INREC 2020 | 9th International Ruhr Energy Conference

Demand response potentials for Germany: potential clustering and comparison of modeling approaches

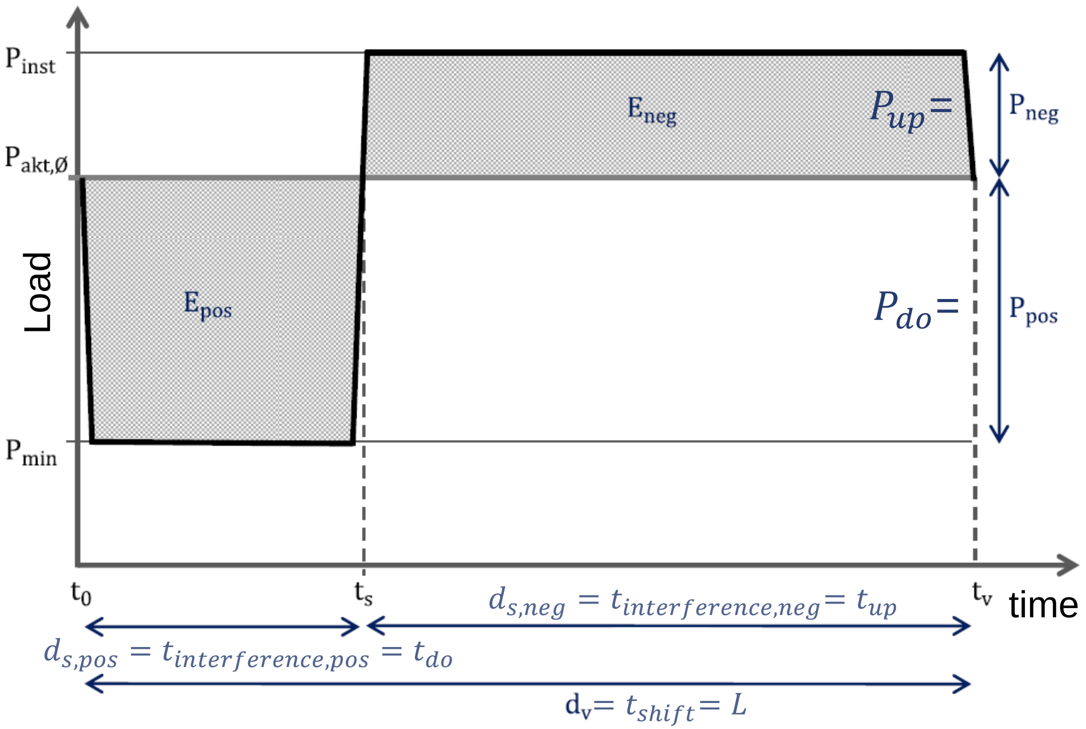
Johannes Kochems | Department of Energy and Resource Management at TU Berlin |
10 September 2020

Agenda

1	**Introduction**
2	**Method**
3	**Clustering results**
4	**Results of the model comparison**
5	**Conclusion**

Demand Response – small terminology

- Definitions of **temporal terms for load shifting**
  - **Shifting time** / delay time L, d_V or t_{shift}:
    Duration of time until the amount of energy must be completely balanced (parameter)
  - **Interference time** d_S or $t_{interference}$:
    Interference time of the load shifting in one direction (parameter)



sources: Steurer (2017), p. 56; own additions according to Gils (2015), pp. 13-14; Zerrahn and Schill (2015a), p. 845

Agenda

Method – part 1: Clustering of technical Demand Response potentials

- **Basis**: meta analysis on technical DR potentials (Kochems 2020)
  → roughly 100 (98) *Demand Response categories*
- Approach: **Grouping** to Demand Response clusters for power market modeling

1. filtering

- exclusion of data for **overall industry sectors**
- exclusion of PtX (except NSH & HP)

2. clustering

- **K-Means**
- cluster parameters: positive interference & shifting duration, cost parameters

3. availability

- positive / negative
- hourly resolution

Demand response clusters

- i.e. a **grouping of *Demand Response categories*** (applications / processes)
- with combined **parameterization** for these
- with combined **availability time series** in positive and negative direction

NSH: night storage heating
HP: heat pumps

source: Kochems (2020)

Method – part 2: Comparison of modeling approaches for Demand Response

1. Choice

- Usage in fundamental power market models and linear formulation
- **storage-alike modeling approach** (not using price elasticities)
- Documentation is given (constraints formulation)

2. Characterization

- Identification of central modeling **characteristics**
- Identification of similarities and differences

3. Implementation

- Implementation as **flexible demand units** („Sinks")
- enclosure of constraints in blocks

4. Comparison

- **Criteria**: Structure and amount of activations, objective value, performance
- Modeling a **highly simplified example power system model** using a **harmonization of parameterization** as far as possible

→
- *Conclusions on the **characteristics of the approaches***
- ***Deriving a suitable approach** for fundamental power market modeling*

Modeling of Demand Response – general implementation for power market models

Inputs

Load time series before DR

Costs for DR
- variable costs (€/MWh)
- fixed costs (€/a)

Technical restrictions
- Interference times (up / down)
- Shifting times
- maximum shiftable load (up / down)

Availability
- hourly availability for downshifts $P_{maxDo}(t) = P(t) - P_{min}(t)$
- hourly availability for upshifts $P_{maxUp}(t) = P_{max}(t) - P(t)$

Model

Dispatch optimization
- Load adjustment

$$\boldsymbol{P_L(t)} = P(t) + \boldsymbol{P_{up}(t)} - \boldsymbol{P_{do}(t)}$$

- Capacity limits

$$\boldsymbol{P_{do}(t)} \leq P_{maxDo}(t)$$

- Energy balance for a load shifting cycle (within t_{shift})

$$\sum \boldsymbol{P_{do}(t)} = \sum \boldsymbol{P_{up}(t)}$$

- Optional energy limits

$$W_{do} \leq \max\{P_{maxDo}(t)\} \cdot t_{do}$$

Outputs

Dispatch of Demand Response and adjusted demand after Demand Response

- **Variables: bold print**
- Parameters: normal print
- Parameters / variables for upshifts are analogous to downshift ones

t :	timestep
$P(t)$:	demand before DR
$P_{min}(t)$:	minimum demand
$P_{maxDo}(t)$:	maximum availability for downshift

$\boldsymbol{P_L(t)}$	demand after DR
$\boldsymbol{P_{do}(t)}$:	downshift
W_{do}:	energy limit for downshift
t_{shift} :	shifting time (syn.: delay time)
t_{do}:	interference duration for downshift

For the sake of simplicity, load shedding is not displayed.

Agenda

Clustering: **parameters and resulting clusters**

Parameters and dimensions

11 flexibility parameters*

8 years

3 estimates

264 parameter values per Demand Response cluster

Resulting clusters

- Filtering: 38 remaining Demand Response categories
- **Clustering**: **5 clusters**

Industry cluster 1

Industry cluster 2

Household cluster

Commerce cluster

Commerce & households cluster

* additional parameters compared to general implementation (slides 12/13):

- installed capacity
- specific investments

investment modeling

- regeneration duration
- maximum activations per year / day

imposing other limitations

Clustering: resulting clusters – **industry cluster 1**

Industry cluster 1	Paper industry	Mechanical and chemical wood pulp, paper machines, paper recycling
	Processes	Chlor-alkali electrolysis, air separation units, Primary aluminium electrolysis, electric arc steel-making, cement mills
	Cross-cutting technologies	ventilation, process cold, climate cold, lighting, compressed air, cooling (food industry), pumps
Industry cluster 2	Processes	copper and zinc electrolysis, foundries (arc furnace), calcium carbide production (arc furnace)
Household cluster	White Goods	refridgerators, dishwashers, tumble dryers, washing machines, freezers, fridge-and-freezer combination
	Other	Heating circulation pump
Commerce cluster	Cross-cutting technologies in general	Process cold, ventilation, lighting, process heat
	Other	pumps in drinking water supply, crushers (recycling industry), watewater treatment, cold stores, process cold in retailing industry
Commerce & households cluster	Heating applications	Heat pumps, night storage heating, hot water supply
	Cooling applications	Climate cold (air conditioning)

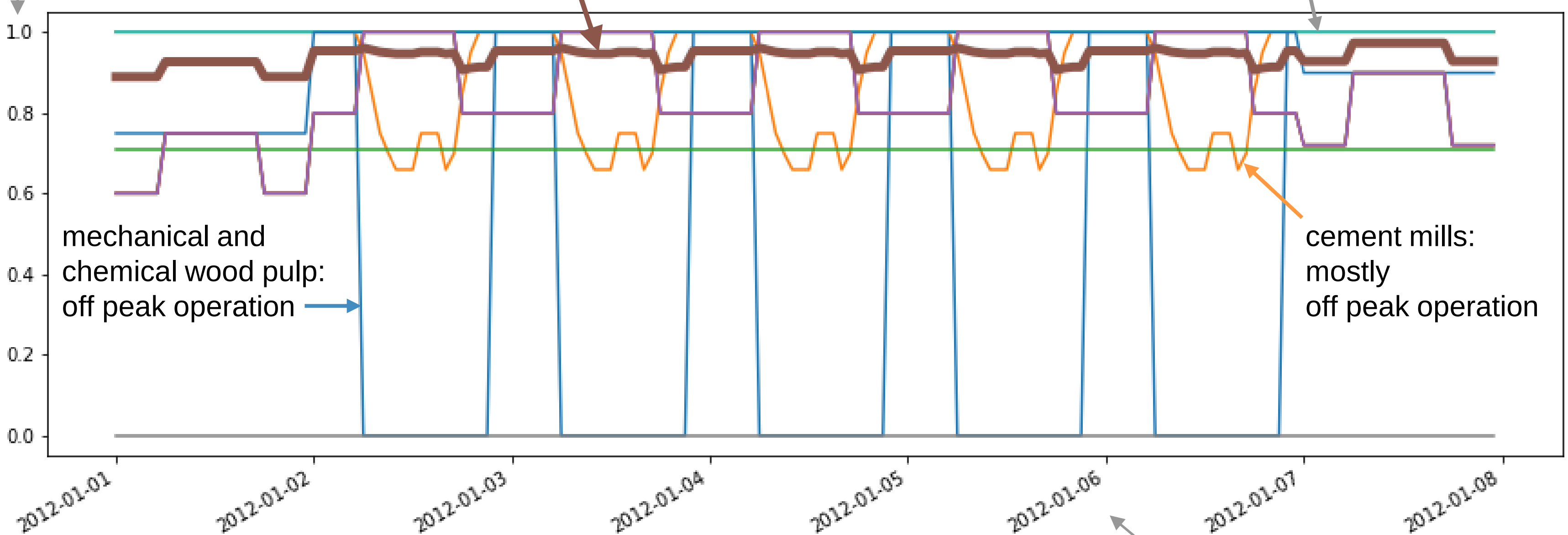
Clustering: deriving **availability time series** for cluster from individual availability time series of DR categories

Example: deriving load reduction capability for industry cluster 1

Normalized values:
1 = max. technical load reduction potential of the year

industry cluster 1:
Capacity weighted average

process industry:
constant profiles
(three shifts a day)



Visualization for an exemplary week:
- Year relevant for temperature-dependent loads
- Month relevant for seasonal pattern
- Weekday relevant if dependency on weekday
- Hour relevant for hourly profile of the day

Agenda

Comparison of modeling approaches: **characteristics**

Modeling approach	Mapping of processes	Symmetric constraints	Balancing variables	DR storage level(s)	Capacity limit	Interference time considered	Short-term energy limit(s)*	Long-term energy limit(s)	Minimum load considered	Distinction in initial upshift / downshif	Fixed shifting cycles
Zerrahn & Schill (2015) DIW	X				X		(X)		X		
Gils (2015) DLR		X	X	X (up / down)	X	X	(X)	(X)	X	X	
Steurer (2017) IER		X			X	X		X	X		
Ladwig (2018) TUD		X		X	X	X	X	X			X

