Model
Load profile
DER operating curves
Storage and Control Operation
Location(s) of interest
Time Series Hosting Capacity Analysis
(Optional: Limited Generation Profiles)
$hc[t]$
$P_{flexible}$
$P_{conventional}$
t
Scenario Analysis
Calculate
Total Export P_{export}
Total Curtailment $P_{curtailment}$
Solar-Plus-Storage
Solar-Only
Conventional
Economic Evaluation
Calculate
Revenue $R(P_{export})$
Lost Total Curtailment $R(P_{curtailment})$
Capital Costs
Solar-Plus-Storage
CAPEX($P_{flexible} + P_{BESS}$)
Solar-Only
CAPEX($P_{flexible}$)
Conventional
CAPEX($P_{conventional}$)
Net Present Value Assessment
[$]
$NPV_{Solar+Storage}$
$NPV_{Solar\ Only}$
$NPV_{conventional}$
$NPV_{curtailment}$
y

Proposed IEEE 9500*

- Extension of the IEEE 8500 Node Test Feeder
- Large feeder with some DER already present
- Enables easy data sharing

Type	Number of Buses	Number of Nodes
Three Phase	847	2541
Two Phase	3	6
Single Phase	1902	1902
Secondary Customer Buses	2550	5100
Total	**5302**	**9549**

Loads, Voltage Control, and DER

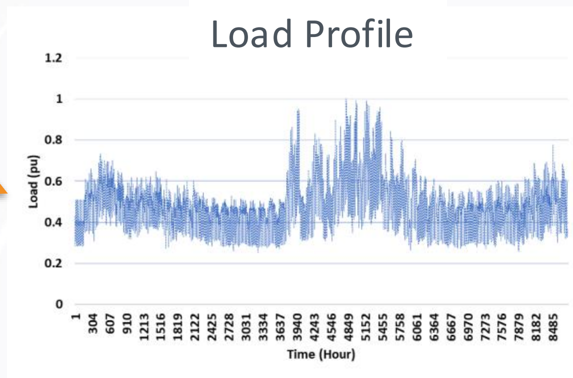
Feeder	No. of Customers	Load		No. of Regulator	No. of Capacitor	No. of DERs
		kW	kVAR			
S_1	268	3432.6	855.9	2	2	7
S_2	475	4803.1	1554.0	2	1	6
S_3	532	5432.8	1355.3	2	1	2
Total	**1275**	**13668.5**	**3765.2**	**6**	**4**	**15**

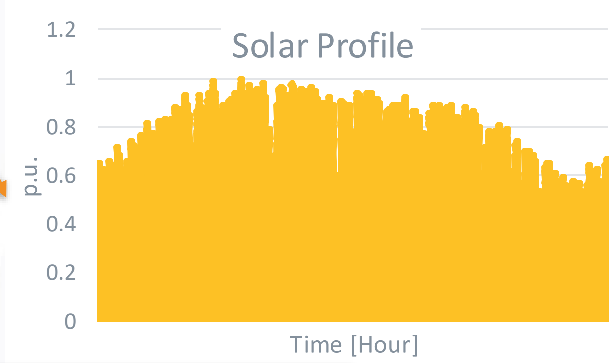
*Anderson, Alexander A., Vadari, Subramanian V., Barr, Jonathan L., Poudel, Shiva, Dubey, Anamika, McDermott, Thomas E., and Podmore, Robin. Introducing the 9500 Node Distribution Test System to Support Advanced Power Applications: An Operations-Focused Approach. United States: N. p., 2022. Web. doi:10.2172/1922914.

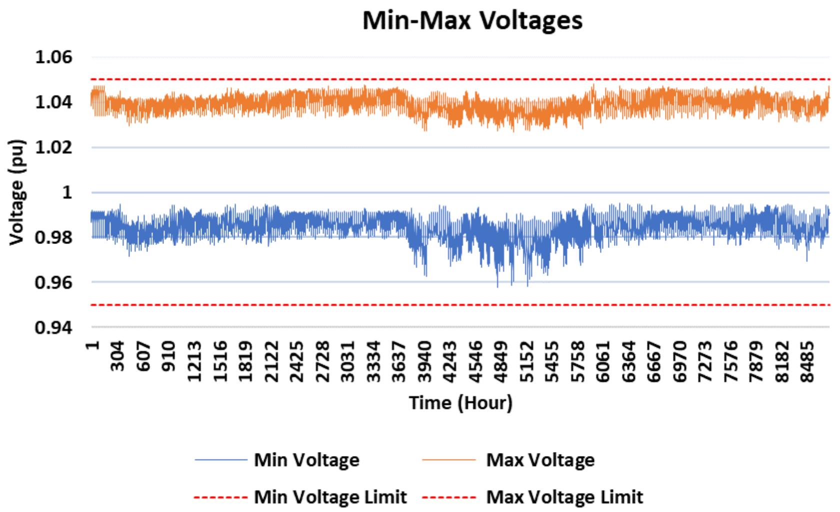
Model is available on the i2X Github repository: https://github.com/pnnl/i2x/tree/master/src/i2x/models/ieee9500

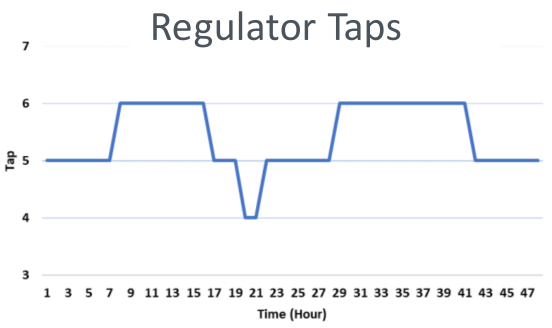
Base Operations

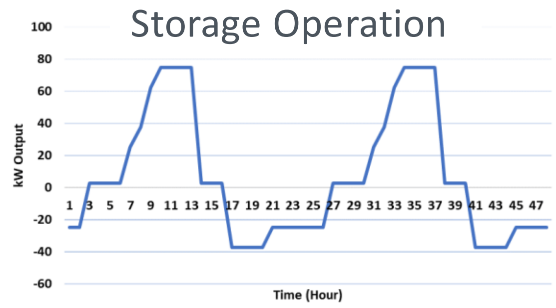
- Load profile from EPRI, available with OpenDSS
- Solar profile (for *existing* PV) from NREL's ReVX* tool for a location close to the Hoosick area in New York state (coordinates 42.803° N, 73.375° W)
- Storage output and regulator taps from base 8760-hour run
- Feeder starting point is within thermal and voltage





