Decarbonizing the electricity system: technologies and strategies

‘Building the Elements’

Madeleine McPherson
Civil Engineering, University of Victoria

February 21, 2019
Grande Bibliothèque, Montreal
Open Modelling Platform for Electrification and Deep Decarbonisation Studies

Building the elements
– elements that contribute to a larger platform & decarbonization objective

Six technologies & strategies:

- Demand response
- Electric vehicles
- System flexibility
- VRE characterization
- Remuneration mechanism
- Market participation

SILVER or PLEXOS Model

Production cost model with mixed-integer linear formulation

- Unit commitment, economic dispatch, and optimal power flow

Grid operators scale

- Spatially – one balancing area (e.g. Ontario)
- Electricity only – other energy carriers can be indirectly quantified
- Temporal resolution – hourly

Analysis: annual electricity system dispatch

- Flexibility requirements
- Production costs
- GHG emissions

Demand response

Demand Response

Changes in end use electricity consumption from their normal consumption patterns in response to changes in electricity price, incentive payments, or system reliability events (FERC)

Net electricity consumption is not changed

Timing of electricity consumption can be shifted

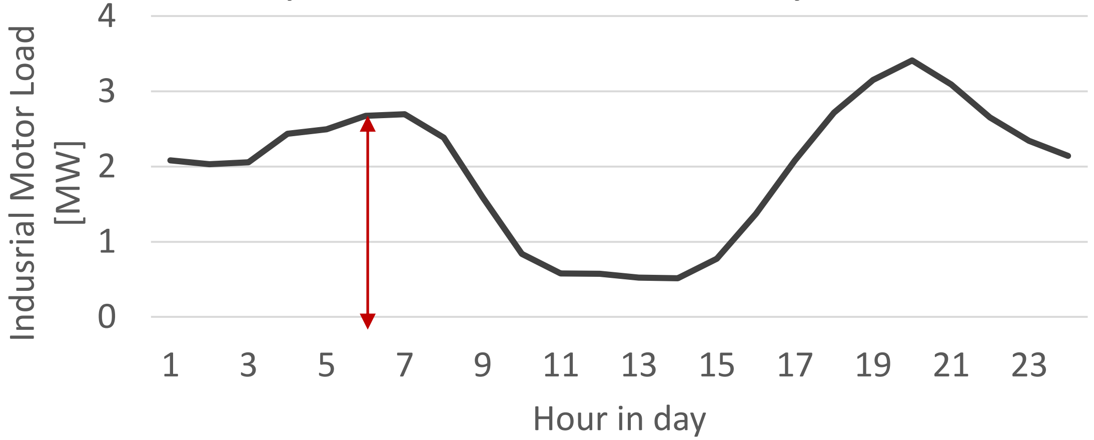
- Must adhere to relatively restrictive constraints, which differ depending on the end-uses

Modeled as ‘storage’ asset:

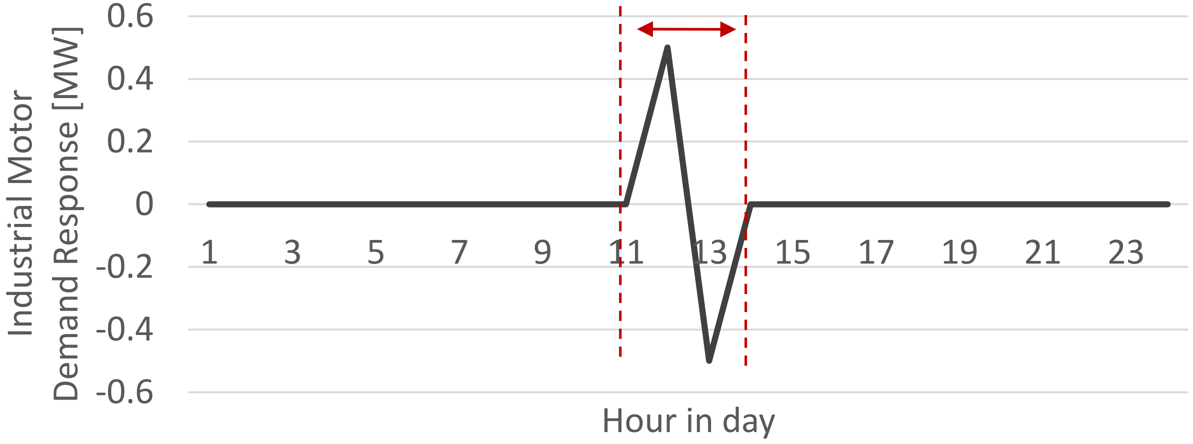
- ‘Pump’ – increase load compared to baseline
- ‘Generate’ – decrease load compared to baseline (‘inject’ power by not using power)

Demand response – constraints

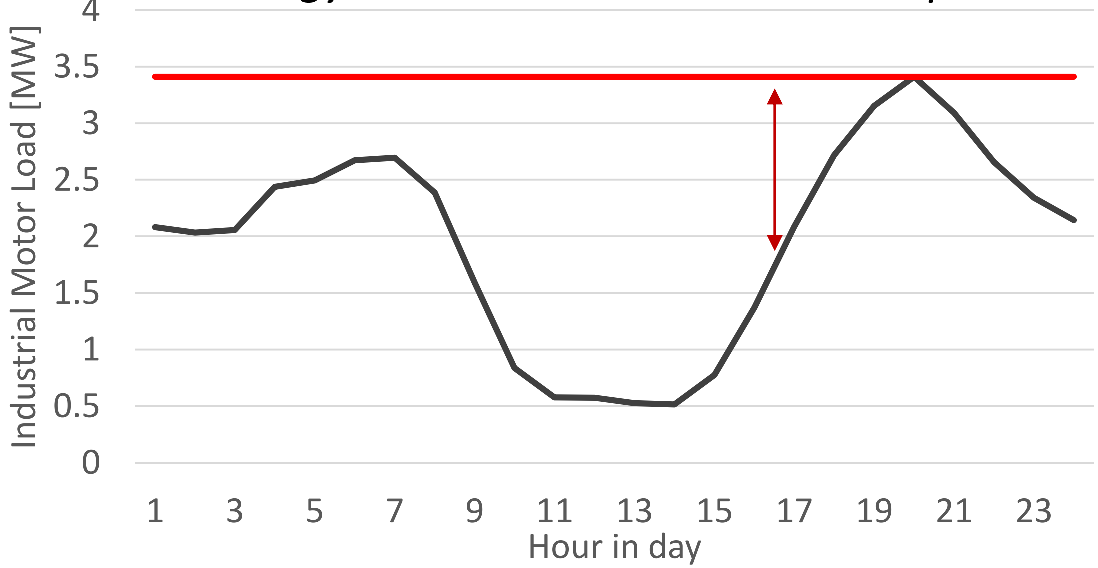
How much power is available in any hour?



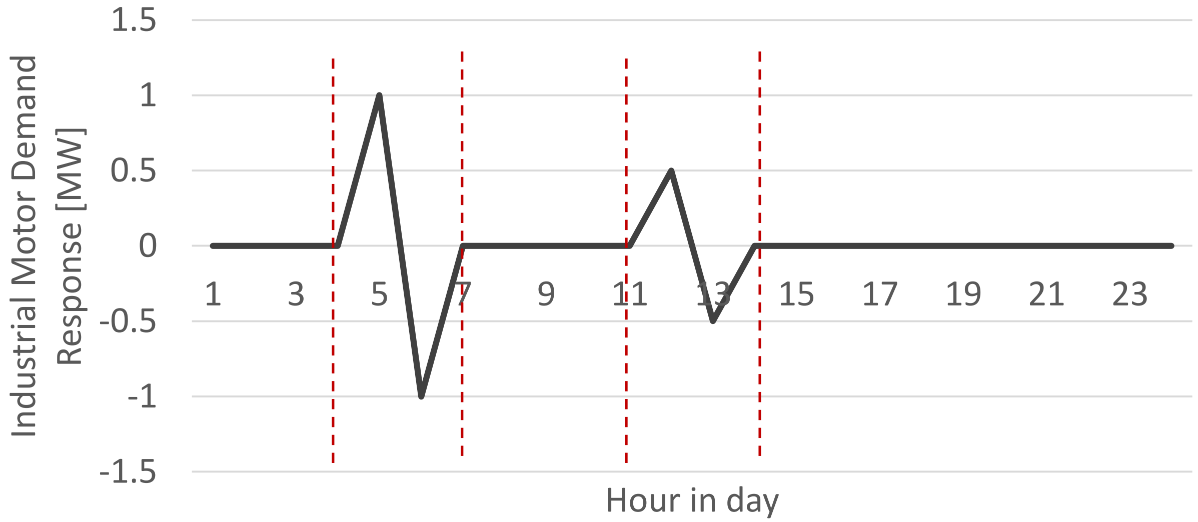
How long can a single DR event last?



How much energy can be recovered in subsequent hours?



How many times per day can the DR be used?