* different kinds of short-term energy limits used:
– time limits for interference time vs.
– actual energy limits for a day

detailed description of the modeling approaches in the **backup slides**

X: element is used
(X): optional addition

source: own collocation based on Zerrahn and Schill (2015a), pp. 842-844; Gils (2015), pp. 67-70; Steurer (2017), pp. 80-82; Ladwig (2018), pp. 90-93

Comparison of modeling approaches: **characteristics** – differences in linking up- & downshifts

Modeling approach	Mapping of processes	Symmetric constraints	Balancing variables	DR storage level(s)	Capacity limit	Interference time considered	Short-term energy limit(s)*	Long-term energy limit(s)	Minimum load considered	Distinction in initial upshift / downshift	Fixed shifting cycles
Zerrahn & Schill (2015) DIW	X				X		(X)		X		
Gils (2015) DLR		X	X	X (up / down)	X	X	(X)	(X)	X	X	
Steurer (2017) IER		X			X	X		X	X		
Ladwig (2018) TUD		X		X	X	X	X	X			X

* different kinds of short-term energy limits used:
– time limits for interference time vs.
– actual energy limits for a day

detailed description of the modeling approaches in the **backup slides**

X: element is used
(X): optional addition

source: own collocation based on Zerrahn and Schill (2015a), pp. 842-844; Gils (2015), pp. 67-70; Steurer (2017), pp. 80-82; Ladwig (2018), pp. 90-93

Comparison of modeling approaches: **characteristics** – differences for energy & time limits

Modeling approach	Mapping of processes	Symmetric constraints	Balancing variables	DR storage level(s)	Capacity limit	Interference time considered	Short-term energy limit(s)*	Long-term energy limit(s)	Minimum load considered	Distinction in initial upshift / downshif	Fixed shifting cycles
Zerrahn & Schill (2015) DIW	X				X		(X)		X		
Gils (2015) DLR		X	X	X (up / down)	X	X	(X)	(X)	X	X	
Steurer (2017) IER		X			X	X		X	X		
Ladwig (2018) TUD		X		X	X	X	X	X			X

* different kinds of short-term energy limits used:
– time limits for interference time vs.
– actual energy limits for a day

detailed description of the modeling approaches in the **backup slides**

X: element is used
(X): optional addition

source: own collocation based on Zerrahn and Schill (2015a), pp. 842-844; Gils (2015), pp. 67-70; Steurer (2017), pp. 80-82; Ladwig (2018), pp. 90-93

Comparison of modeling approaches: **characteristics** – special aspects

Modeling approach	Mapping of processes	Symmetric constraints	Balancing variables	DR storage level(s)	Capacity limit	Interference time considered	Short-term energy limit(s)*	Long-term energy limit(s)	Minimum load considered	Distinction in initial upshift / downshif	Fixed shifting cycles
Zerrahn & Schill (2015) DIW	X				X		(X)		X		
Gils (2015) DLR		X	X	X (up / down)	X	X	(X)	(X)	X	X	
Steurer (2017) IER		X			X	X		X	X		
Ladwig (2018) TUD		X		X	X	X	X	X			X

* different kinds of short-term energy limits used:
- time limits for interference time vs.
- actual energy limits for a day

detailed description of the modeling approaches in the **backup slides**

X: element is used
(X): optional addition

source: own collocation based on Zerrahn and Schill (2015a), pp. 842-844; Gils (2015), pp. 67-70; Steurer (2017), pp. 80-82; Ladwig (2018), pp. 90-93

Comparison of modeling approaches: model setup* and parameterization

Stylized example

- **48** (hourly) **timesteps**
- default **flat demand timeseries**
- Generation units & costs

Unit	Effective costs
Coal plant	32.5 (€/MWh)
Generic generation (fixed)	**0**
Excess	1 (€/MWh)
Shortage	200 (€/MWh)

- Analysis of **different cases** → demand resp. generation **variations**
- Analysis of **parameter sensitivities**

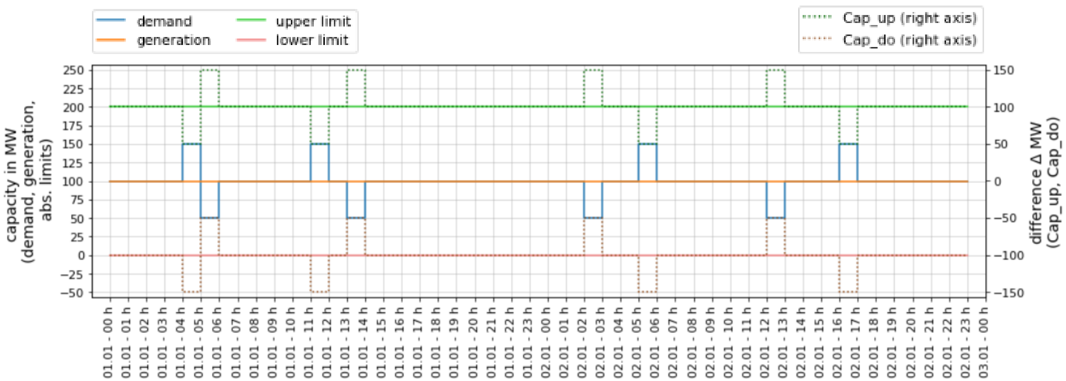
Demand Response parameterization

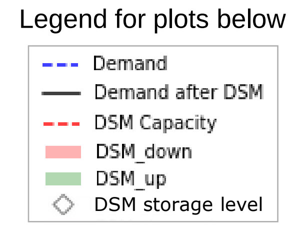
- **Harmonization** of parameterization as far as possible
- **Capacity**
  - lower capacity limit: 0
  - upper capacity limit: 200 MW
- **Times**
  - shifting time (delay time): 4 (hours)
  - interference time (if applicable): 2 (hours) up / down
- **Costs**
  - Overall: 0.1 (€/MWh)
  - Evenly attributed to upwards resp. downwards shift (each half of overall costs)

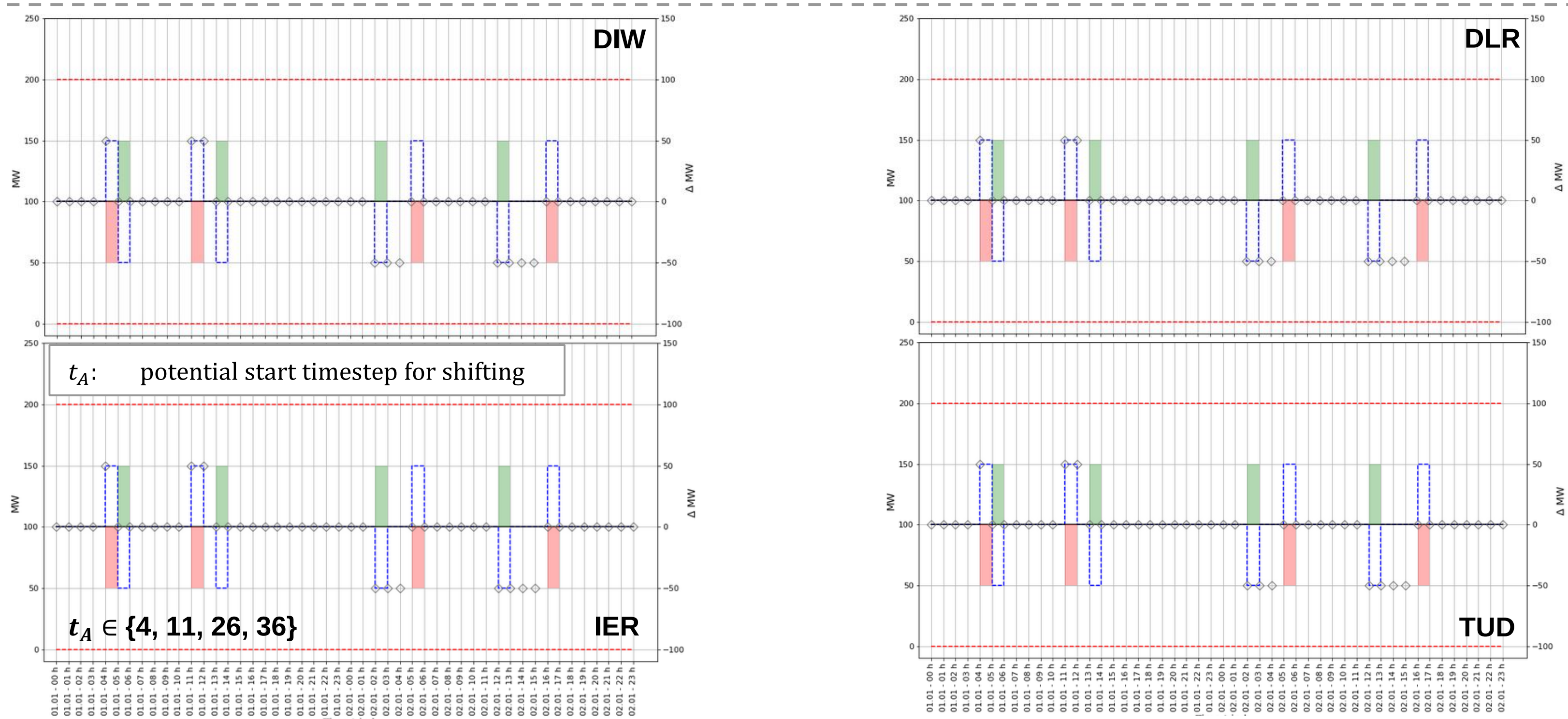
** Building upon the jupyter notebooks from Julian Endres & Guido Pleßmann: https://github.com/windnode/SinkDSM_example*

source: Gährs et al. (2020); Endres & Plessmann (2020)

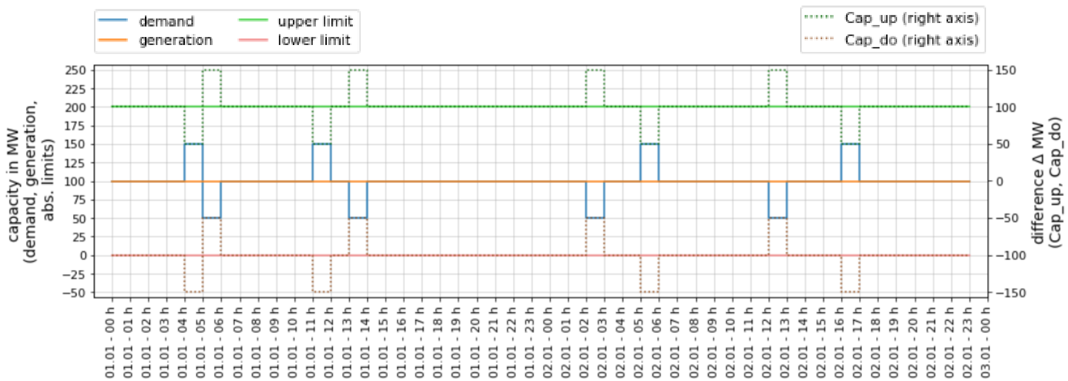
Comparison of modeling approaches: DR utilization – Case A: demand variations - **same amplitude**