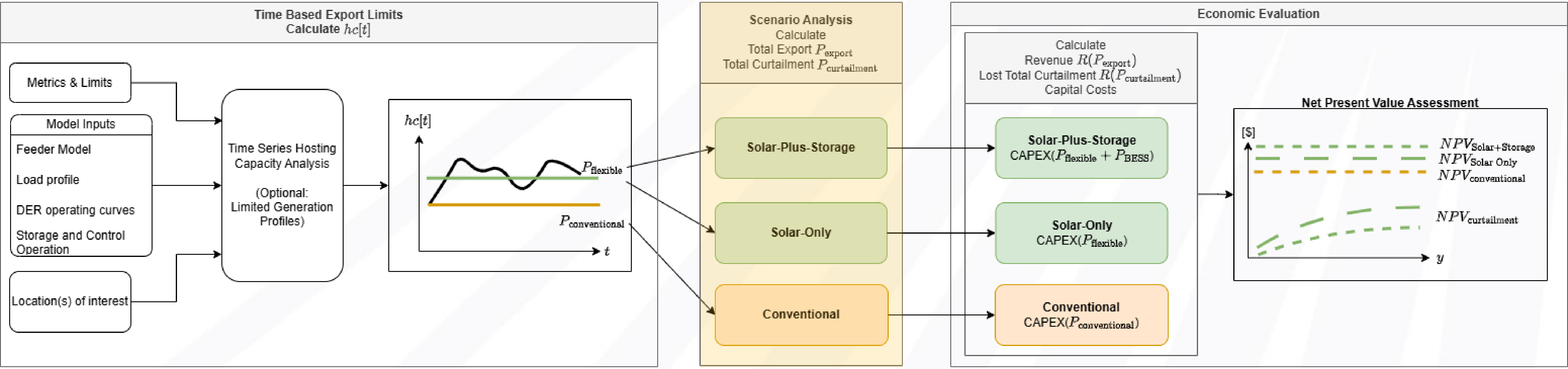




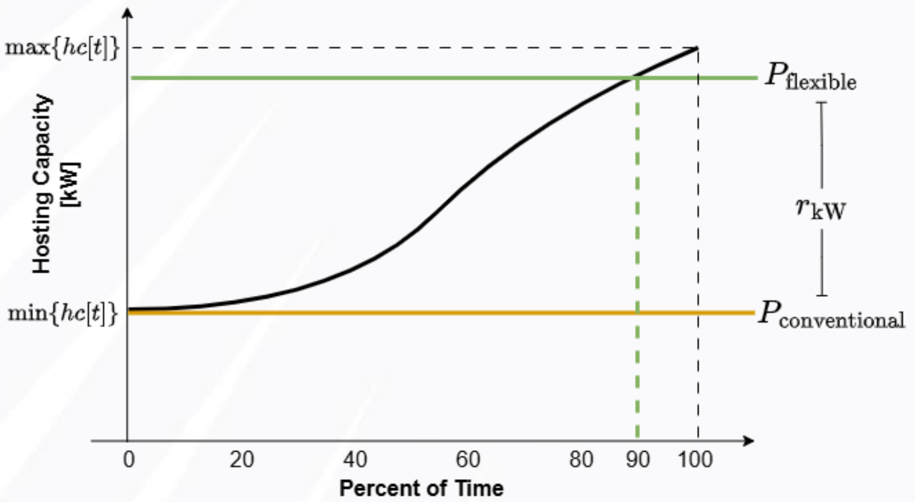


*https://github.com/NREL/reVX

Scenario Analysis



Scenario Description



Conventional Interconnection

- Rating, $P_{\text{conventional}}$, equal to minimum hosting capacity
- Export is equal to the rating times the solar profile

$$\boldsymbol{P}_{\textbf{export}}[\boldsymbol{t}] = P_{\text{conventional}} \cdot pv[t]$$

- Curtailment is, by definition, zero

Solar-Only Flexible Interconnection

- Rating, P_{flexible}, equal to 90th percentile of hosting capacity
- Export is the minimum of rating times solar profile and the hosting capacity

$$\boldsymbol{P}_{\textbf{export}}[\boldsymbol{t}] = \min\{P_{\text{flexible}} \cdot pv[t], hc[t]\}$$

- Curtailment is the difference between the capability and the export

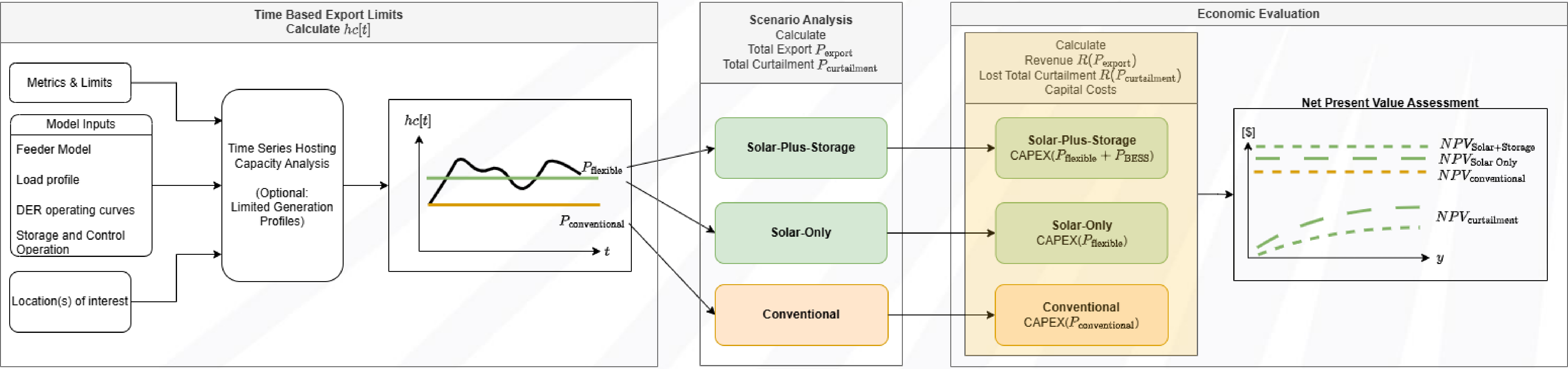
$$\boldsymbol{P}_{\textbf{curtailment}}[\boldsymbol{t}] = P_{\text{flexible}} \cdot pv[t] - P_{\text{export}}[t]$$

Solar-Plus-Storage Flexible Interconnection (solved by optimization)

- Same solar P_{flexible}. 2hr Battery rating, r_{kW}, equal to $P_{\text{flexible}} - P_{\text{conventional}}$
- Net export is the solar capability *plus* battery export *minus* any charging and curtailment

$$\boldsymbol{P}_{\textbf{export}}[\boldsymbol{t}] = P_{\text{flexible}} \cdot pv[t] + b_{\text{discharge}}[t] - \left(b_{\text{charging}}[t] + \boldsymbol{P}_{\textbf{curtailment}}[\boldsymbol{t}]\right)$$

Revenues and Capital Expenditures (CAPEX)