End-Uses – example consumer tolerance assumptions

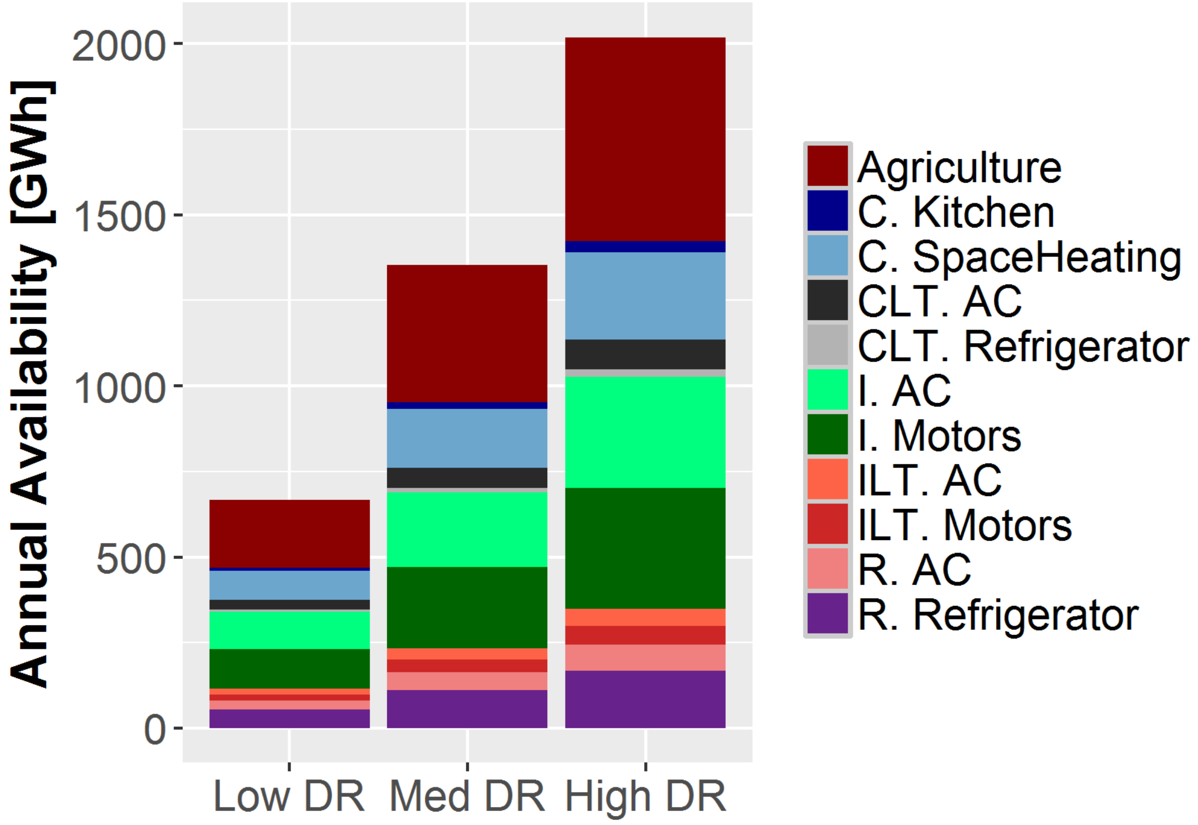
Sector	End-Use	Recovery Time [hours]	Min Up Time [hours]	Max Use Time [time/use]	Max Starts [per day]
Residential	AC	4 hours		15 min	2
	Refrigerator	4 hours		15 min	2
Commercial	Kitchen appliances	4 hours		1 hour	2
	Space cooling	4 hours		15 min	2
Industrial	Motors	2 hours		15 min	2
	Air conditioning	4 hours		15 min	2
Agriculture	Agriculture	24 hours	3 hours	7 hours	1

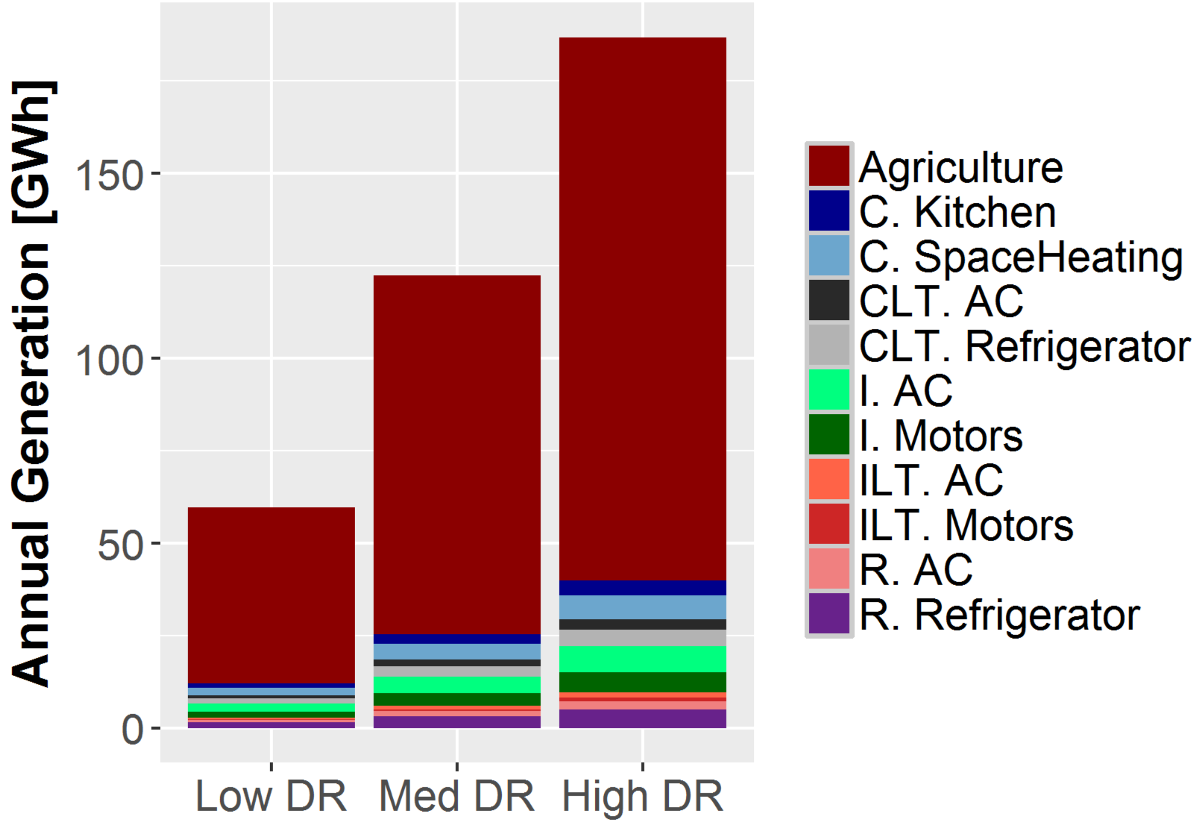
End-Uses – example consumer tolerance assumptions

Sector	End-Use	Recovery Time [hours]	Min Up Time [hours]	Max Use Time [time/use]	Max Starts [per day]
Residential	AC	4 hours		15 min	2
	Refrigerator	4 hours		15 min	2
Commercial	Kitchen appliances	4 hours		1 hour	2
	Space cooling	4 hours		15 min	2
Industrial	Motors	2 hours		15 min	2
	Air conditioning	4 hours		15 min	2
Agriculture	Agriculture	24 hours	3 hours	7 hours	1

Demand Response – key observation

Intraday constraints materially impact DR utilization





Building the elements – next steps

Ensure complete representation of DR constraints (intraday)

-> they have a material impact

Electric vehicles

Electric Vehicles

Net electricity consumption

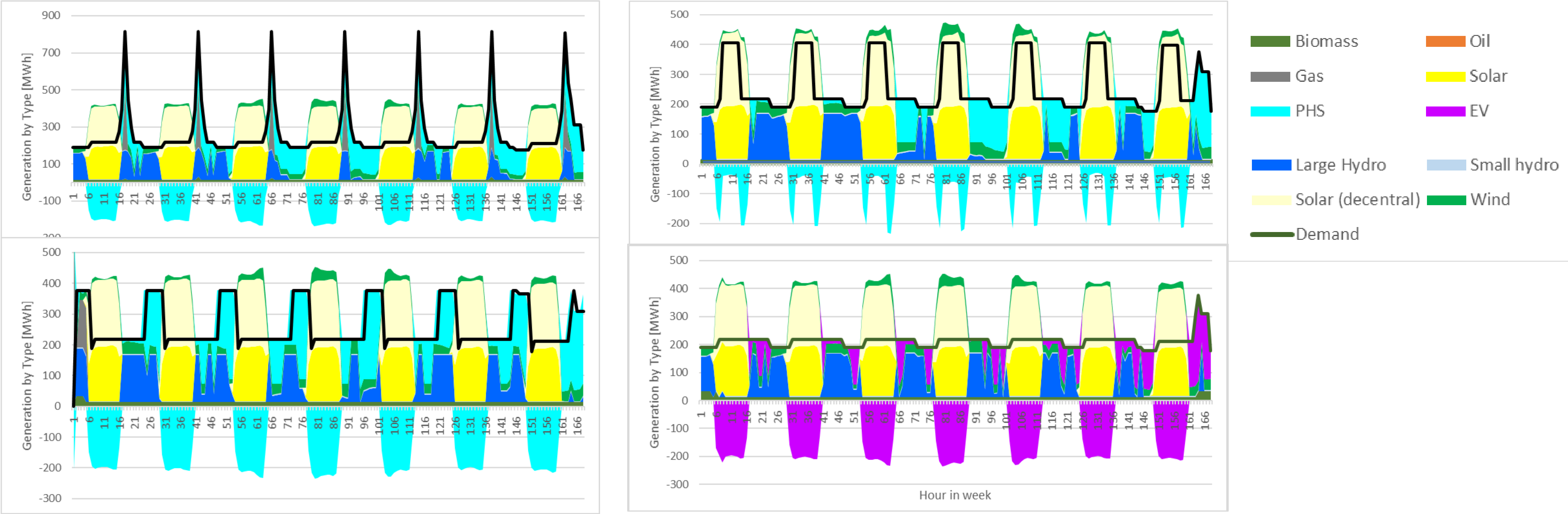
Analysis: timing of electricity consumption is shifted