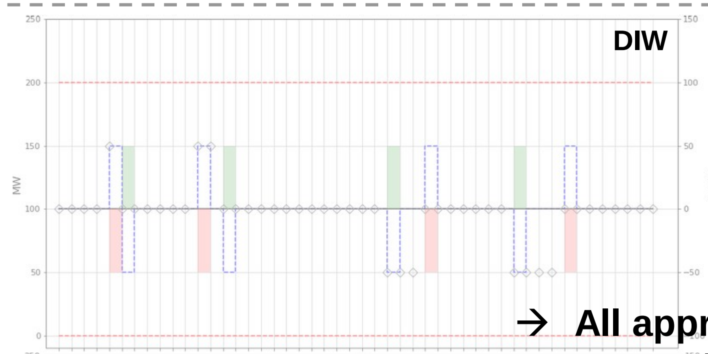


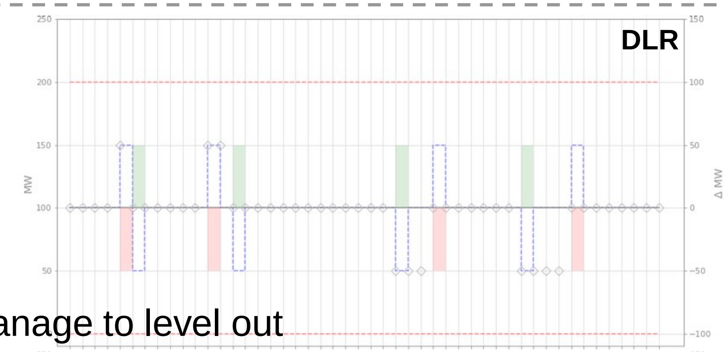
Comparison of modeling approaches: DR utilization – Case A: demand variations - **same amplitude**



Legend for plots below

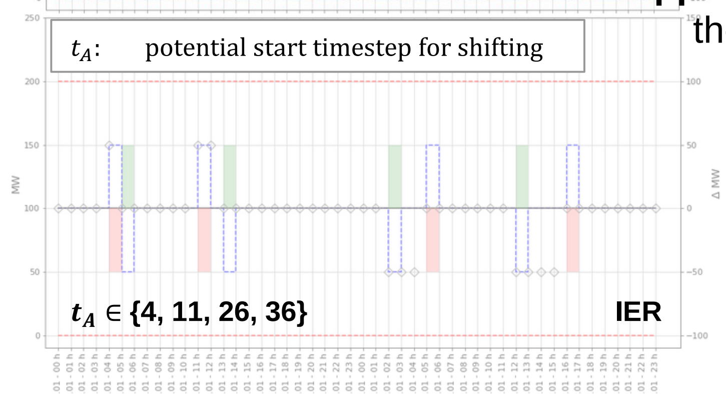
- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level



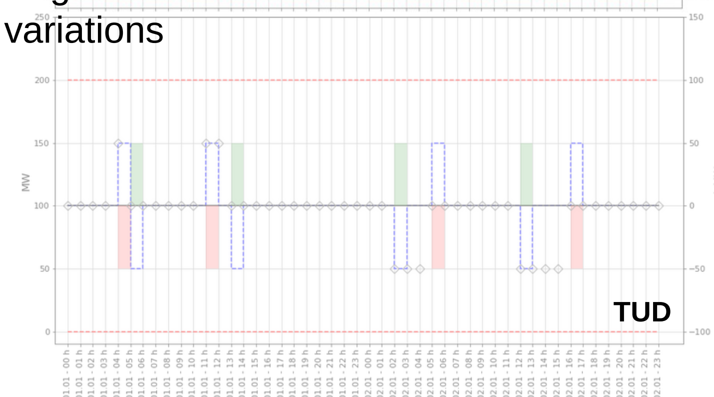


→ **All approaches** manage to level out the demand variations

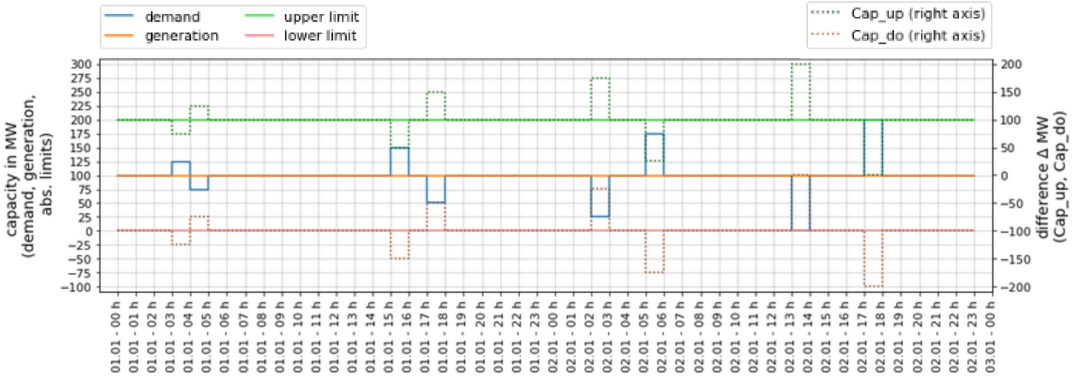
t_A: potential start timestep for shifting



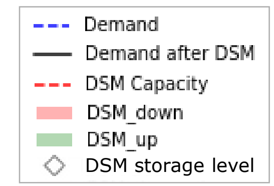
$t_A \in \{4, 11, 26, 36\}$

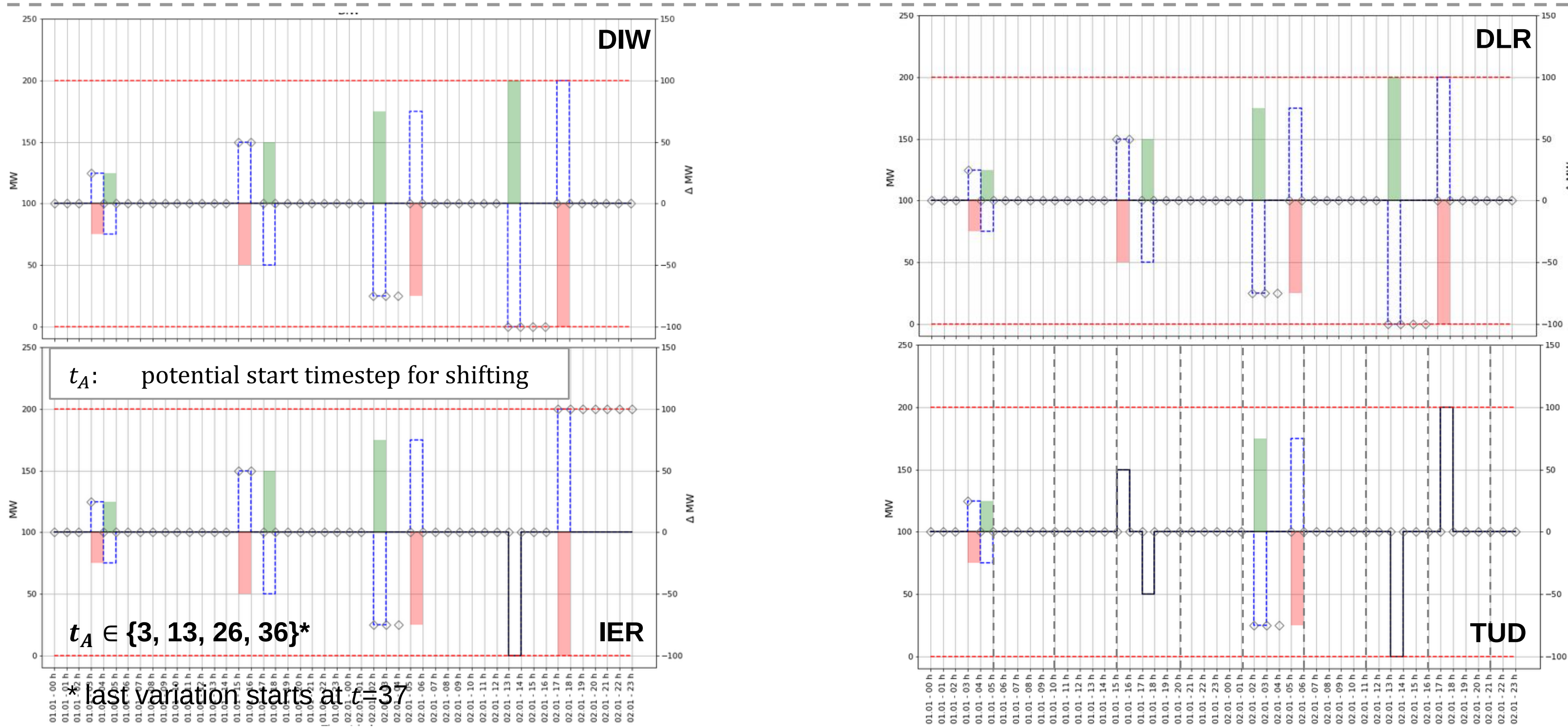


Comparison of modeling approaches: DR utilization – Case C: demand variations - **changed starts**

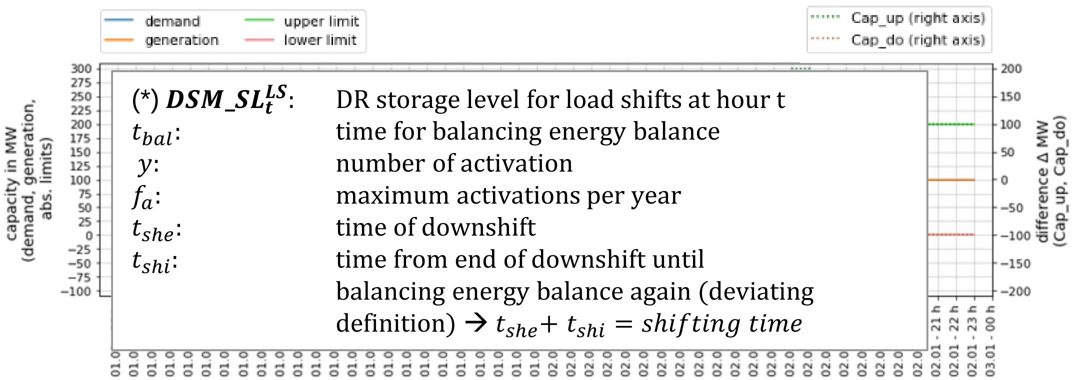


Legend for plots below



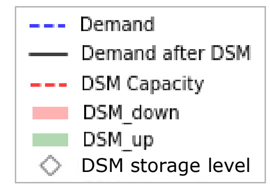


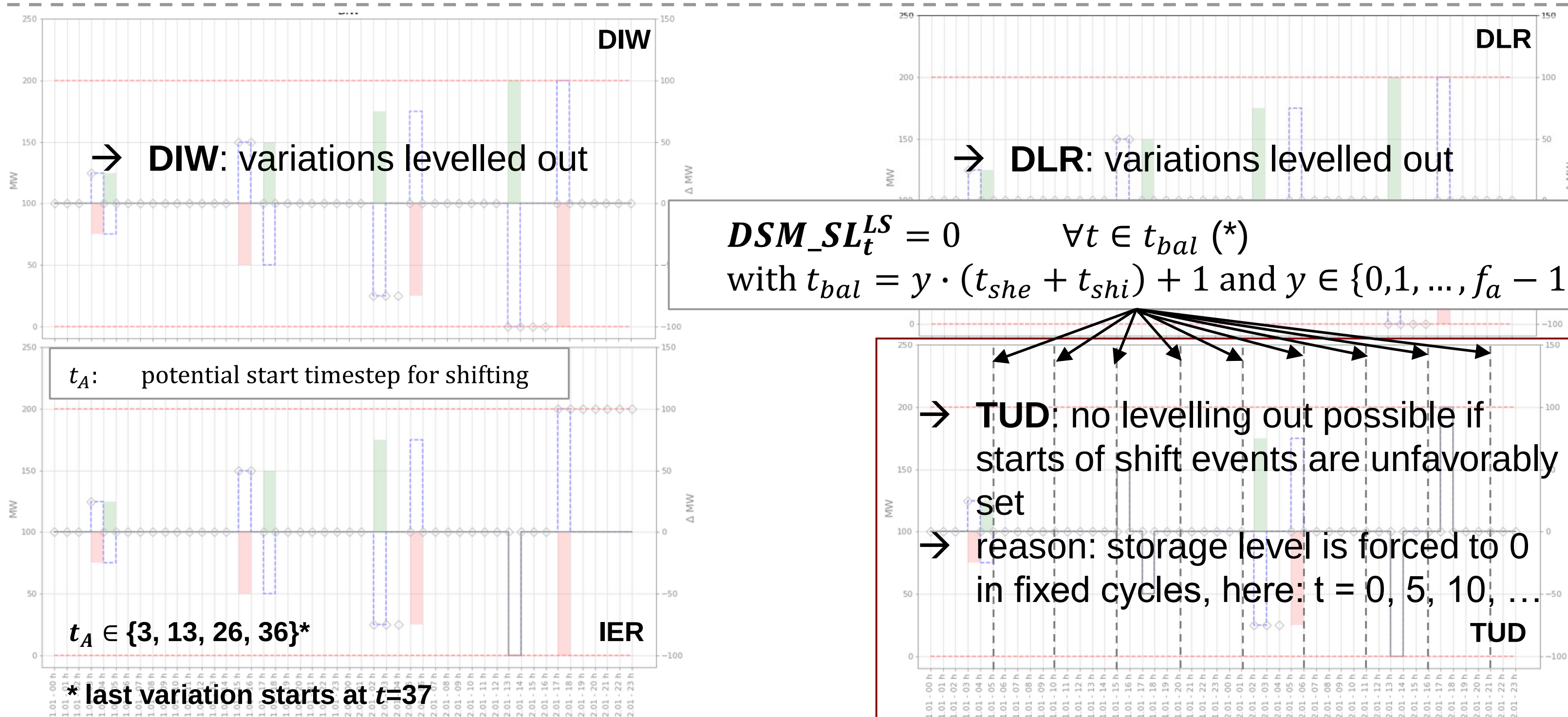
Comparison of modeling approaches:
DR utilization – Case C: demand variations - **changed starts**