Capital Cost Calculation

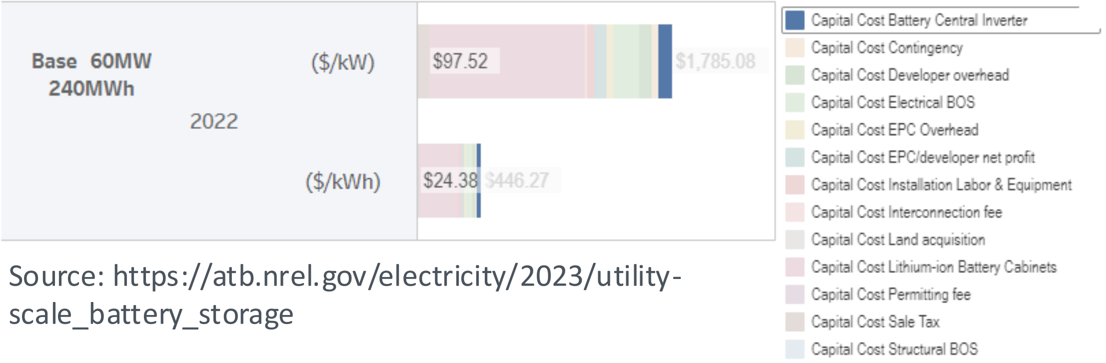
- Annualized capital costs based on lifetime (25 years)

$$C_{\text{annualized}} = C_{\text{total}} \times \frac{r}{1-(1+r)^{-n}}$$

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

- Added ~5.5% saving for joint inverter for solar and storage

Figure 3. Cost details for utility-scale storage (4-hour duration, 240-MWh usable)



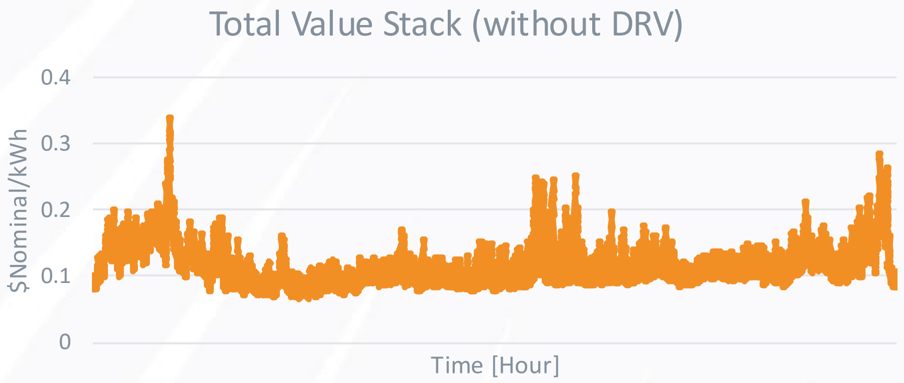
Source: https://atb.nrel.gov/electricity/2023/utility-scale_battery_storage

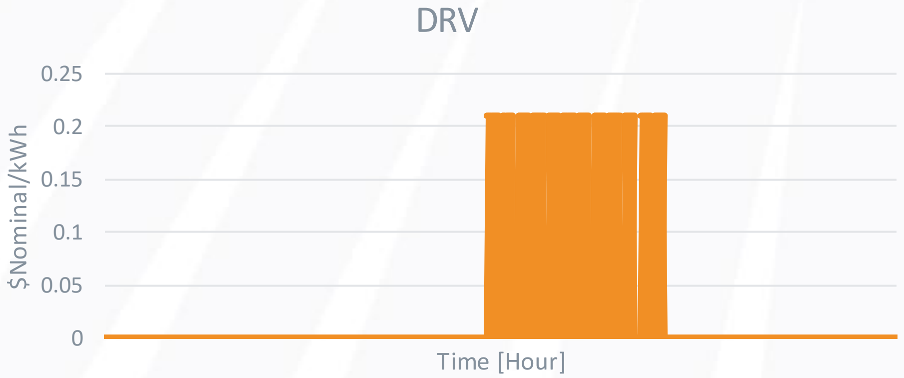
	PV	BESS	Source
CAPEX [$/kW]	1289.51	979.97	2023 ATB*
CAPEX Inverter Savings [%]	0	5.5	2023 ATB*
Fixed O&M [$/kW-a]	20.99	24.50	2023 ATB*
Escalation, s [%/a]	2	2	NYSERDA Value Stack Calculator**
Degradation, d [%/a]	0.5	0.5	NYSERDA Value Stack Calculator**
Discount Rate, r [%/a]	8	8	NYSERDA Value Stack Calculator**

*https://atb.nrel.gov/electricity/2023/index
**https://www.nyserda.ny.gov/All-Programs/NY-Sun/Contractors/Value-of-Distributed-Energy-Resources/Solar-Value-Stack-Calculator

Energy Price

- Extracted from the NYSERDA value stack calculator* with components (all in \$/kWh):
  - DRV (demand reduction value)
  - LSRV (locational system relief value)
  - Community Credit
  - System Capacity
  - Energy
  - Environmental value
- DRV is scaled by a yearly factor, $f_{\mathrm{DRV}}[y]$, and is therefore separated out from the rest of the value stack





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

Revenues and Opportunity Cost to NPV

- Cost of curtailment is treated as the opportunity cost of **not** receiving payment for possible production

Revenue is a function of **exports**:

$$R[y](P_{\text{export}})$$

Opportunity Cost is a function of **curtailment**:

$$R[y](P_{\text{Curtailment}})$$

$$R_0\ [\$] = \sum_t P[t][\text{kWh}] \times c[t][\$/\text{kWh}]$$

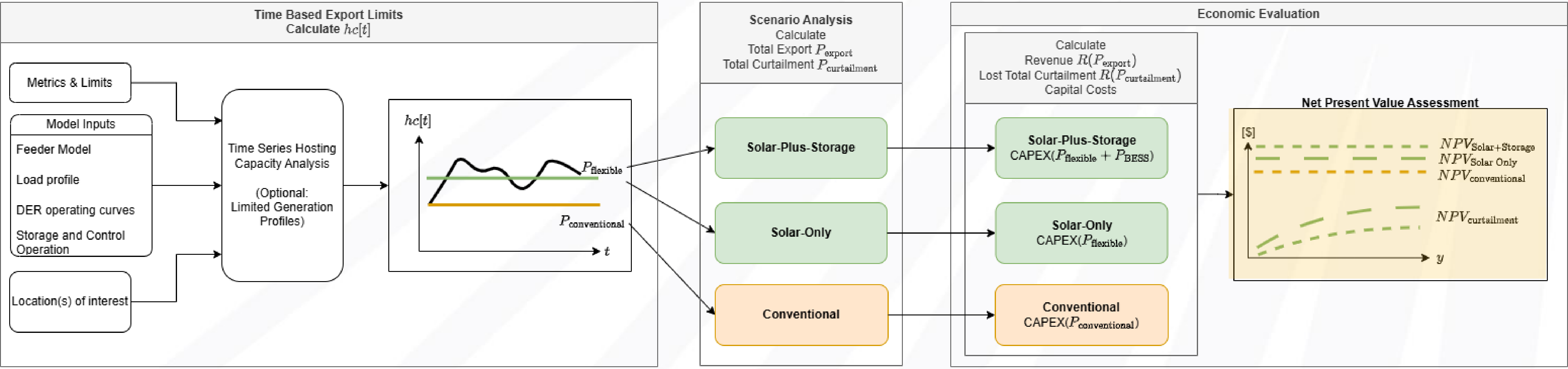
$$R_{0,\text{DVR}}\ [\$] = \sum_t P[t][\text{kWh}] \times c_{DRV}[t][\$/\text{kWh}]$$

$$R[y][\$] = \left(R_0 + R_{0,\text{DVR}} \times f_{\text{DVR}}[y]\right) \times (1-d)^y \times (1+s)^y$$

$$NPV = \sum_y \frac{R[y] - C[y]}{(1+r)^y}$$

Note: CAPEX for Opportunity Cost is zero

NPV Assessment



Avoided vs. Deferred Costs

Permanent Flexible Interconnection: Avoided Upgrades

- Curtailment assumed for project lifetime:

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

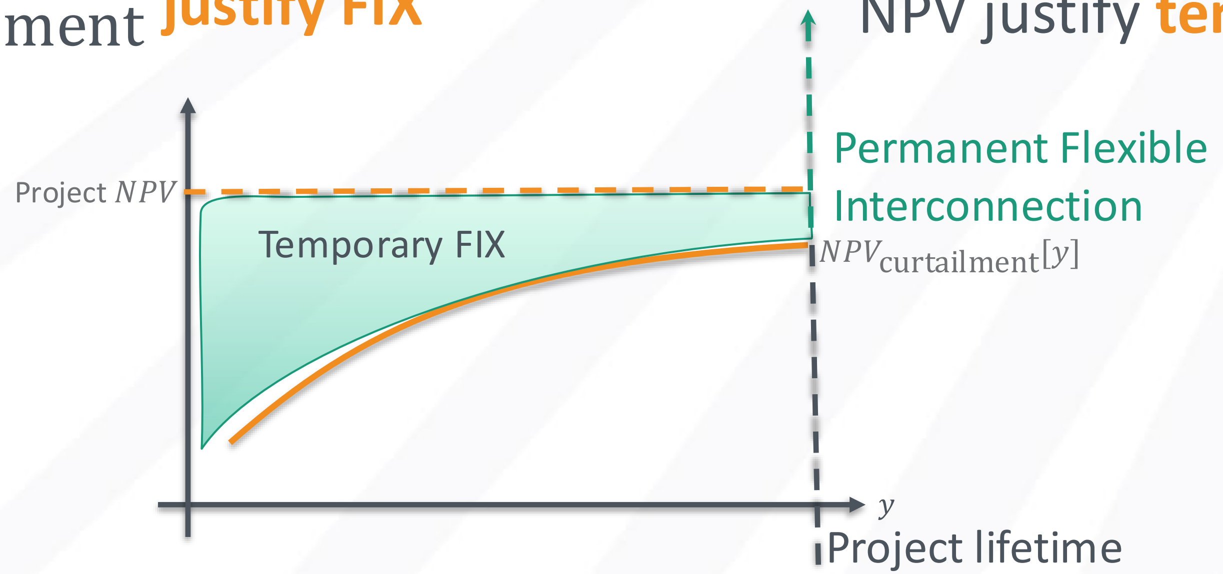
- Upgrades that are **greater** than $NPV_{\text{curtailment}}$ **justify FIX**

Temporary Flexible Interconnection: Deferred Upgrades

- Curtailment assumed for only some time:

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

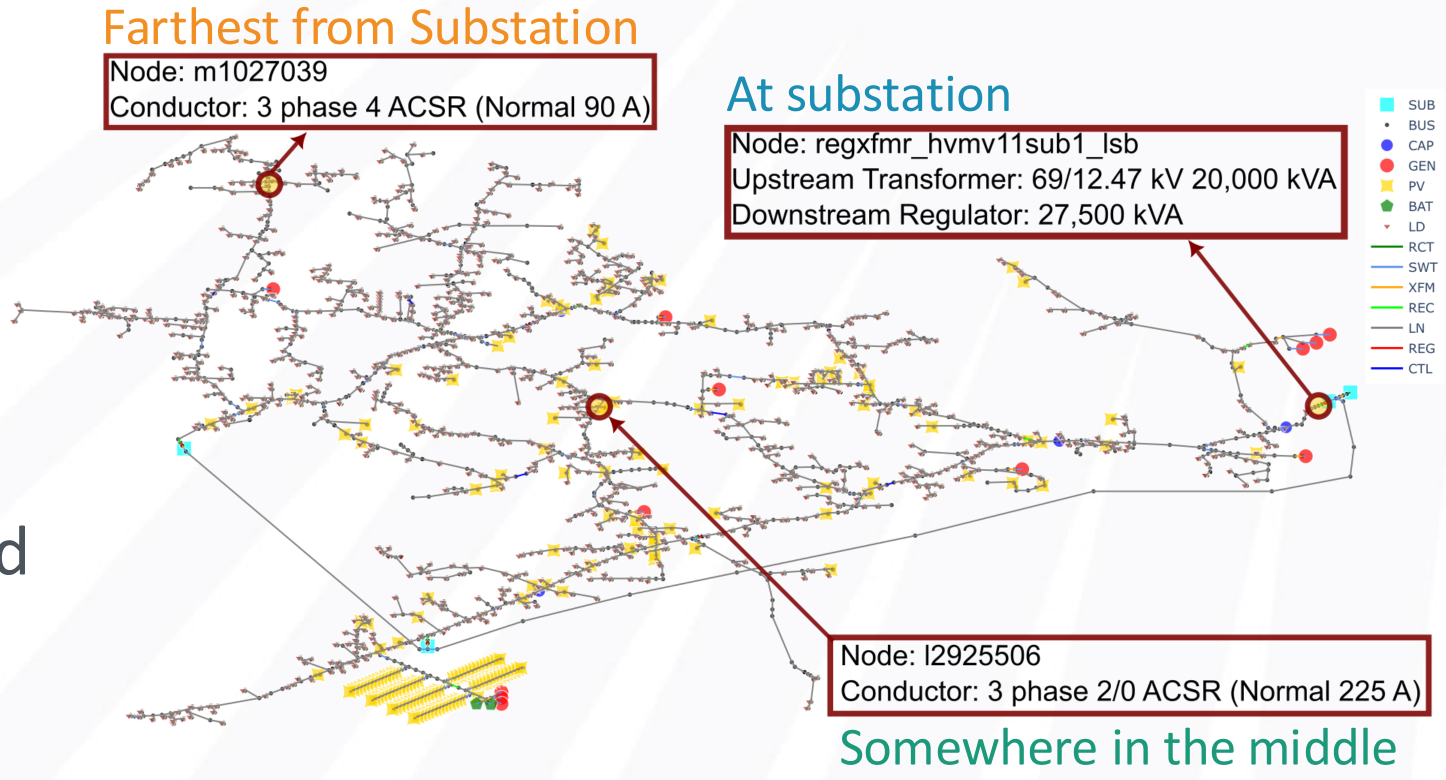
- Upgrades that are **greater** than $NPV_{\text{curtailment}}$ but **below** the project NPV justify **temporary FIX**