- Mobility patterns are held constant – journey departure, travel, arrival time
- Different charging assumptions

V2G Modeled as ‘storage’ asset:

- ‘Pump’ – consuming electricity from the grid
- ‘Generate’ – injecting electricity onto the grid

EV charging profiles – charging schedule dispatch



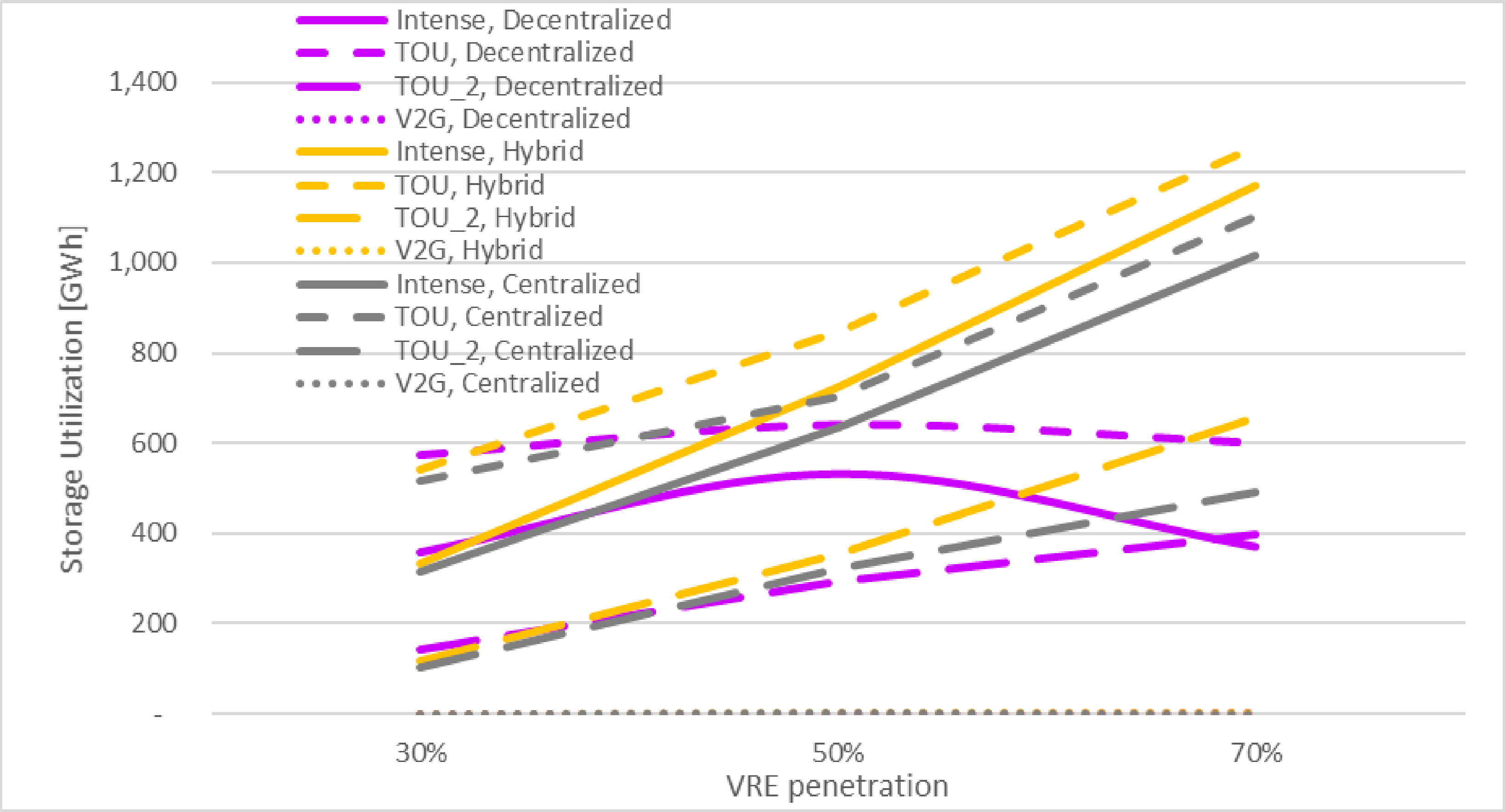
"Intense": all EVs are charged upon arrival home

"TOU": EV charging offsets baseline demand

"TOU_2": EV charging matches solar generation

"V2G": EV charging is optimized by system operator for any hours in which EV is not in transit

EV charging – key observations



Storage utilization rates under increasing VRE penetrations, alternative degrees of system centralization, and alternative EV charging schedules

Storage system requirements & utilization is highly sensitive to EV charging schedule…

- *Storage utilization drops to zero with V2G*

… and solar PV configuration:

- Decentralized; non-export
- Centralized; utility-scale & transmission connected
- Hybrid: 50-50 combination

Building the elements – next steps

Ensure complete representation of DR constraints (intraday)

-> they have a material impact

System design that is robust against potential EV charging scenarios

-> interdependencies: EV charging and system configuration (e.g. PV)