(*) $\boldsymbol{DSM\_SL_t^{LS}}$: DR storage level for load shifts at hour t
t_{bal}: time for balancing energy balance
y: number of activation
f_a: maximum activations per year
t_{she}: time of downshift
t_{shi}: time from end of downshift until balancing energy balance again (deviating definition) → $t_{she} + t_{shi} = shifting\ time$

Legend for plots below





→ **DIW**: variations levelled out

→ **DLR**: variations levelled out

$$\boldsymbol{DSM\_SL_t^{LS}} = 0 \qquad \forall t \in t_{bal}\ (*)$$
$$\text{with } t_{bal} = y \cdot (t_{she} + t_{shi}) + 1 \text{ and } y \in \{0,1,\dots,f_a - 1\}$$

t_A: potential start timestep for shifting

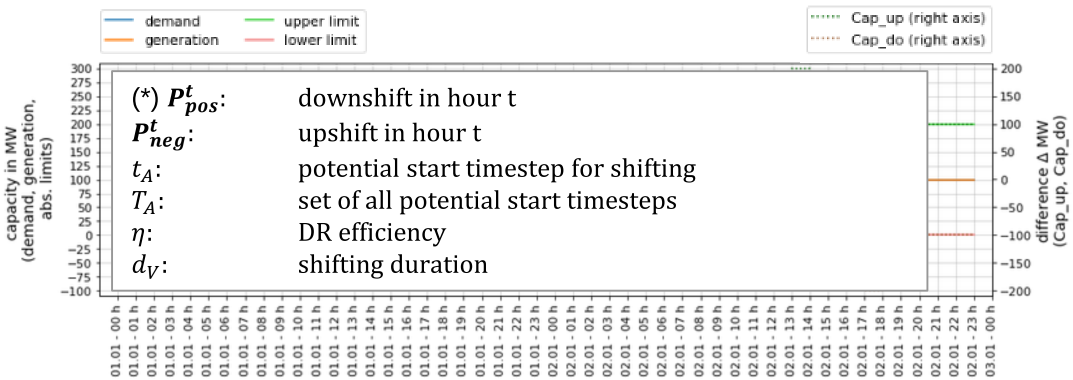
$t_A \in$ **{3, 13, 26, 36}***

*** last variation starts at t=37**

→ **TUD**: no levelling out possible if starts of shift events are unfavorably set

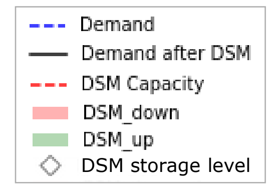
→ reason: storage level is forced to 0 in fixed cycles, here: t = 0, 5, 10, …

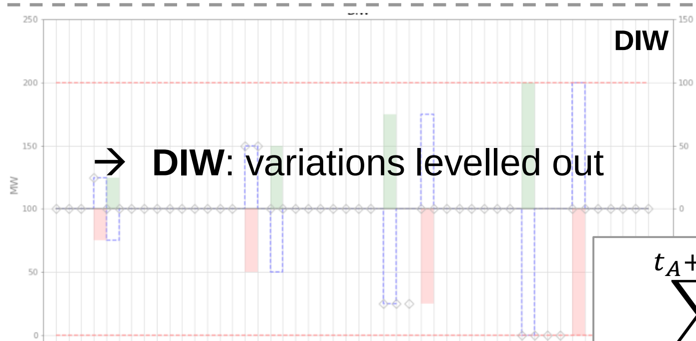
Comparison of modeling approaches: DR utilization – Case C: demand variations - **changed starts**



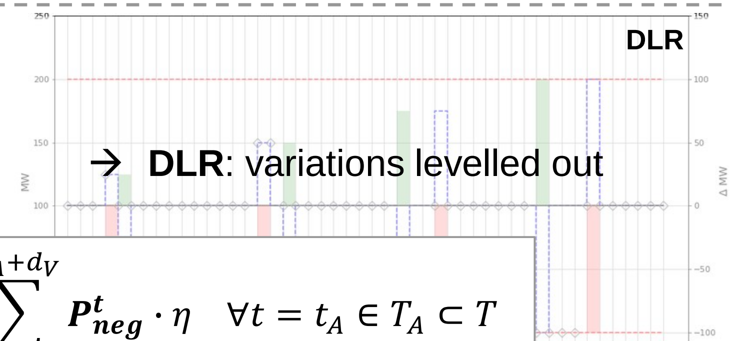
(*) P_{pos}^{t}: downshift in hour t
P_{neg}^{t}: upshift in hour t
t_A: potential start timestep for shifting
T_A: set of all potential start timesteps
η: DR efficiency
d_V: shifting duration

Legend for plots below





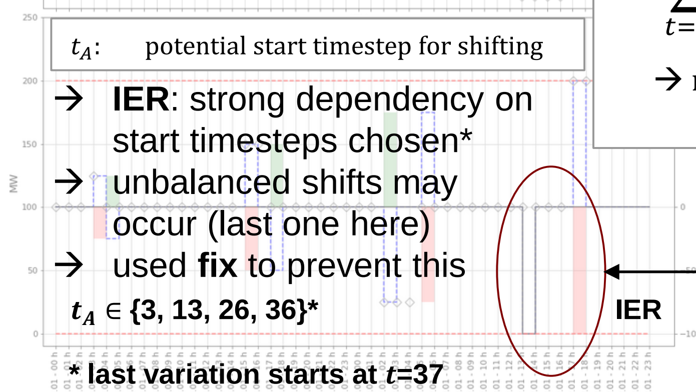
→ **DIW**: variations levelled out



→ **DLR**: variations levelled out

$$\sum_{t=t_A}^{t_A+d_V} P_{pos}^{t} = \sum_{t=t_A}^{t_A+d_V} P_{neg}^{t} \cdot \eta \quad \forall t = t_A \in T_A \subset T$$

→ no balancing constraint applicable here for $t = 41$ (end of last demand variation)

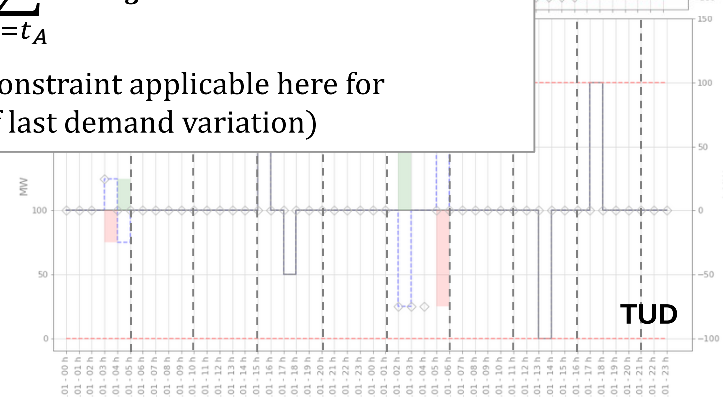


t_A: potential start timestep for shifting

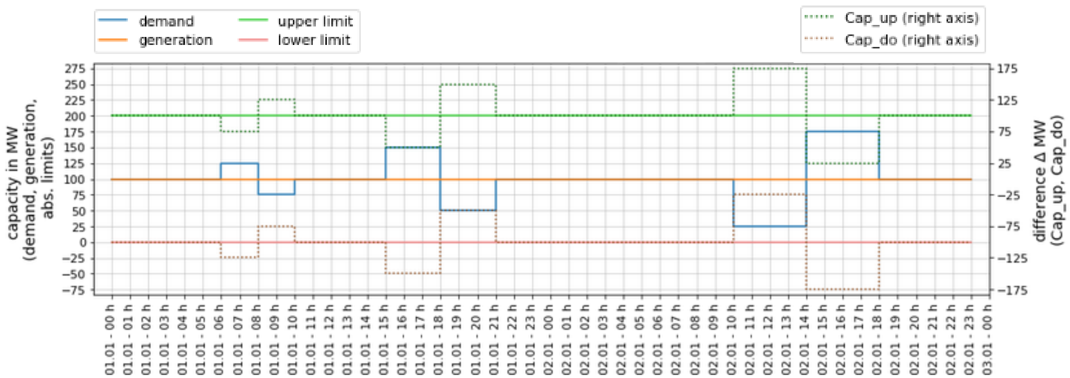
→ **IER**: strong dependency on start timesteps chosen*
→ unbalanced shifts may occur (last one here)
→ used **fix** to prevent this

$t_A \in$ **{3, 13, 26, 36}***

*** last variation starts at t=37**

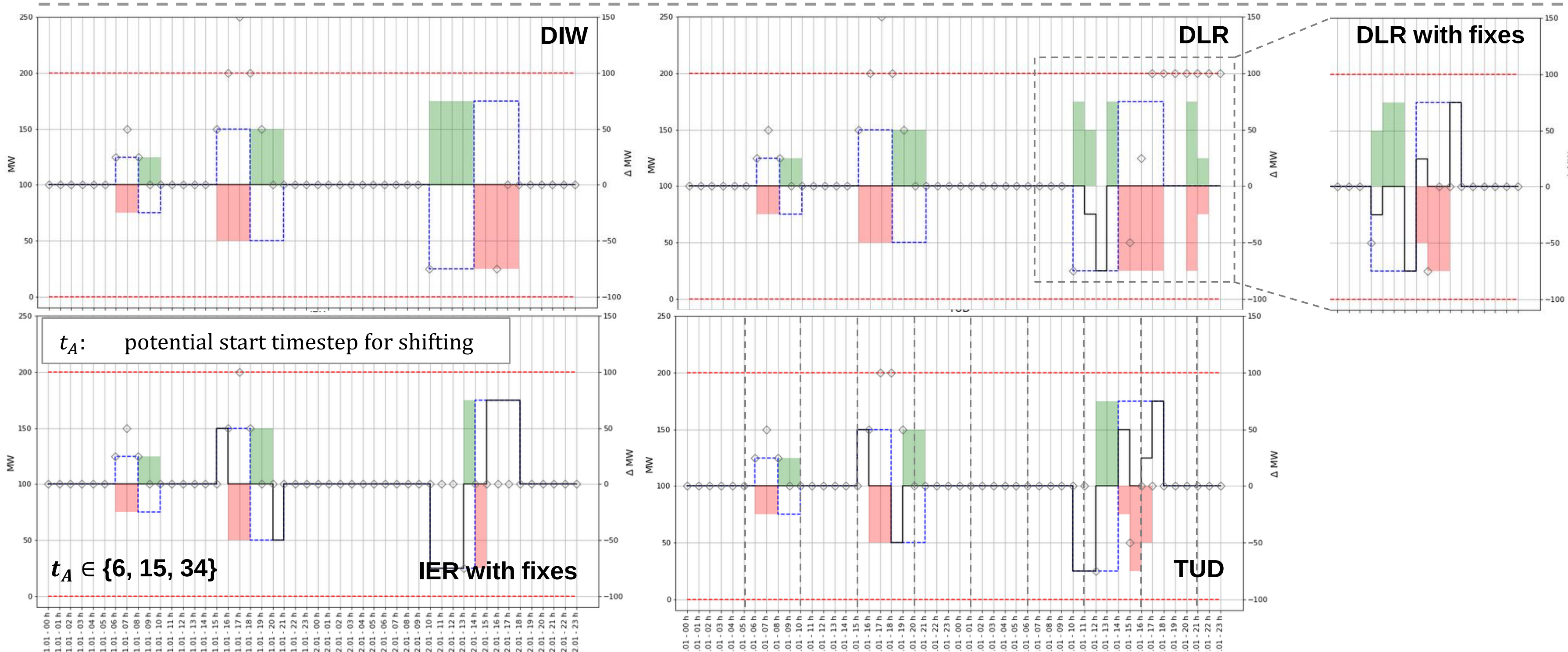


Comparison of modeling approaches: DR utilization – Case D: demand variations - **longer duration**