Examples

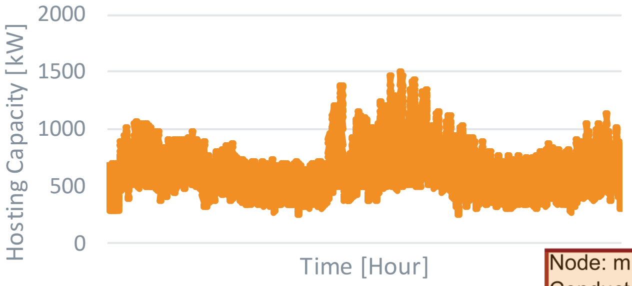
Overview

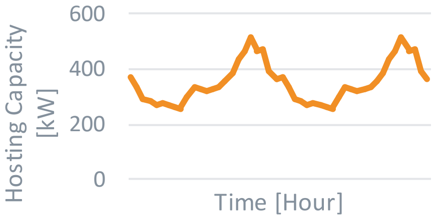
- Three locations chosen at progressively closer points to the substation
- **Different project sizes at different locations based on hosting capacity!**
- Analysis with hourly hosting capacity as well as daily limited generation profile (LGP)



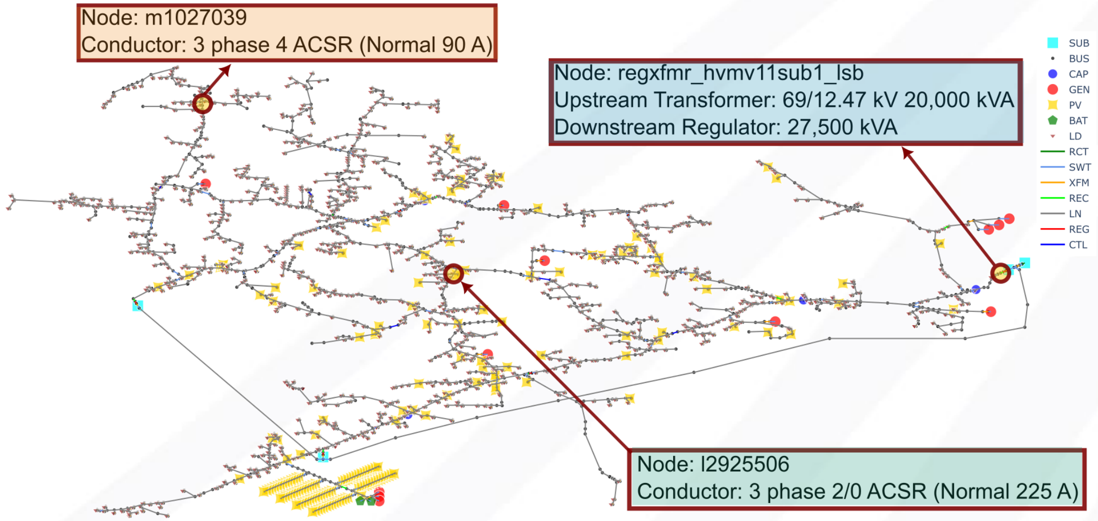
Hosting Capacity Results

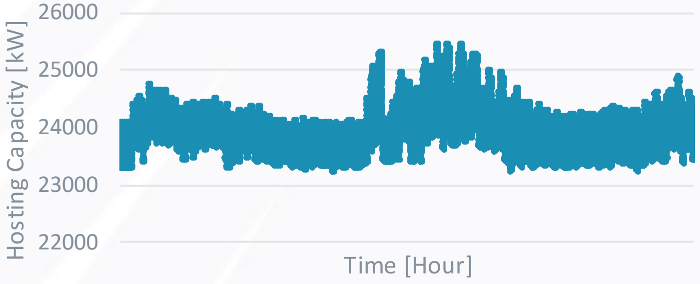
Farthest from Substation

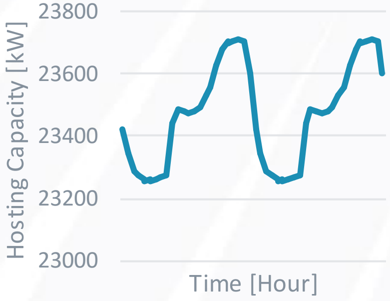




Percentile	HC [kW]	LGP [kW]
Min	259.6	259.6
90	875	469.4
Max	1511.1	515.8
Range [%]	482.1	98.7

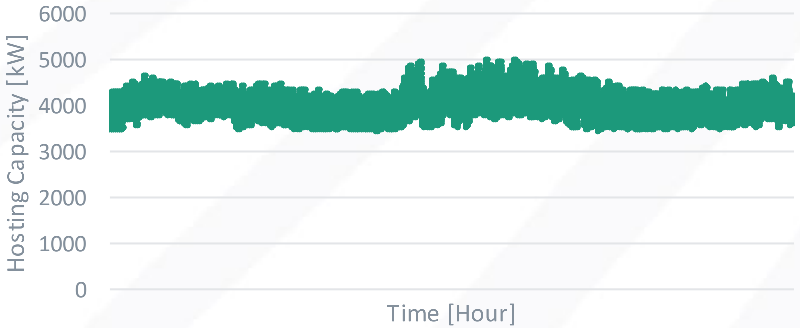


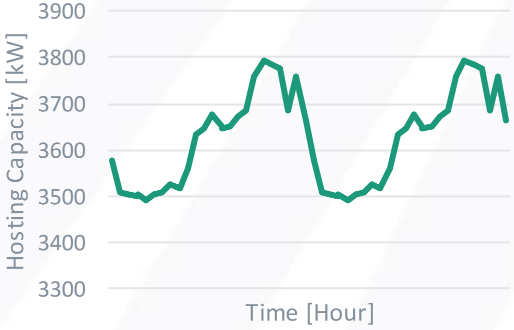




Percentile	HC [kW]	LGP [kW]
Min	23260.1	23260.1
90	24415.9	23705.3
Max	25468.9	23708.8
Range[%]	9.5	1.9

At substation



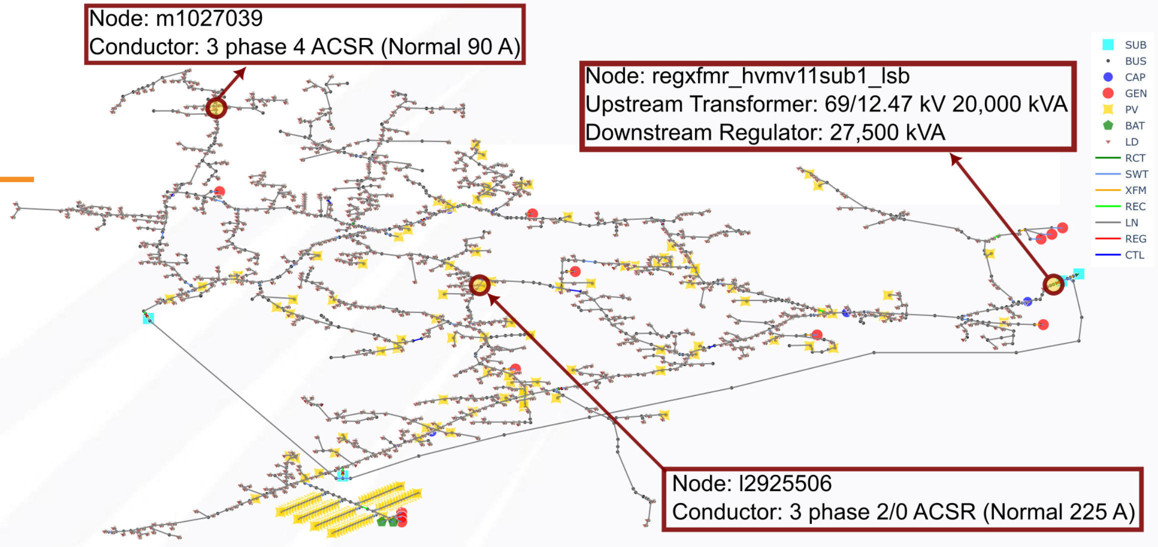


Somewhere in the middle

Percentile	HC [kW]	LGP [kW]
Min	3493.4	3493.4
90	4393.8	3776.9
Max	4999.9	3792.1
Range [%]	43.1	8.6