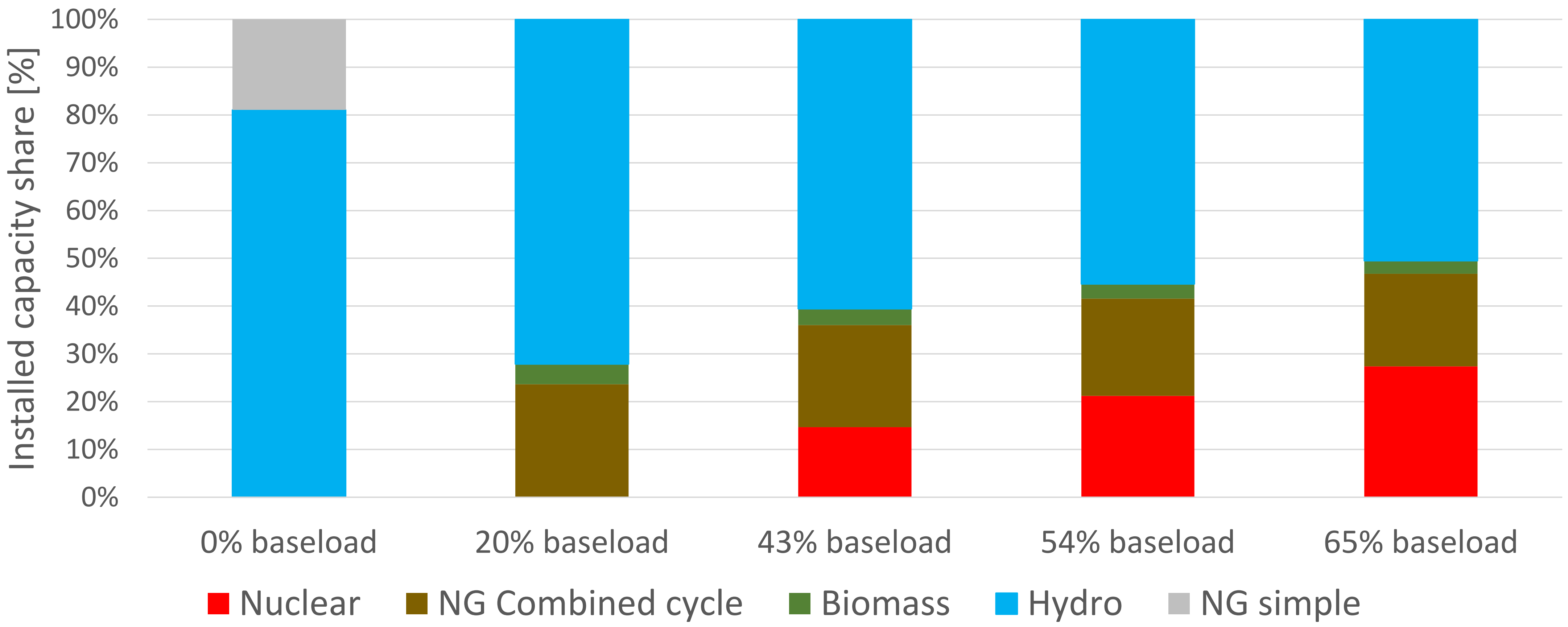
System flexibility

System flexibility

Percentage of must-run baseload generation

Low start up costs and no/short minimum up/down times >> flexible asset

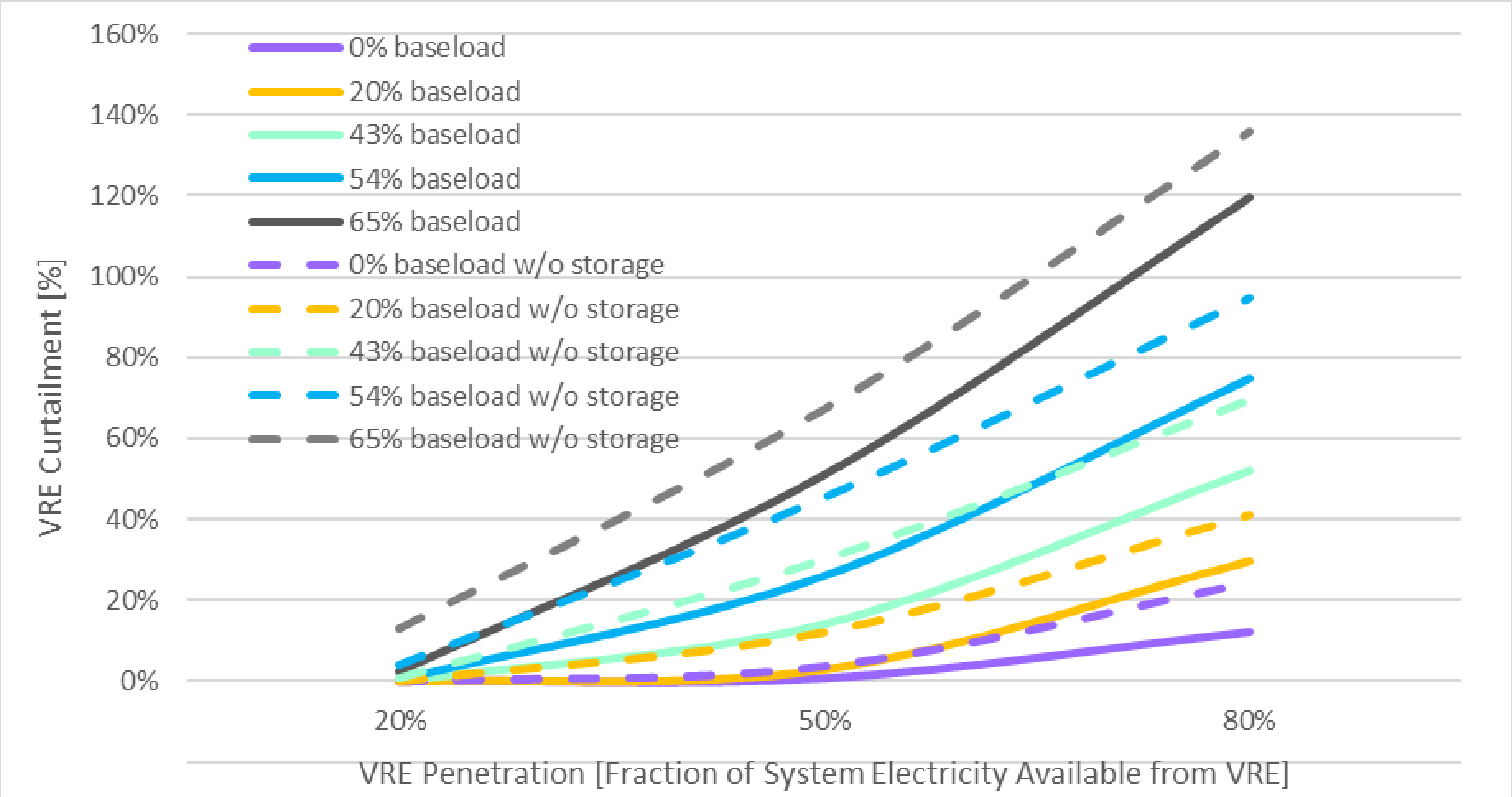
High start-up costs plus long minimum off times >> must-run baseload



System flexibility – key observation

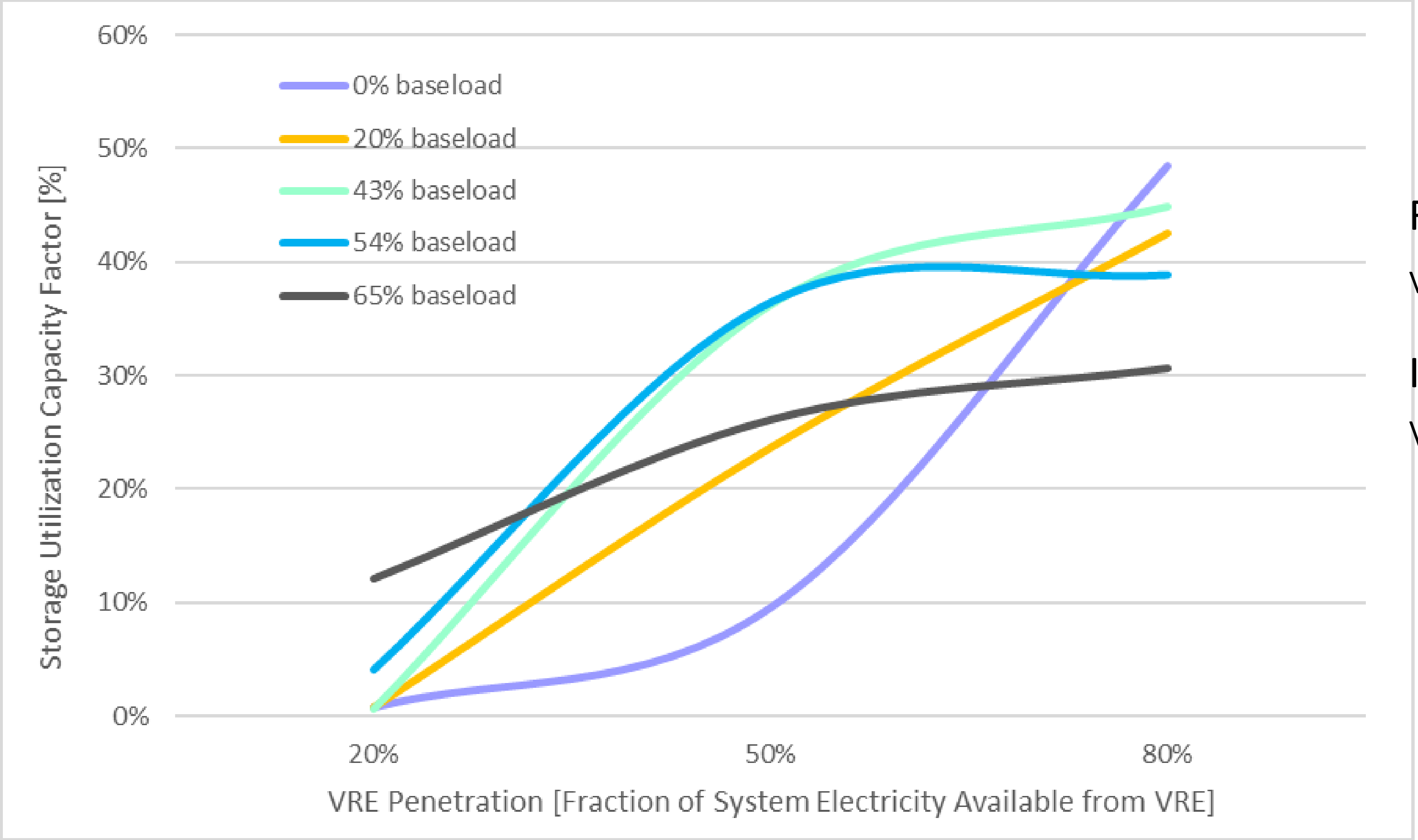
Pairing high VRE penetrations with flexible non-VRE generators emerges as one of the most significant design priorities

Phasing in variable renewables needs to be accompanied by phasing out inflexible baseload generators



System flexibility

What about utilizing storage to add flexibility?



Storage has limited ability to add flexibility to high-VRE, high-baseload systems

Flexible system: storage is utilized to mitigate VRE variability

Inflexible system: storage utilization plateaus at high VRE penetration

- Energy perspective: PHS Storage assets can't mitigate annual over-generation
- Cost perspective: Storage can't reduce costs by dispatching low-marginal cost (VRE generation) because of high-marginal cost assets are must-run

Building the elements – next steps

Ensure complete representation of DR constraints (intraday)

-> they have a material impact

System design that is robust against potential EV charging scenarios

-> interdependencies: EV charging and system configuration (e.g. PV)

Maximize system flexibility (limited daily storage impact in inflexible system)

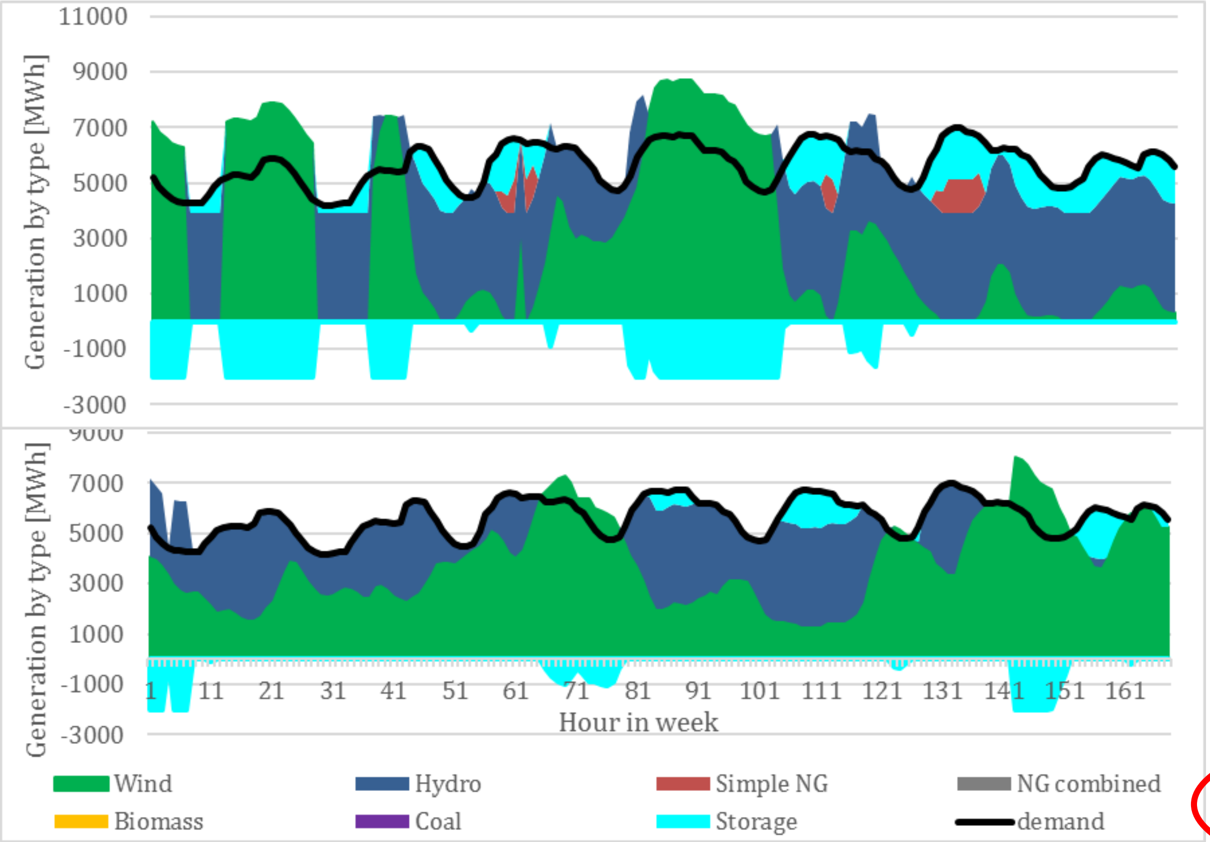
-> one of the key drivers of curtailment rates