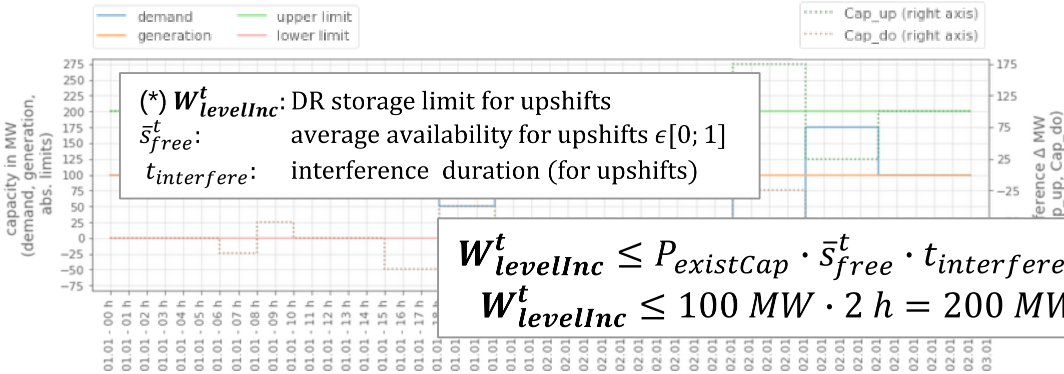


Legend for plots below

- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level



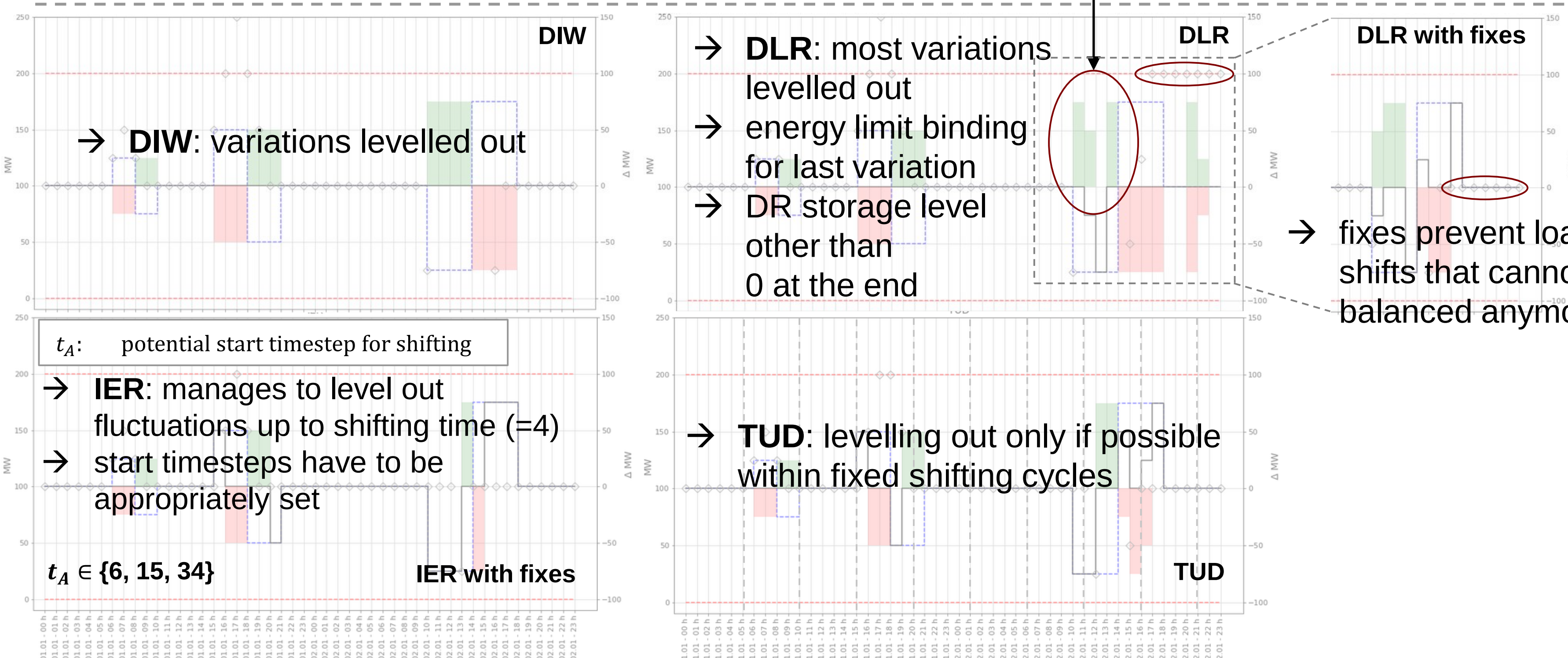
Comparison of modeling approaches: DR utilization – Case D: demand variations - **longer duration**



(*) $W^t_{levelInc}$: DR storage limit for upshifts
$\bar{s}^t_{free}$: average availability for upshifts $\epsilon[0;1]$
$t_{interfere}$: interference duration (for upshifts)

$$W^t_{levelInc} \leq P_{existCap} \cdot \bar{s}^t_{free} \cdot t_{interfere} \; (*)$$
$$W^t_{levelInc} \leq 100\ MW \cdot 2\ h = 200\ MWh$$

Legend for plots below



→ **DIW**: variations levelled out

→ **DLR**: most variations levelled out
→ energy limit binding for last variation
→ DR storage level other than 0 at the end

→ fixes prevent load shifts that cannot be balanced anymore

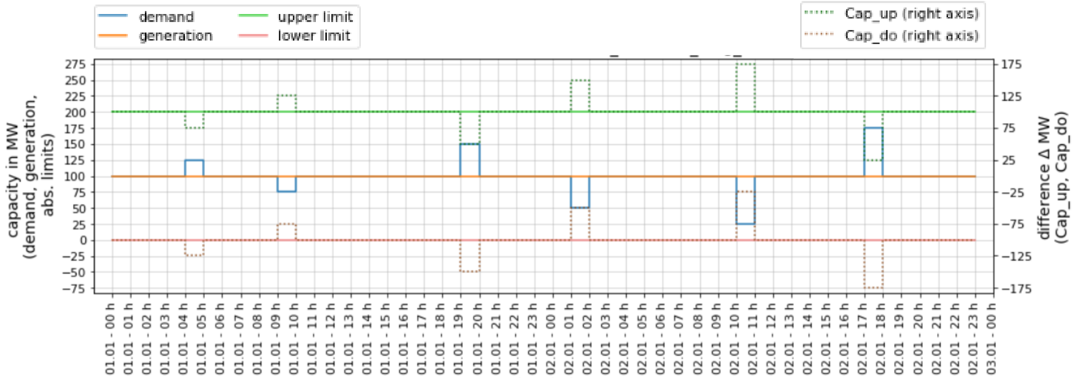
t_A: potential start timestep for shifting

→ **IER**: manages to level out fluctuations up to shifting time (=4)
→ start timesteps have to be appropriately set

$t_A \in$ {6, 15, 34}

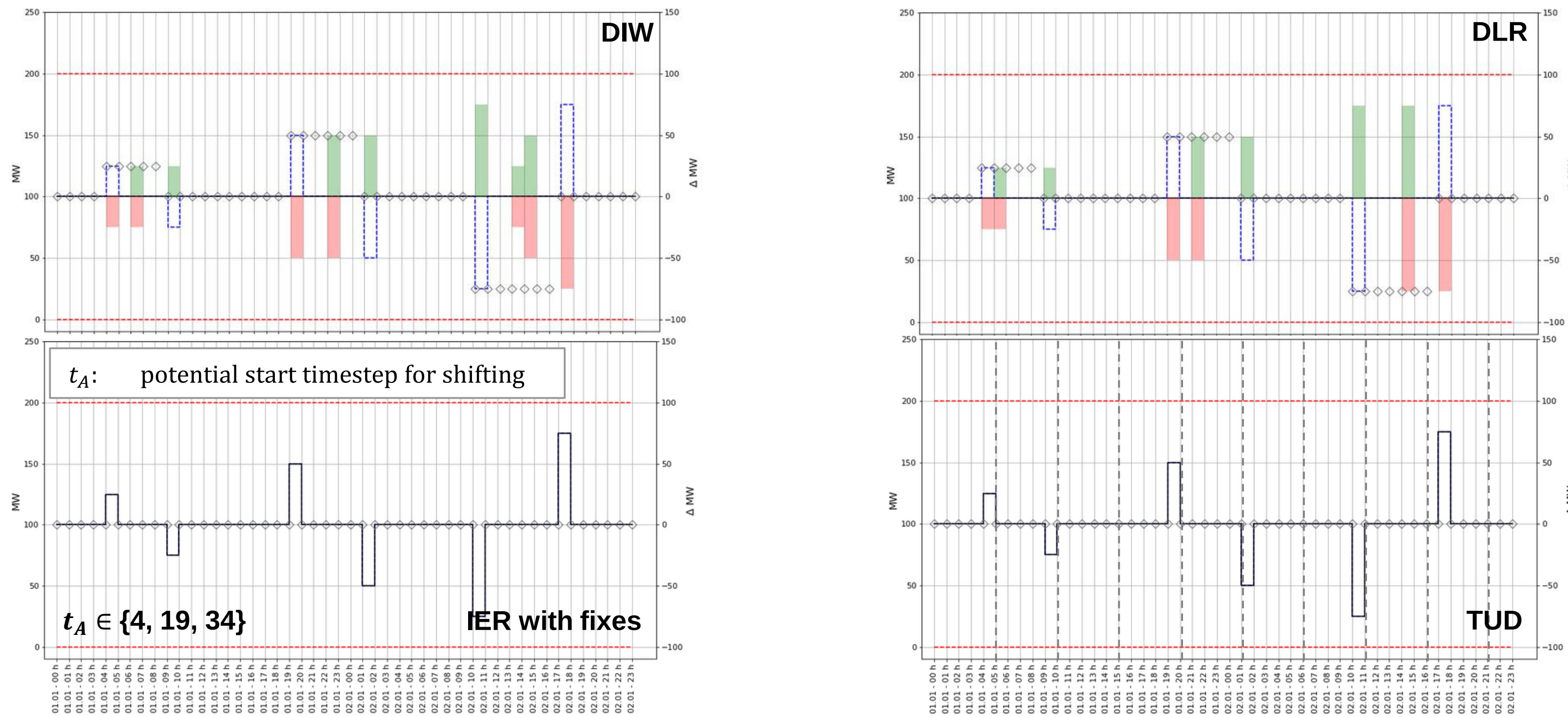
→ **TUD**: levelling out only if possible within fixed shifting cycles