Sizing and Operational Results

- Note:
  - differences in project size
  - As sizes converge, so do the differences in export and curtailment



Increasing Hosting Capacity

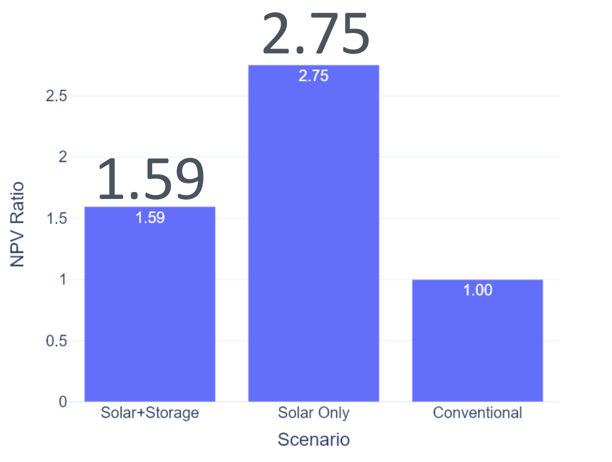
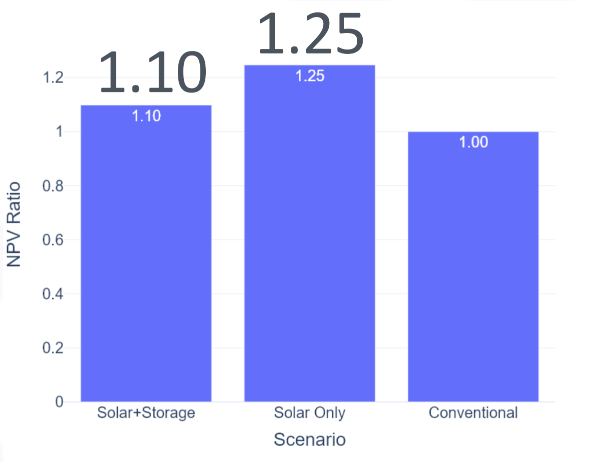
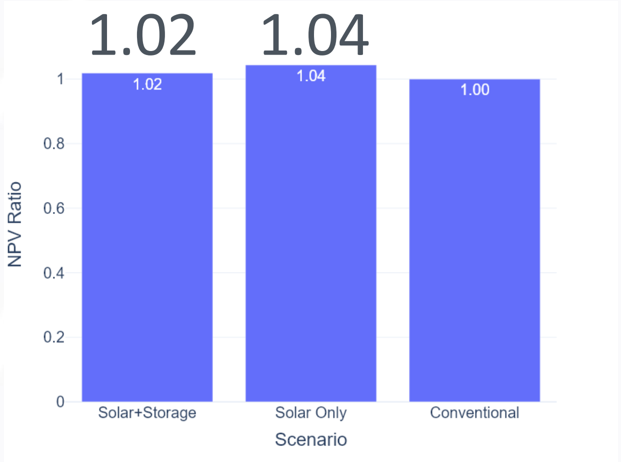
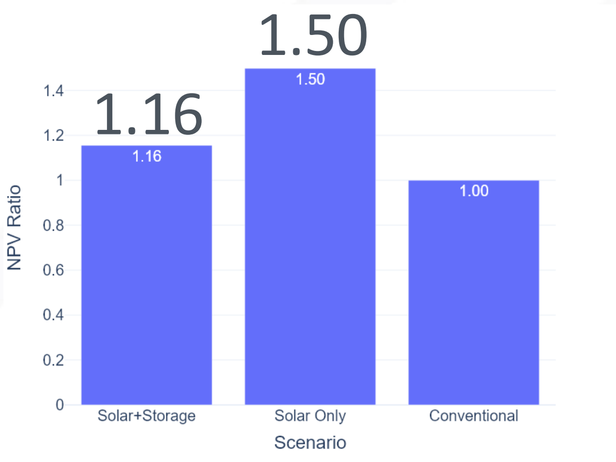
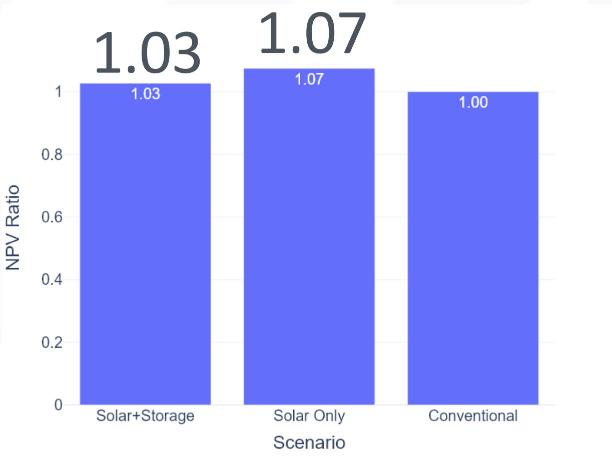
Increasing Hosting Capacity **Range**

	m1027039 (farthest)					l2925506 (middle)					Substation				
	Conv.	Solar Only		Solar and Storage		Conv.	Solar Only		Solar and Storage		Conv.	Solar Only		Solar and Storage	
	HC	HC	LGP	HC	LGP	HC	HC	LGP	HC	LGP	HC	HC	LGP	HC	LGP
$P_{\text{conventional}}$ [kW]	259					3493					23260				
P_{flexible} [kW]		875	470	875	470		4395	3775	4395	3775		24400	23700	24400	23700
$r_{\text{kW}}/r_{\text{kWh}}$ [kW/kWh]				620/ 1240	210/ 420				900/ 1800	285/ 570				1000/ 2000	440/ 880
$\sum_t P_{\text{export}}[t]$ [MWh] (% of conventional)	454	1387 (205%)	756 (176%)	1489 (228%)	803 (177%)	6119	7665 (125%)	6597 (108%)	7682 (126%)	6599 (108%)	40747	42650 (105%)	41427 (102%)	42650 (105%)	41427 (102%)
$\sum_t P_{\text{curtailment}}[t]$ [MWh] (% of export)		143 (10%)	66 (8.7%)	41 (2.8%)	18 (2.2%)		17.6 (0.2%)	1.8 (0.0%)	0 (0%)	0 (0%)		0.8 (0.0%)	0.2 (0.0%)	0 (0.0%)	0 (0%)

NPV Comparison to Conventional

Increasing Hosting Capacity **Range** (←)