VRE Characterization

VRE characterization: integration hypothesis

Characterization Metric	Metric Formulation		Corresponding integration strategy
Variability over hourly timescale	Hourly ramp events frequency and magnitude	$E_{MARV} = \frac{\sum\lvert v_i - v_{i-1}\rvert}{\mathrm{n}-1}$	Daily storage technologies, curtailment, and system flexibility
Variability over weekly-seasonal timescale	Relative frequency distribution curve	$E_{MRF} = \frac{\max\limits_{0<i\leq 23} y_i}{\mathrm{n}}$	Seasonal storage technologies, and system firm capacity
Inter-annual variability	Annual average capacity factor distribution	$E_{IAV} = \frac{\sum_{n=1}^{35}(y_i - \mu)^2}{35}$	Long-term storage technologies, sector integration, and backup generation
Correlation with demand profile	Average resource in high demand hours	$\mathrm{E_{DR}} = y_1 + 2 * y_2 + 3 * y_3 + 4 * y_4$	Demand response initiatives
Geographic coincidence factor	Coincidence of an geographic area	$\mathrm{E_{CF}} = \frac{\max\limits_{1\leq hr\leq 24}\{\sum_{n=1}^{N}\widehat{y_n}\}}{\sum_{hr=1}^{24}(\max\limits_{1\leq n\leq N}\widehat{y_n})}$	Transmission capacity expansion with neighboring areas
Inter-resource coincidence factor	Correlation between wind and solar resources	$E_{IRC} = \sum_{n=1}^{24}\chi_n$ $\chi_n = \begin{cases} 1 & \psi_{n,w} = \psi_{n,s} \\ 0 & \psi_{n,w} \neq \psi_{n,s} \end{cases}$ $\psi_n = \begin{cases} 1 & y_n > \overline{y_n} \\ -1 & \text{otherwise} \end{cases}$	The respective share of wind versus solar resources

VRE characterization: hourly variability



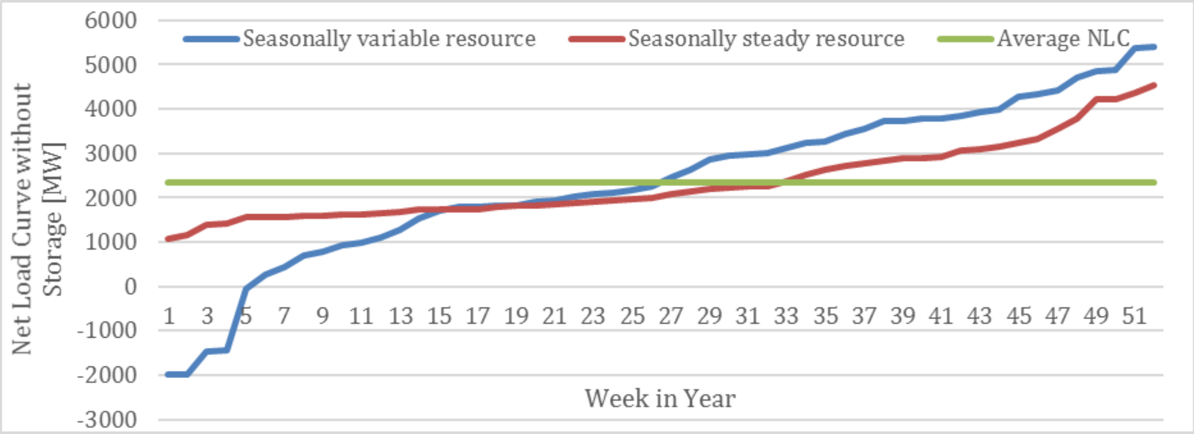
Weekly dispatch integrating a highly variable wind resource (top) versus a steady wind resource (bottom)

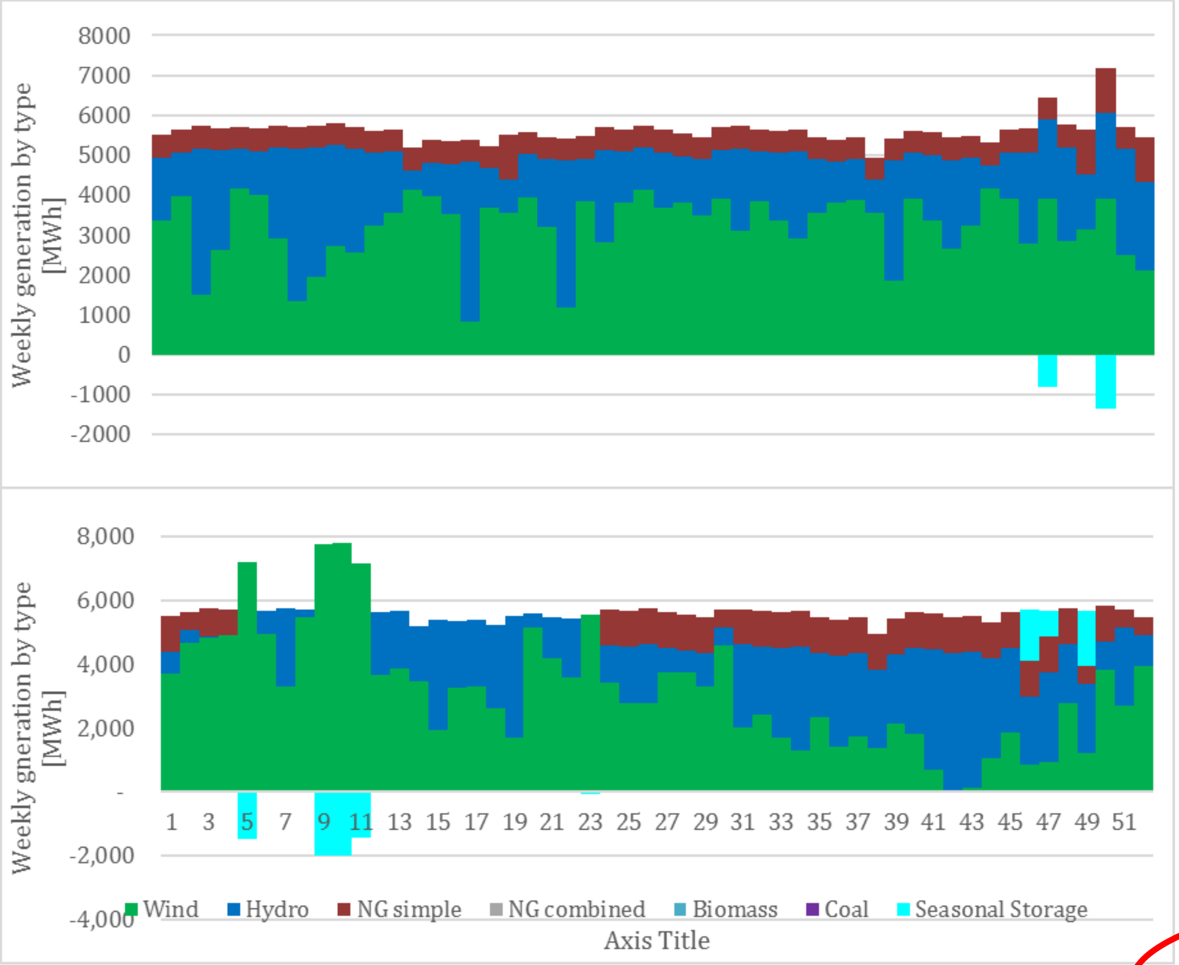
Impacts (annual) of integrating an hourly-variable resource compared to an hourly-stable resource:

Ramping events:	48% increase
System marginal cost:	52% increase
GHG emissions:	61% increase
Storage utilization:	82% increase
Marginal cost variability:	118% increase
Wind curtailment:	330% increase