Comparison of modeling approaches:
DR utilization – Case E: demand variations - **longer shifts**

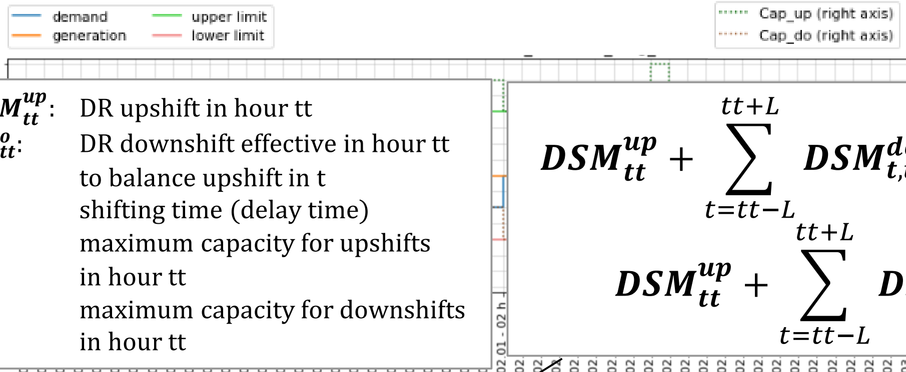


Legend for plots below

- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level



Comparison of modeling approaches:
DR utilization – Case E: demand variations - **longer shifts**



(*) DSM_{tt}^{up}: DR upshift in hour tt

$DSM_{t,tt}^{do}$: DR downshift effective in hour tt to balance upshift in t

L: shifting time (delay time)

C_{tt}^{up}: maximum capacity for upshifts in hour tt

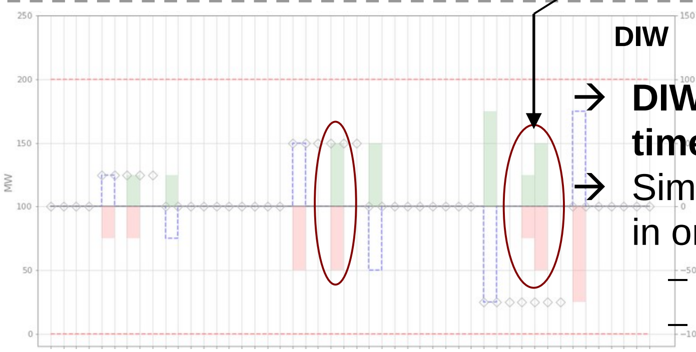
C_{tt}^{do}: maximum capacity for downshifts in hour tt

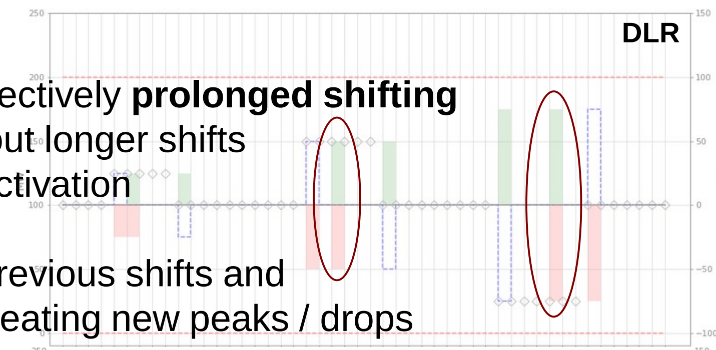
$$DSM_{tt}^{up} + \sum_{t=tt-L}^{tt+L} DSM_{t,tt}^{do} \leq \max\{C_{tt}^{up}, C_{tt}^{do}\} \; (*)$$

$$DSM_{tt}^{up} + \sum_{t=tt-L}^{tt+L} DSM_{t,tt}^{do} \leq 100MW$$

Legend for plots below

- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level



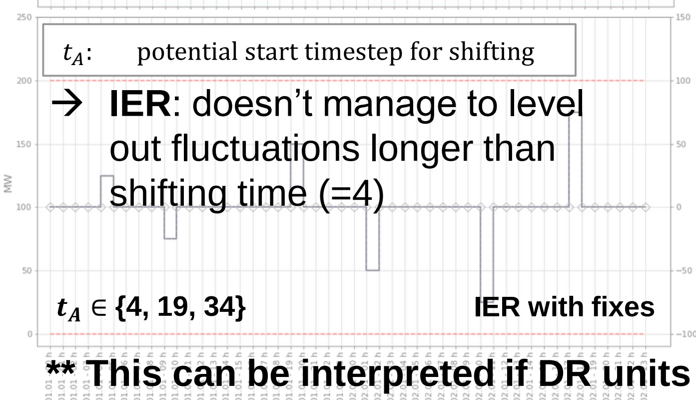


→ **DIW & DLR**: effectively **prolonged shifting time**** to level out longer shifts

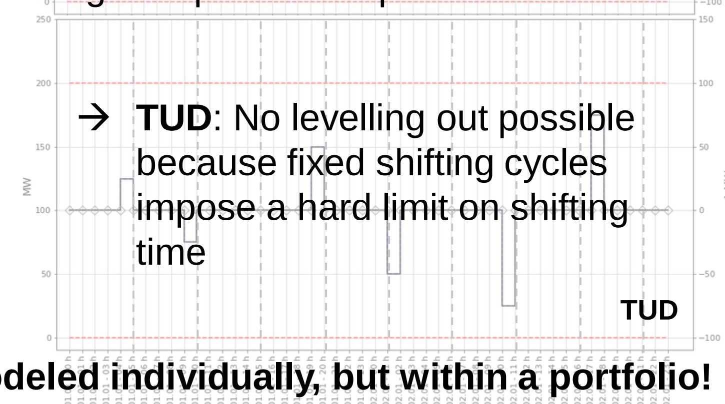
→ Simultaneous activation in order to

- balance previous shifts and
- prevent creating new peaks / drops

t_A: potential start timestep for shifting



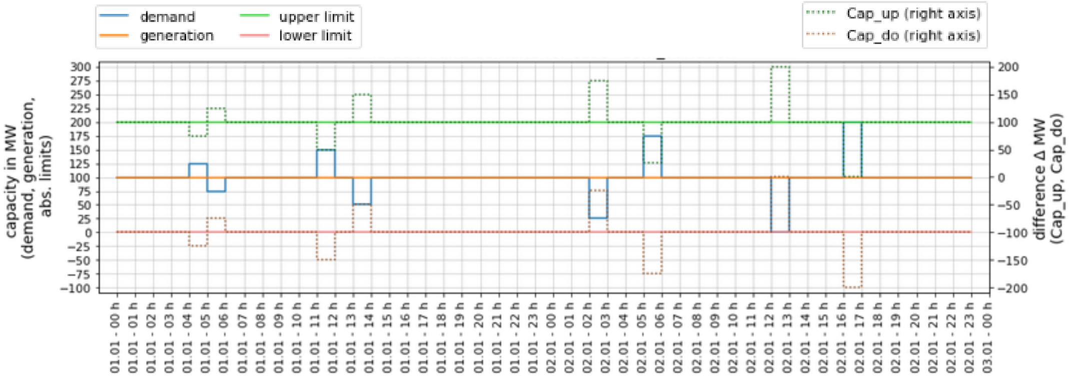
→ **IER**: doesn't manage to level out fluctuations longer than shifting time (=4)



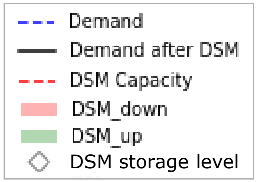
→ **TUD**: No levelling out possible because fixed shifting cycles impose a hard limit on shifting time

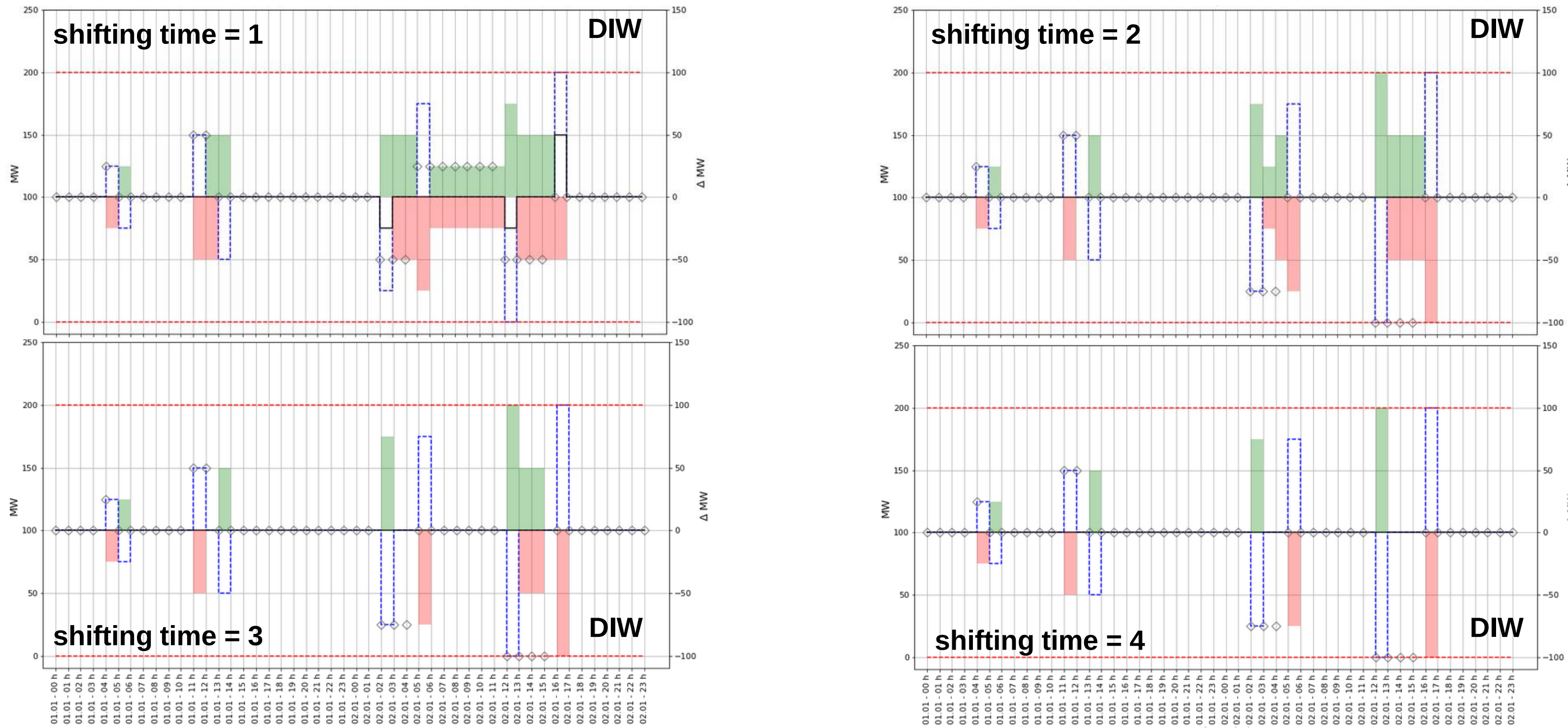
**** This can be interpreted if DR units are not modeled individually, but within a portfolio!**

Comparison of modeling approaches: Parameter variations: **shifting time** (delay time)