Increasing Hosting Capacity **Range** (↑)

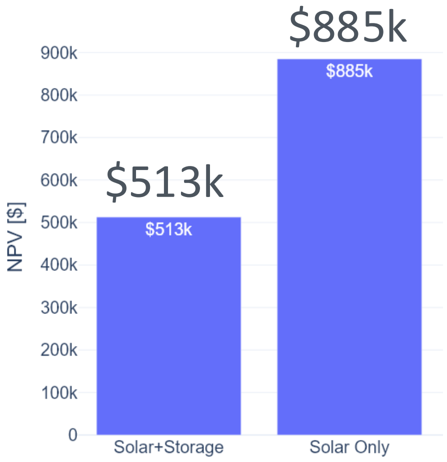
	m1027039 (farthest)	l2925506 (middle)	Substation
HC			
LGP			

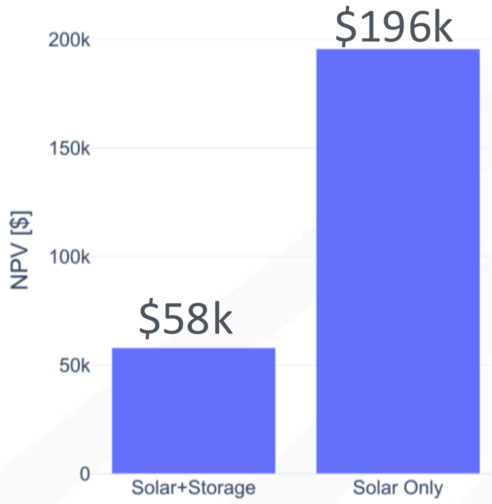
Avoided and Deferred Upgrades*

Increasing Hosting Capacity Range

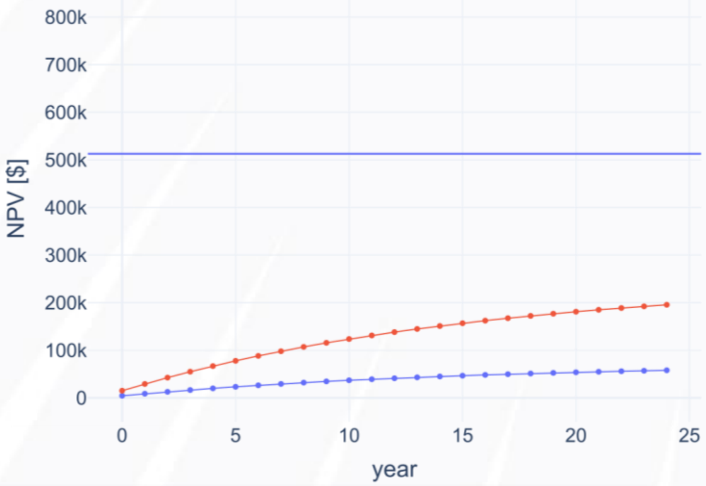
HC

Avoided upgrades from $372k and up favor Solar + Storage



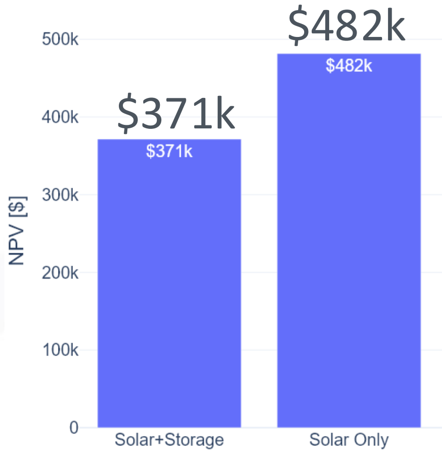


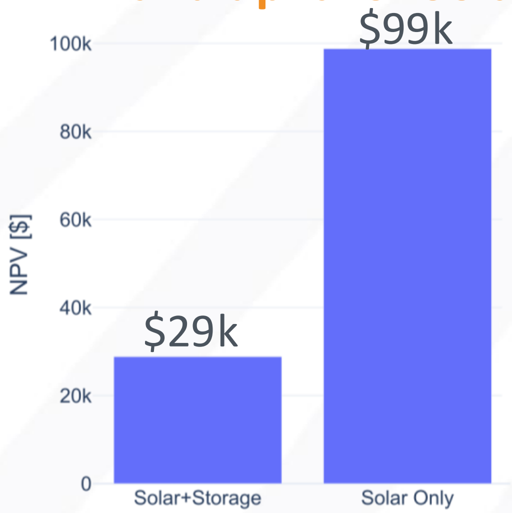
Quick interconnection is generally worthwhile

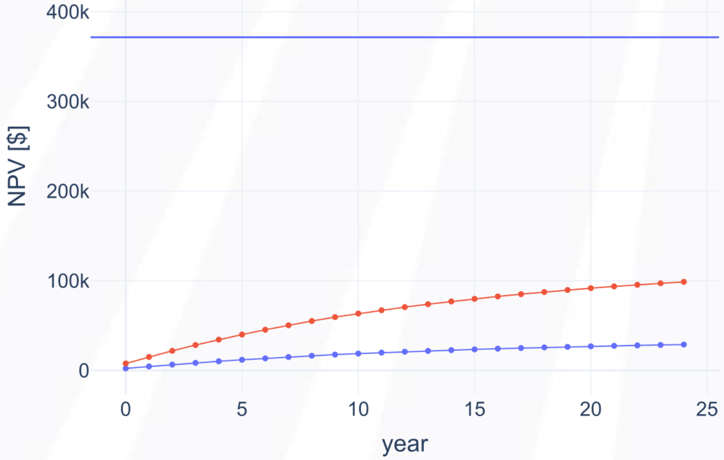


LGP

Avoided upgrades from $111k and up favor Solar + Storage





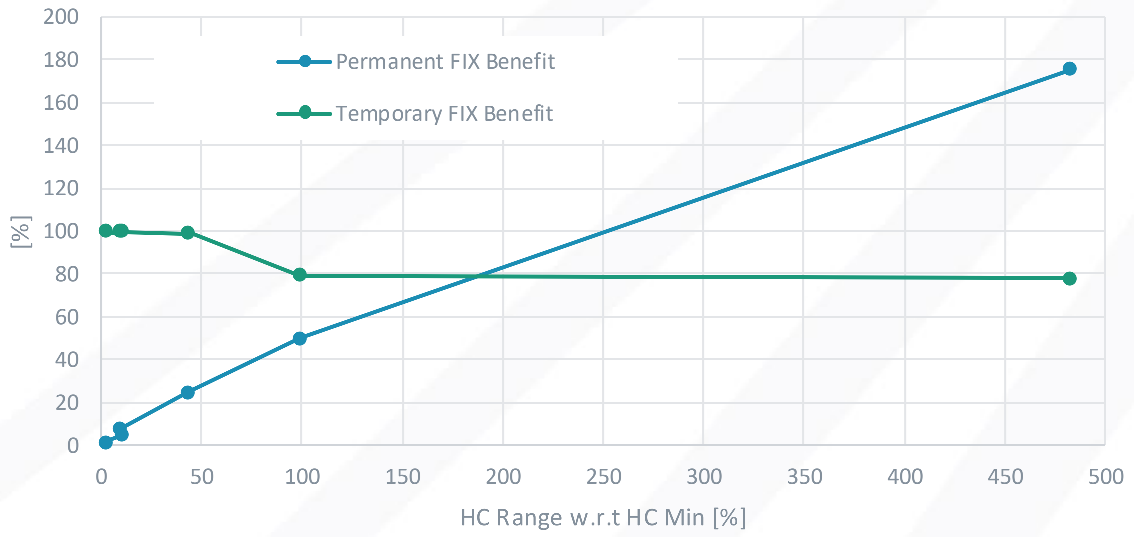


*Shown for m1027039 only since curtailment at other two locations is so small that the NPV values are effectively 0.