VRE characterization: seasonal variability

Net load curve of a seasonally-variable versus seasonally-steady wind resource





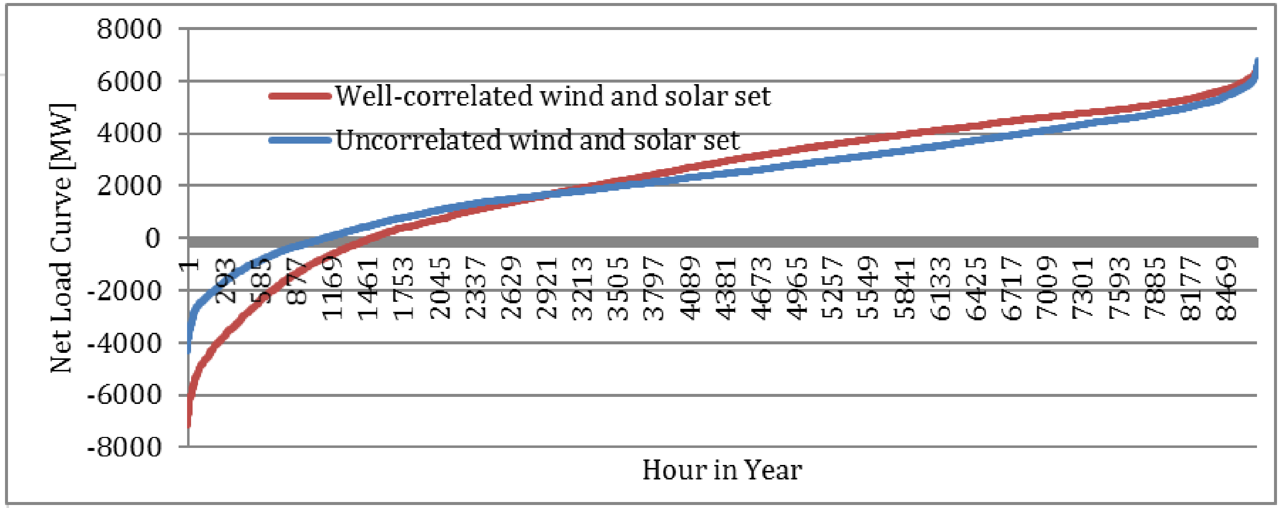
Dispatch integrating a seasonally steady resource (top) versus a seasonally variable resource (bottom)

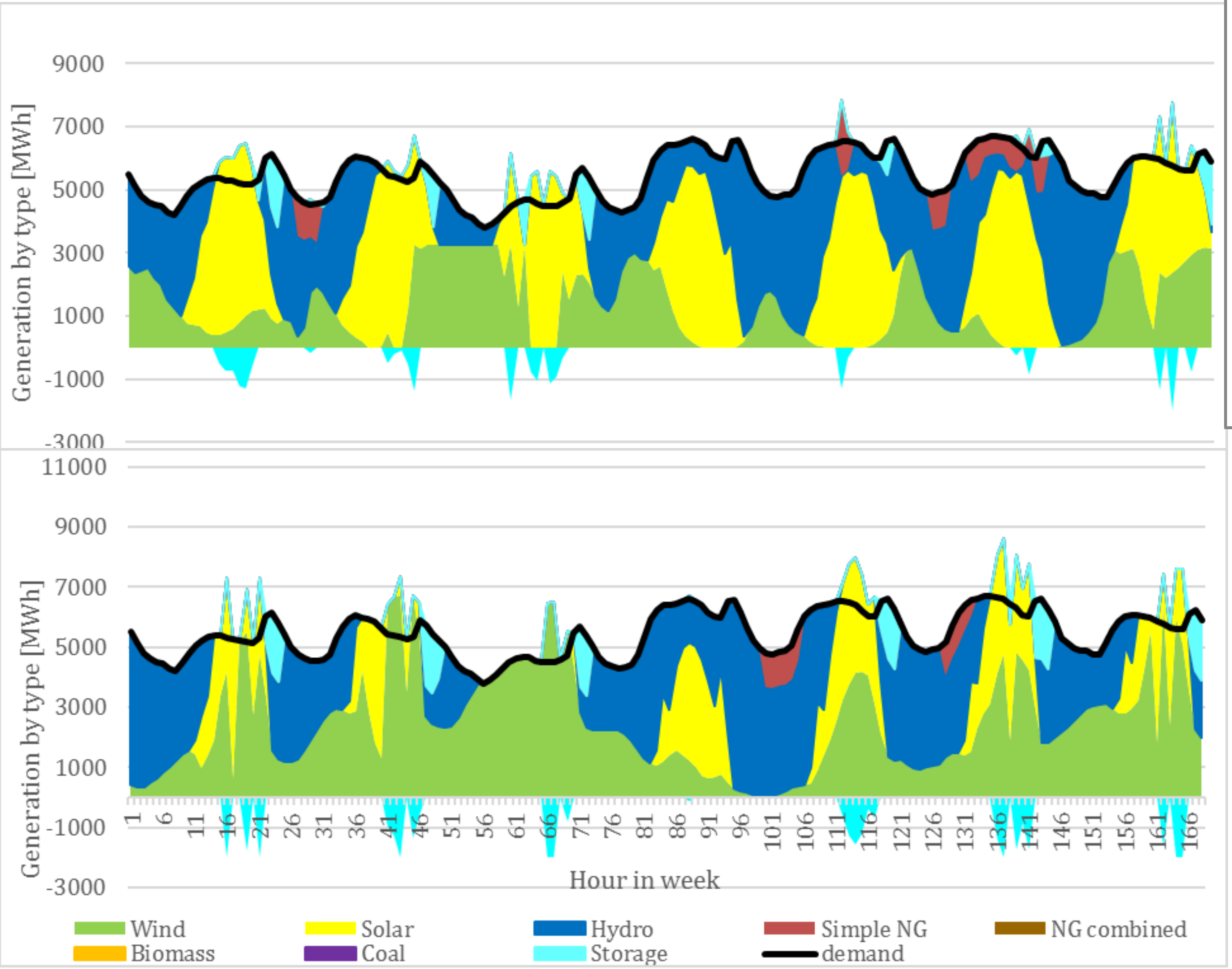
Impacts (annual) of integrating an seasonally-variable resource compared to an seasonally-stable resource:

Wind curtailment:	< 1% w/ storage
GHG emissions:	6% increase
System marginal cost:	6% increase
Ramping events:	26% increase
Storage (energy) utilization:	410% increase
Storage (capacity) utilization:	211% increase

VRE characterization: wind/solar correlation

Net load curve for two well-correlated and two uncorrelated wind-solar grid point pairs





Dispatch for an uncorrelated (top) versus a well-correlated (bottom) wind and solar pair

Impacts of integrating a well-correlated vs. uncorrelated wind/solar pair:

Ramping events:	19% increase
GHG emissions:	15% increase
System marginal cost:	20% increase
Marginal cost variability:	37% increase
Storage utilization:	52% increase
Wind curtailment:	180% increase
Solar curtailment:	800% increase

Building the elements – next steps

Ensure complete representation of DR constraints (intraday)

-> they have a material impact

System design that is robust against potential EV charging scenarios

-> interdependencies: EV charging and system configuration (e.g. PV)

Maximize system flexibility (limited daily storage impact in inflexible system)

-> one of the key drivers of curtailment rates

VRE characterization is a useful tool for system design

-> combine VRE characterization with appropriate strategy

Remuneration Mechanism

Flexibility resources remuneration in Ontario

Demand response:

- IESO's annual DR auction:
  - determines clearing prices ($/MW-day) & quantities (MW)
- Paid a fixed price for each unit of electricity (MWh) shifted

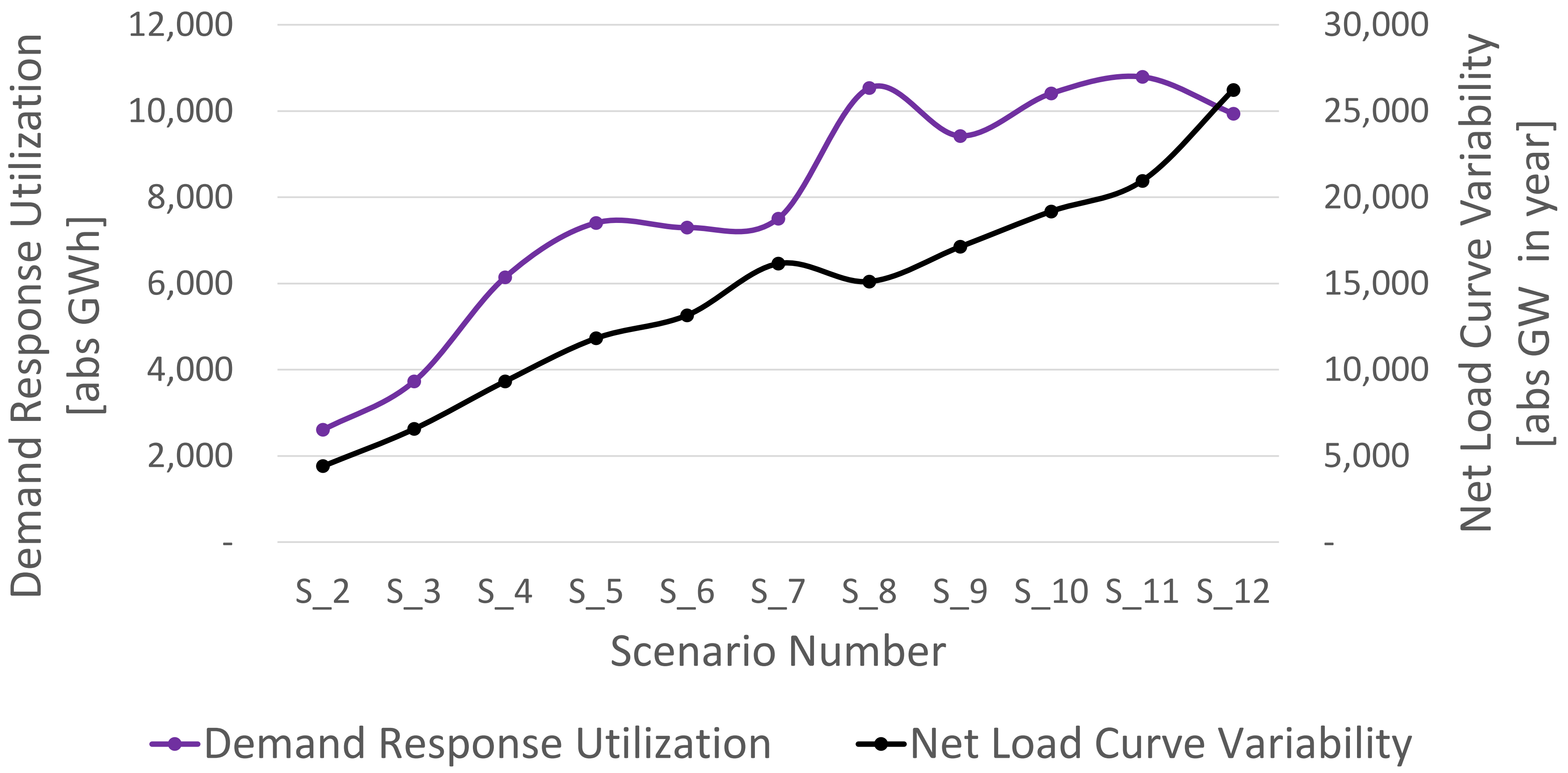
Utility-scale storage:

- IESO's Phase I Procurement: ancillary services
- IESO's Phase II Procurement: price arbitrage (buy low, sell high)
- 'Fuel' price = price of electricity during hours of pumping

Key difference:

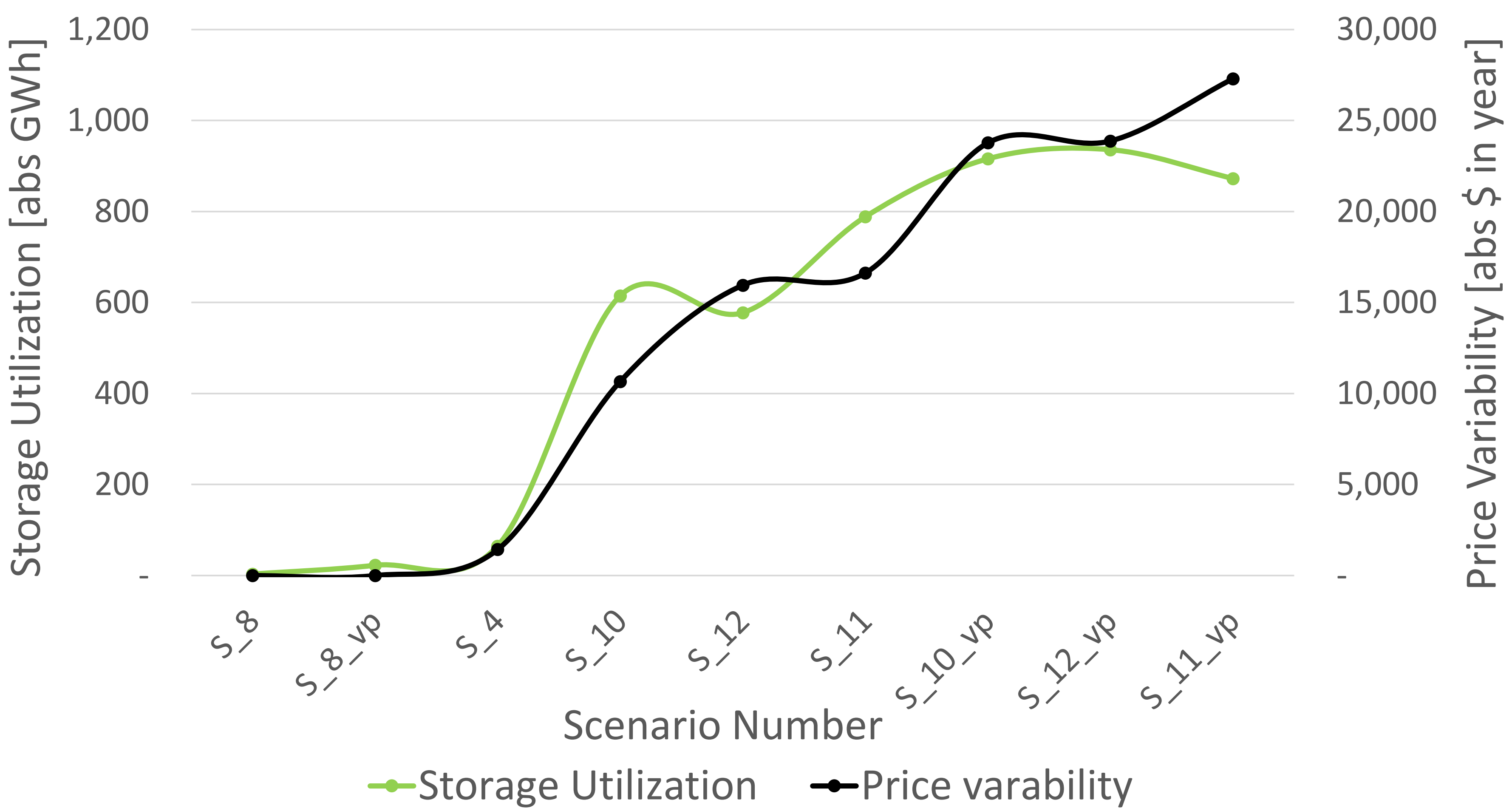
- DR cost is NOT sensitive to hourly market price fluctuations
- Storage 'fuel' cost IS sensitive to hourly market price fluctuations

Demand response utilization vs. NLC variability



- Net load curve (NLC): demand (baseline) minus VRE generation
- DR utilization increases with variability in the net load curve >> VRE penetration
- Correlation: 0.88

Storage utilization vs. Price variability

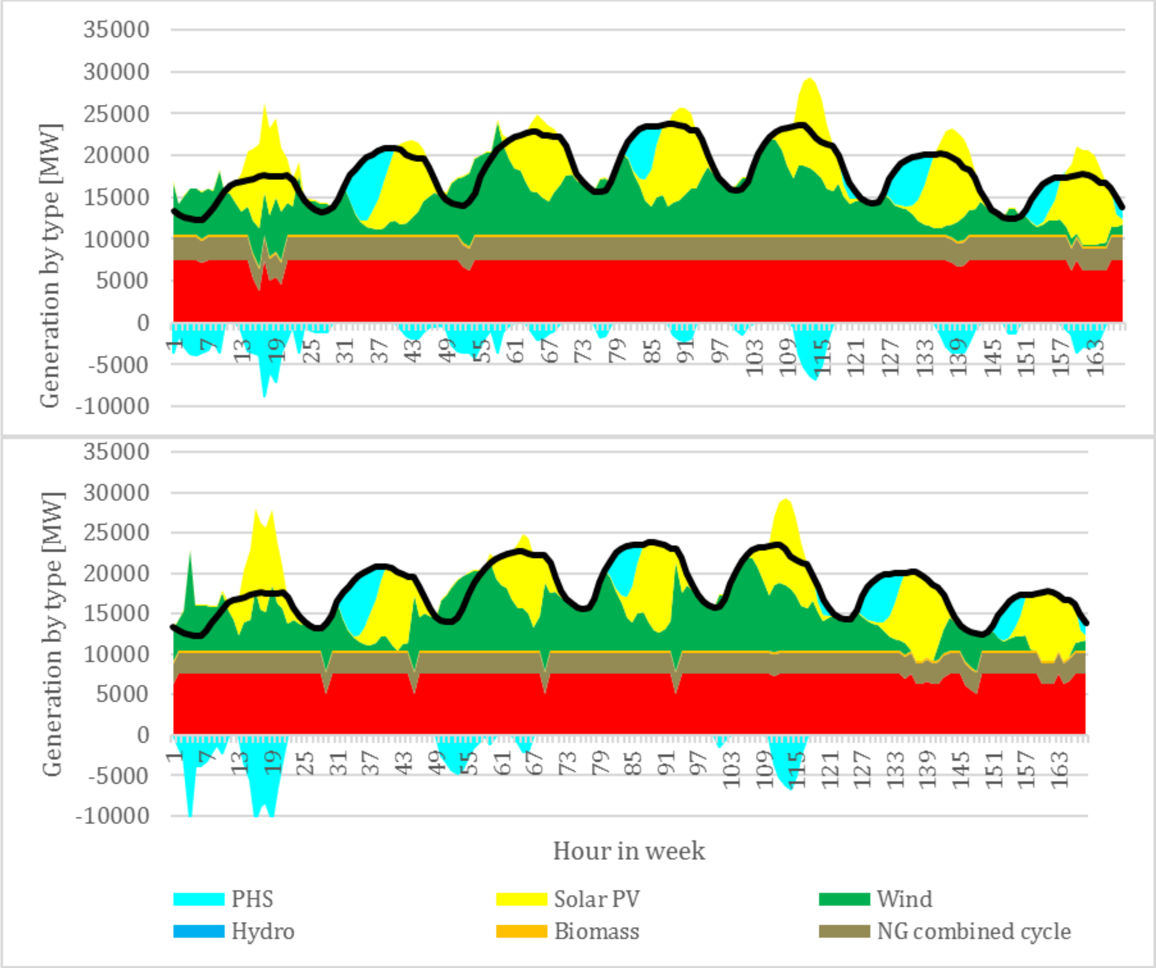


- Storage utilization increases with price variability >> shape of marginal cost curve
- Correlation: 0.97

Remuneration mechanism:

How are flexilibty assets remunerated by the electricity market?

Impact on dispatch



<u>Fixed contract payments:</u> generation from storage asset is paid fix price (like a FIT)

<u>Spot market prices:</u> storage asset pays hourly market price for pumping

Building the elements – next steps

Ensure complete representation of DR constraints (intraday)

-> they have a material impact

System design that is robust against potential EV charging scenarios

-> interdependencies: EV charging and system configuration (e.g. PV)

Maximize system flexibility (limited daily storage impact in inflexible system)

-> one of the key drivers of curtailment rates

VRE characterization is a useful tool for system design

-> combine VRE characterization with appropriate strategy

Remuneration policy drives utility & competitiveness

-> models need to represent remuneration policies properly

Market Participation

Storage asset market participation

Storage’s bidding strategy is obfuscated by opportunity cost evaluations:

- should the asset generate now, given a known electricity price,
- or later, given an expected electricity price forecast?