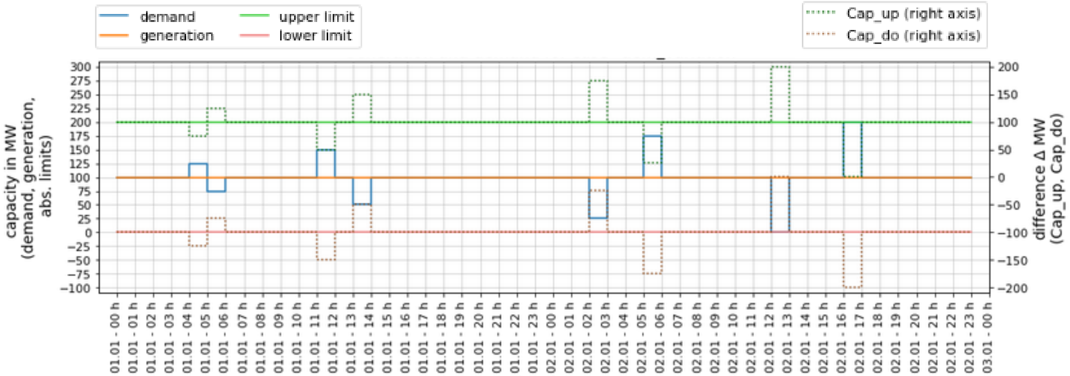


Legend for plots below

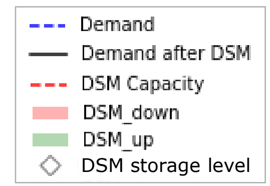


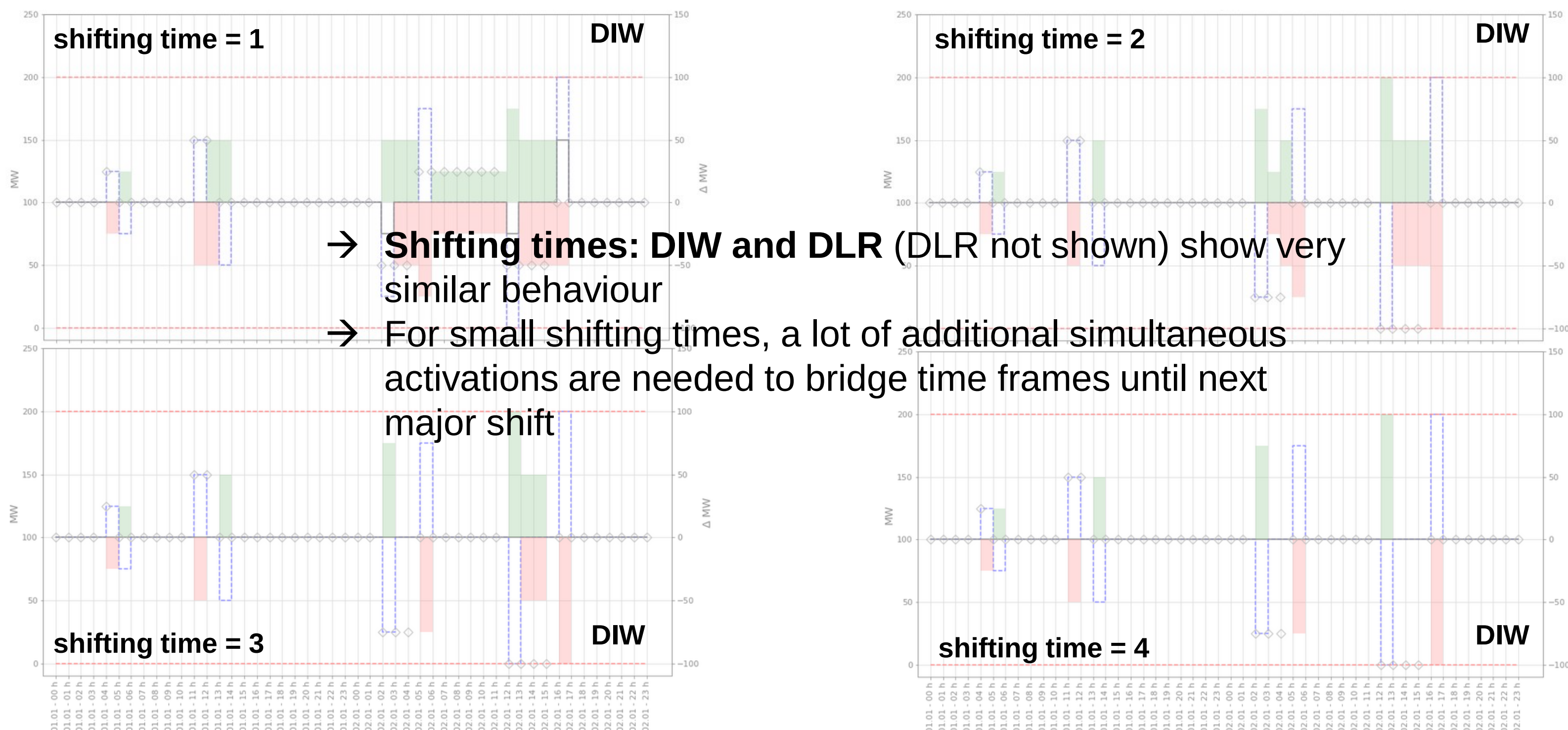


Comparison of modeling approaches:
Parameter variations: **shifting time** (delay time)



Legend for plots below

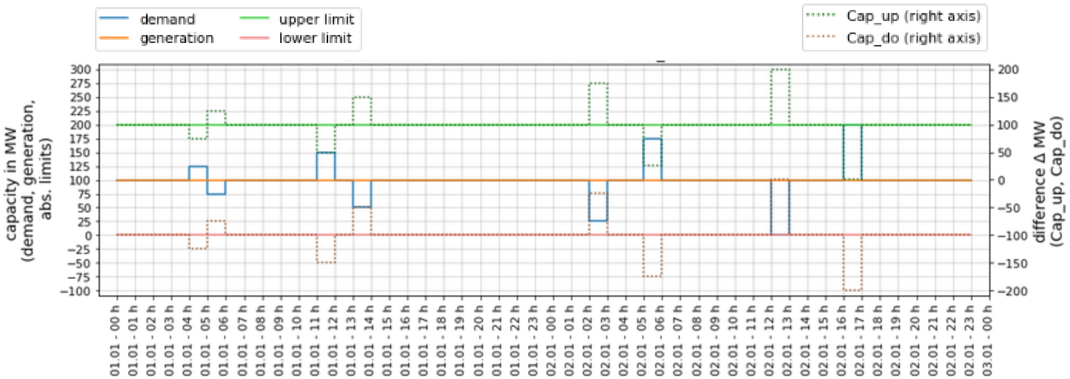




→ **Shifting times: DIW and DLR** (DLR not shown) show very similar behaviour

→ For small shifting times, a lot of additional simultaneous activations are needed to bridge time frames until next major shift

Comparison of modeling approaches: Parameter variations: **costs for DR**



Definition of costs is the same for all approaches:
<u>Half of the costs</u> is attributed to upshifts and downshifts each

- What does DR do from a cost perspective in the stylized example?
  - mostly **prevent activation of expensive coal power plant** with costs $c_{pp,coal} = 32.5 \frac{€}{MWh}$
  - In addition to that **prevent excess** of generation with costs $c_{excess} = 1 \frac{€}{MWh}$

- In case of symmetric variations in demand as shown above
  - **a load shift of 1 MW in both directions prevents 1 MW coal generation and 1 MW of excess**
  - This leads to an activation of DR until a price of

$$\frac{c_{\mathrm{pp,coal}} + c_{excess}}{2} = \frac{32.5 + 1}{2} = 16.75 \left(\frac{€}{MWh}\right)$$

  - Costs of this value of higher lead to no activation of DR at all → penny switching

Comparison of modeling approaches: **amount of DR activations** (sum of effective capacity shifts)

	Basic cases: Demand variation			Other basic cases	
Approach	**C: changed starts**	**D: longer duration**	**E: longer shifts**	**gen. variation (asymmetric)**	**combined variation**
DIW	500	1,000	300	350	550
DLR (with fixes)	500	800	300	350	550
IER (with fixes)	300	450	0	300	350
TUD	200	600	0	300	250

	Parameter variations		
Approach	**shifting time = 5**	**interference time = 1**	**recovery time = 4**
DIW	500	1,200	350
DLR (with fixes)	500	500	550
IER (with fixes)	500	500	550
TUD	200	700	300

Comparison of modeling approaches: **amount of DR activations** (sum of effective capacity shifts)

	Basic cases: Demand variation			Other basic cases	
Approach	C: changed starts	D: longer duration	E: longer shifts	gen. variation (asymmetric)	combined variation
DIW	**500**	**1,000**	**300**	**350**	**550**
DLR (with fixes)	**500**	800	**300**	**350**	**550**
IER (with fixes)	300	**450**	**0**	**300**	350
TUD	**200**	600	**0**	**300**	**250**

	Parameter variations		
Approach	shifting time = 5	interference time = 1	recovery time = 4
DIW	**500**	**1,200**	350
DLR (with fixes)	**500**	**500**	**550**
IER (with fixes)	**500**	**500**	550
TUD	**200**	700	**300**

- **DIW** shows **highest amount of DR activations**, except for recovery time introduction.
- **IER** and **TUD** show **lowest amount of DR activations**.

Comparison of modeling approaches: **optimal objective values** (mean values for 100 runs)

- Model setting and parameters for 100 runs each:
  - **random** demand (ave. 100 MW) and DR availability (ave. +/- 50 MW); const. generic generation
  - shifting time = 4; interference time = 2; DR costs = 0.1 €/MWh (half for up- / downshifts)

Approach	Objective value	84 timesteps	168 timesteps	252 timesteps	336 timesteps
No DR	absolute [€]	31,418	63,121	95,597	127,571
	relative reduction to no DR [%]	0%	0%	0%	0%
DIW	absolute [€]	3,924	7,339	10,943	14,010
	relative reduction to no DR [%]	-88%	-88%	-89%	-89%
DLR (with fixes)	absolute [€]	4,437	8,522	12,996	16,723
	relative reduction to no DR [%]	-86%	-86%	-86%	-87%
IER	absolute [€]	11,729	23,857	36,344	48,386
	relative reduction to no DR [%]	-63%	-62%	-62%	-62%
TUD	absolute [€]	14,439	27,855	41,924	54,747
	relative reduction to no DR [%]	-54%	-56%	-56%	-57%

Comparison of modeling approaches: **optimal objective values** (mean values for 100 runs)