Take Aways

Hosting Capacity Variability

- The **higher** the hosting capacity variability, the more permanent FIX (avoided upgrades) are worth while
- The **lower** the hosting capacity variability, the more temporary FIX (deferred upgrades) are worth while



Permanent Benefit:

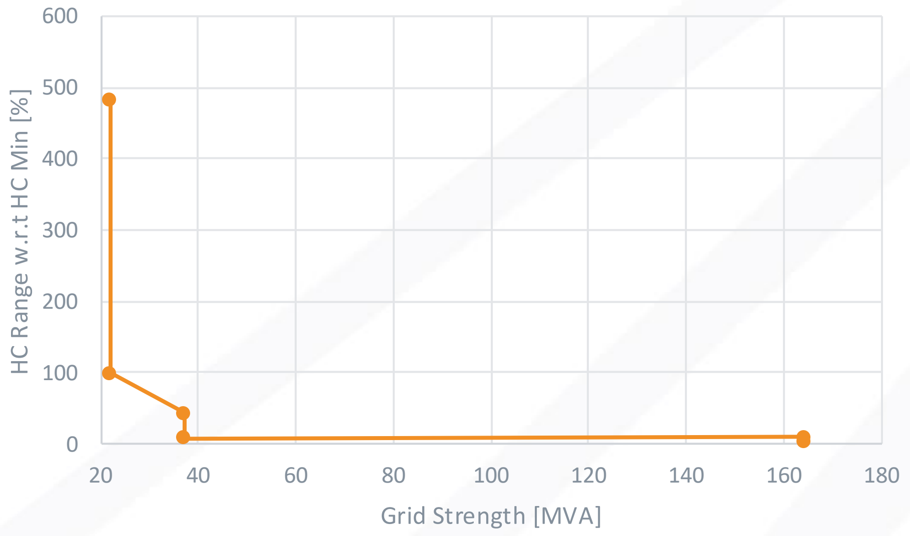
$$\frac{\left(NPV_{\text{Solar-Only}} - NPV_{\text{Conventional}}\right)}{NPV_{\text{Conventional}}}$$

Temporary Benefit:

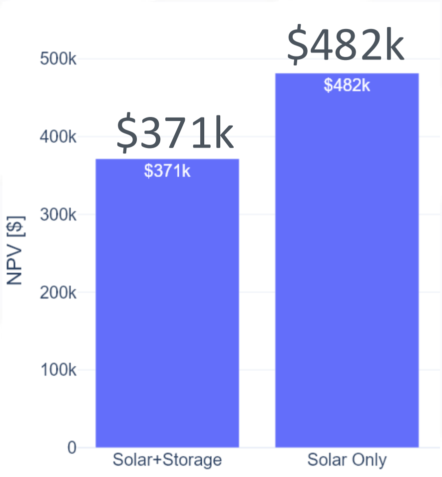
$$\frac{\left(NPV_{\text{Solar-Only}} - NPV_{\text{Curtailment}}\right)}{NPV_{\text{Solar-Only}}}$$

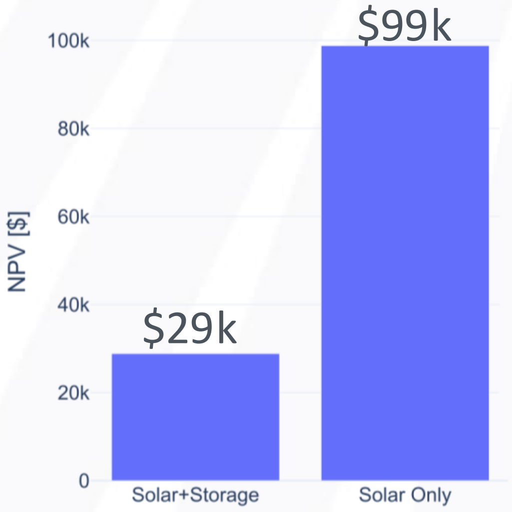
Storage and Uncertainty

- Permanent flexible interconnection is **most valuable** in **weaker** parts of the system with **more** hosting capacity variability.
- Assessment **assumes** a given set of profiles → single realization of uncertainty.
- Storage reduces curtailment thus improving the case for flexible interconnection



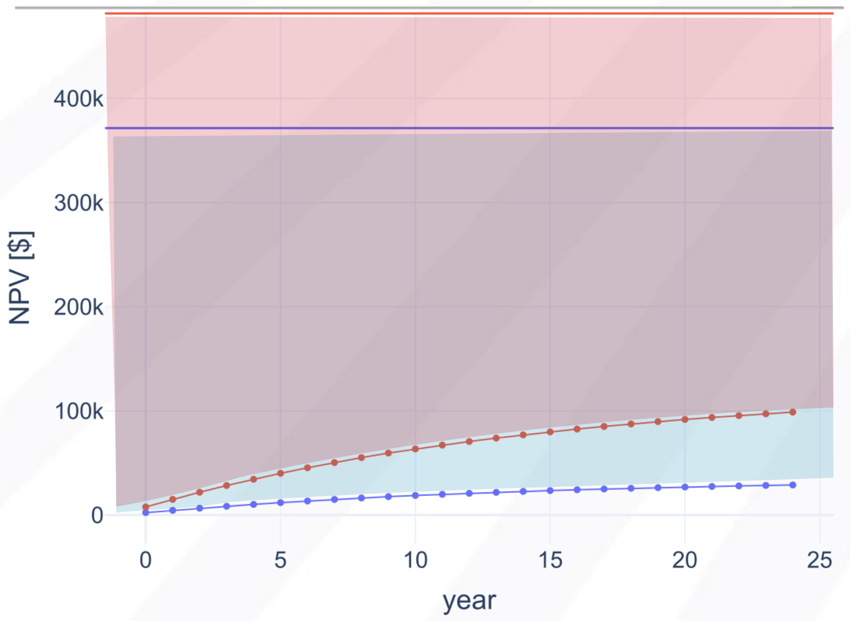
Avoided upgrades from $111k and up favor Solar + Storage





Temporary Flexible Interconnection

- In **all** cases, the analysis shows it better to connect and temporarily curtail rather than wait for upgrades
- Benefit **increases** in stronger parts of the system
- Curtailment is low →low opportunity cost



Thank You!

Full Report: https://doi.org/10.2172/2476686
Code Available: https://github.com/pnnl/i2x

Solar and Storage Industries Institute

Questions