(1) should storage assets bid into day-ahead or real-time markets, or redispatch bids in both markets, and

(2) how accurately does forecast information have to be to improve real-time redispatches over the day-ahead schedule?

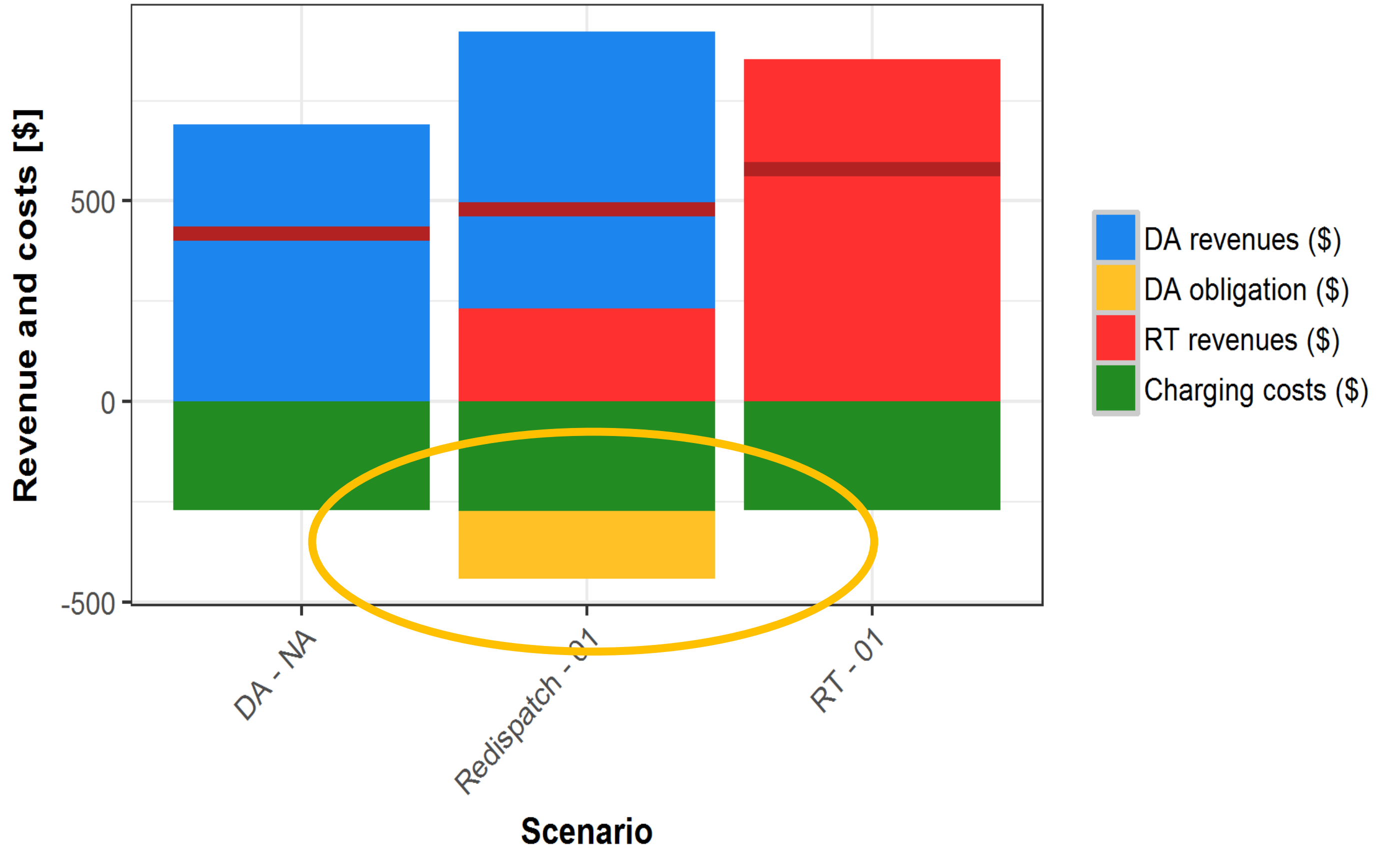
Market Rules

Must consider market rules in the model formulation:

- Day-ahead financial obligations
- Virtual transactions
- Consumption bids
- Day-ahead and real-time market timing
- Deviation charges

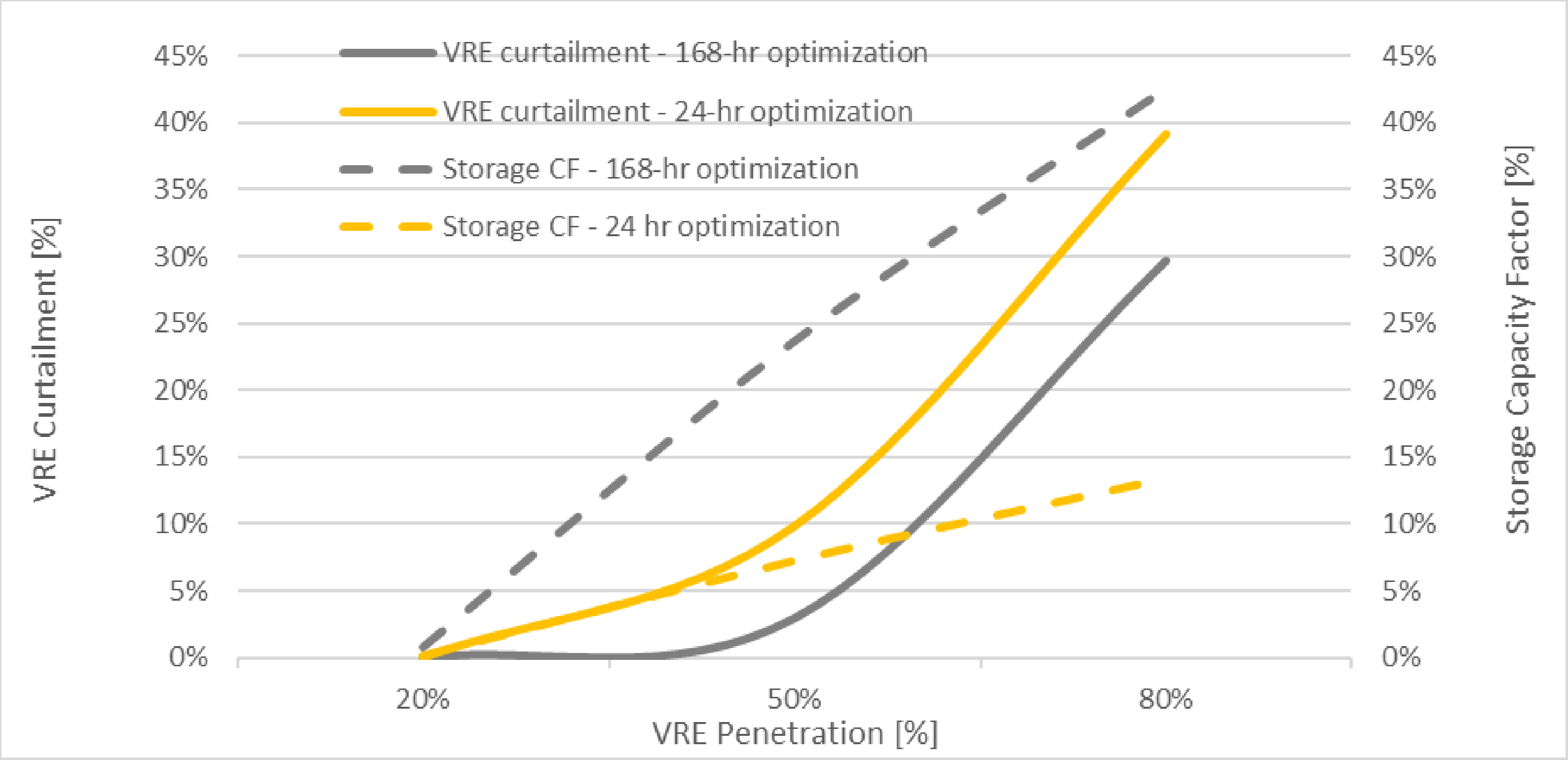
…to inform an accurate representation of storage bidding behavior in competitive day-ahead and real-time electricity markets

Market rules impact – e.g. DA obligation



Accounting (or not) for DA obligation changes the storage operator's decision to participate in the RT market only or re-dispatch DA bids in the RT market

Market rules impact – e.g. dispatch horizon



Longer dispatch planning horizon will enable better utilization of flexibility resources that employ time shifting

Building the elements – next steps

Ensure complete representation of DR constraints (intraday)

-> they have a material impact

System design that is robust against potential EV charging scenarios

-> interdependencies: EV charging and system configuration (e.g. PV)

Maximize system flexibility (limited daily storage impact in inflexible system)

-> one of the key drivers of curtailment rates

VRE characterization is a useful tool for system design

-> combine VRE characterization with appropriate strategy

Remuneration policy drives utility & competitiveness

-> models need to represent remuneration policies properly

Restructuring of the electricity market to accommodate storage

-> large implications for the energy system transformation

Next Steps:

ChargedUP

Application of these integration technologies and strategies to explore pathways to meeting Canada's Paris Agreement

Capacity expansion & production cost models

Three-year project

Build on previous work

Thank you

mmcpherson@uvic.ca