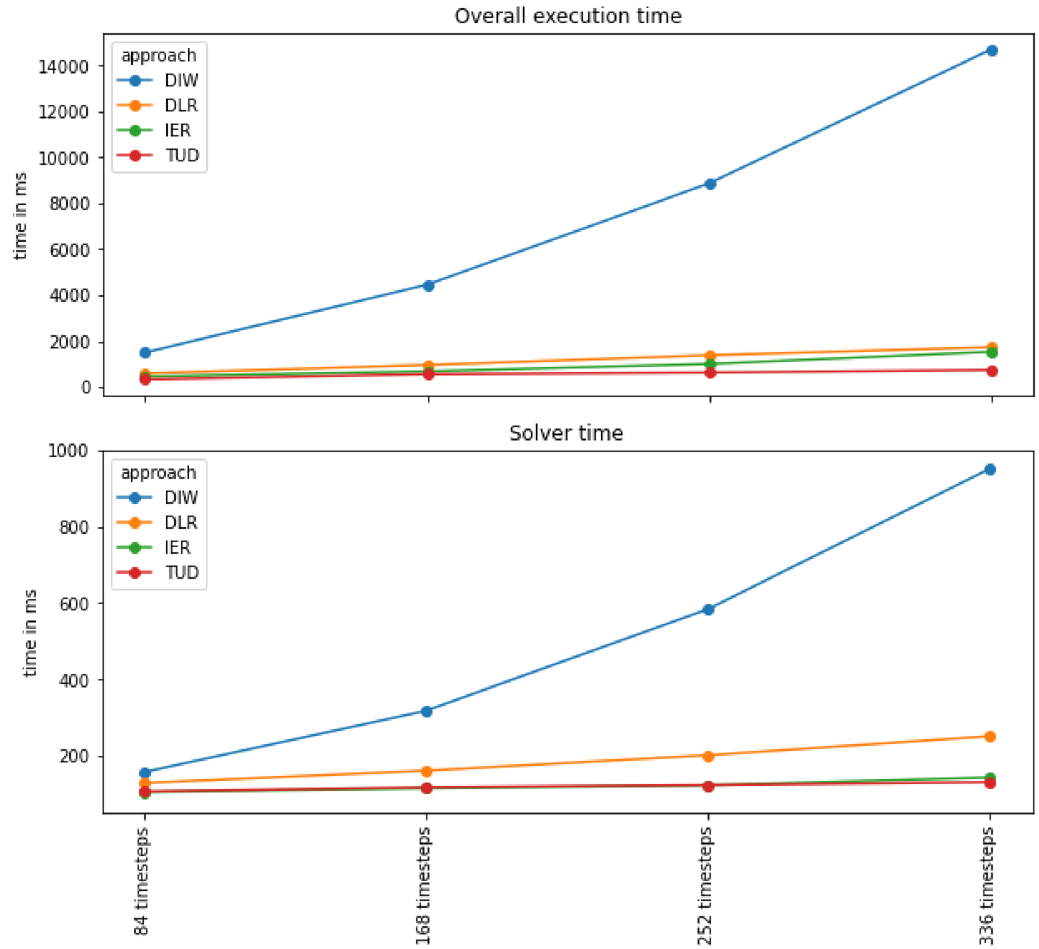
- Model setting and parameters for 100 runs each:
  - **random** demand (ave. 100 MW) and DR availability (ave. +/- 50 MW); const. generic generation
  - shifting time = 4; interference time = 2; DR costs = 0.1 €/MWh (half for up- / downshifts)

Approach	Objective value	84 timesteps	168 timesteps	252 timesteps	336 timesteps
No DR	absolute [€]	31,418	63,121	95,597	127,571
	relative reduction to no DR [%]	**0%**	**0%**	**0%**	**0%**
DIW	absolute [€]	3,924	7,339	10,943	14,010
	relative reduction to no DR [%]	**-88%**	**-88%**	**-89%**	**-89%**
DLR (with fixes)	absolute [€]	4,437	8,522	12,996	16,723
	relative reduction to no DR [%]	**-86%**	**-86%**	**-86%**	**-87%**
IER	absolute [€]	11,729	23,857	36,344	48,386
	relative reduction to no DR [%]	**-63%**	**-62%**	**-62%**	**-62%**
TUD	absolute [€]	14,439	27,855	41,924	54,747
	relative reduction to no DR [%]	**-54%**	**-56%**	**-56%**	**-57%**

- **DIW** shows **lowest objective values**, **DLR** is close to that.
- Fixed shifting cycles for **TUD** come at the expense of high amounts of DR activations (**highest objective values**).

Comparison of modeling approaches: **runtimes** (mean values for 100 runs)

- Model setting and parameters for 100 runs each:
  - **random** demand (ave. 100 MW) and DR availability (ave. +/- 50 MW); const. generic generation (same for every run)
  - shifting time = 4; interference time = 2; DR costs = 0.1 €/MWh (half for up- / downshifts)



– **TUD** performs best in terms of runtimes.
– **DIW** is computationally intensive.

➡ Fixed cycles save computation time while high interlinkage creates computational effort.

rough linear extrapolation for 8,760 timesteps

approach	overall time [h]
DIW	10.7
DLR	0.94
IER	0.86
TUD	0.31

Agenda

1 Introduction

2 Method

3 Clustering results

4 Results of the model comparison

5 **Conclusion**

Conclusion on potential clustering: **method and results**

Achievements

- Filtering and clustering can lead to a **number of clusters** that can be **handled within power market modeling**.
- Data for **11 flexibility parameters** has been put together.
- Parameterization and **availability time series** per DR cluster can be derived.
- Addressing DR parameter uncertainties possible by distinction of **pessimistic, neutral and optimistic estimate**.

Challenges

- Heterogeneous data basis creates challenges.
- Trade-off between granularity and model complexity has to be addressed.
- Availability information: Contradictions in the literature have to be handled.

Conclusion on comparison of modeling approaches: **parameter variations**

- **Costs**
  - All approaches are very sensitive to cost → LP penny switching

- **Shifting time**
  - Large effect on TUD approach
  - Longer shifting times are possible for DIW and DLR approach

- **Interference time**
  - Not included in DIW approach

- **Recovery time / max. activations**
  - DIW approach is highly dependent on structure of demand pattern
  - DLR approach is quite robust to imposing additional limits; IER is even more robust

- **Additions**
  - **Fixes** for DLR and IER approach added
  - Refinements for TUD approach were included for the sake of comparability
  - Some **assumptions** had to be made → especially for first and last timesteps

Conclusion on comparison of modeling approaches: **overall evaluation of approaches**

modeling approach	advantages	drawbacks
Zerrahn & Schill (2015) DIW	▪ parsimonious ▪ overall capacity limit included	▪ no interference times or further energy limit → overestimation on tendency ▪ high computation times
Gils (2015) DLR	▪ explicitly shows balancing / mapping ▪ further restriction via energy limits / storage level limits	▪ complexity of formulation ▪ missing overall capacity limit
Steurer (2017) IER	▪ parsimonious ▪ computation is quite fast	▪ starting time points for load shifts needed → sensitive behavior; no overall balancing ▪ unbalanced shifts may occur → fixes used
Ladwig (2018) TUD	▪ only one storage level ▪ computationally efficient	▪ fixed storage cycles may prevent shifts → underestimation of potentials ▪ limits shifts to lie within the first timesteps

source: own collocation based on Zerrahn and Schill (2015a), pp. 842-844; Gils (2015), pp. 67-70; Steurer (2017), pp. 80-82; Ladwig (2018), pp. 90-93

Sources

- Endres, Julian & Pleßmann, Guido (2020): Explanations and examples of the oemof custom component SinkDSM, https://github.com/windnode/SinkDSM_example, accessed 12.05.2020.
- Gährs, Swantje, Deisböck, Alexander, Cremer, Noelle, & Cremerius, Paula. (2020). Regional flexibility in households and supermarkets (Version 1.0) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.3745515, accessed 12.05.2020.
- Gerhardt, Norman; Böttger, Diana; Trost, Tobias; Scholz, Angela; Pape, Christian; Gerlach, Ann-Katrin; Härtel, Philipp; Ganal, Irina (2017): Analyse eines europäischen -95%-Klimazielszenarios über mehrere Wetterjahre. Teilbericht im Rahmen des Projektes: Klimawirksamkeit Elektromobilität - Entwicklungsoptionen des Straßenverkehrs unter Berücksichtigung der Rückkopplung des Energieversorgungssystems in Hinblick auf mittel- und langfristige Klimaziele. im Auftrag des BMUB. Fraunhofer IWES, Kassel.
- Gils, Hans Christian (2015): Balancing of Intermittent Renewable Power Generation by Demand Response and Thermal Energy Storage. Dissertation. Universität Stuttgart, Stuttgart.
- Kochems, Johannes (2020): Lastflexibilisierungspotenziale in Deutschland - Bestandsaufnahme und Entwicklungsprojektionen. Langfassung. In: IEE TU Graz (Hg.): EnInnov 2020 - 16. Symposium Energieinnovation. Energy for Future - Wege zur Klimaneutralität. Graz, 12.-14.02, https://www.tugraz.at/fileadmin/user_upload/tugrazExternal/4778f047-2e50-4e9e-b72d-e5af373f95a4/files/lf/Session_E5/553_LF_Kochems.pdf, accessed 11.05.2020.
- Ladwig, Theresa (2018): Demand Side Management in Deutschland zur Systemintegration erneuerbarer Energien. Dissertation. Technische Universität Dresden, Dresden, zuletzt geprüft am 04.09.2018.
- Steurer, Martin (2017): Analyse von Demand Side Integration im Hinblick auf eine effiziente und umweltfreundliche Energieversorgung, Dissertation an der Universität Stuttgart.
- Zerrahn, Alexander and Schill, Wolf-Peter (2015b): A Greenfield Model to Evaluate Long-Run Power Storage Requirements for High Shares of Renewables, DIW Discussion Papers, No. 1457.
- Zerrahn, Alexander; Schill, Wolf-Peter (2015a): On the representation of demand-side management in power system models. In: Energy 84, S. 840–845. DOI: 10.1016/j.energy.2015.03.037.

Contact information

Johannes Kochems
Department of Energy and Resource Management
Technical University of Berlin
Secretariat FH 5-3
Fraunhoferstr. 33-36
Germany-10623 Berlin

Phone: + 49 30 314 23214
Fax: + 49 30 314 25582

e-mail: kochems@er.tu-berlin.de

Thank you very much for your attention!

INREC 2020 | 9th International Ruhr Energy Conference

Backup for the presentation Demand response potentials for Germany: potential clustering and comparison of modeling approaches

Johannes Kochems | Department of Energy and Resource Management at TU Berlin |
10 September 2020

Backup Agenda

1	**Additional results from clustering**
2	**Model formulations of the approaches**
3	**Additional results of the comparison of modeling approaches**

Clustering: **parameters and dimensions**

11 flexibility parameters	
max. capacity for positive shifts (reduction) in MW	max. capacity for negative shifts (increase) in MW
positive interference duration	negative interference duration
shifting duration (delay time)	regeneration duration
max. activations per year / day	variable costs
fixed costs	specific investments
installed capacity	

×

8 years			
status quo	2025	2035	2045
2020	2030	2040	2050

×

3 estimates		
lower quartile (25%) / pessimistic	median (50%)	upper quartile (75%) / optimistic

= **264 parameter values per Demand Response cluster**
(clusters within the sectors*)

* exception: aggregation of applications for power-based heat provision in commmerce and households
→ reason: same technologies / similar profiles

Clustering: **resulting clusters**

- Filtering: 38 remaining Demand Reponse categories
- Clustering: 5 clusters

Industry cluster 1	Paper industry	Mechanical and chemical wood pulp, paper machines, paper recycling
	Processes	Chlor-alkali electrolysis, air separation units, Primary aluminium electrolysis, electric arc steel-making, cement mills
	Cross-cutting technologies	ventilation, process cold, climate cold, lighting, compressed air, cooling (food industry), pumps
Industry cluster 2	Processes	copper and zinc electrolysis, foundries (arc furnace), calcium carbide production (arc furnace)
Household cluster	White Goods	refridgerators, dishwashers, tumble dryers, washing machines, freezers, fridge-and-freezer combination
	Other	Heating circulation pump
Commerce cluster	Cross-cutting technologies in general	Process cold, ventilation, lighting, process heat
	Other	pumps in drinking water supply, crushers (recycling industry), watewater treatment, cold stores, process cold in retailing industry
Commerce & households cluster	Heating applications	Heat pumps, night storage heating, hot water supply
	Cooling applications	Climate cold (air conditioning)

Clustering: **example parameter set** – neutral estimate (50%) for the status quo

Cluster	max. activations per year	Regeneration duration	Shifting duration (delay time)	Neg. interference duration (increase)	Pos. interference duration (decrease)
Unit	**[1/a]**	**[h]**	**[h]**	**[h]**	**[h]**
Industry cluster 1	71	2	6	3	2.5
Industry cluster 2	25	2	6	4	2
Commerce cluster	132	0	2	1	1
Households cluster	2,909	0	0.5	1.5	1.5
Com. & Hoho. cluster	320	0	6.5	6.5	3.5

Cluster	Specific investments	Variable costs	Fixed costs	Installed capacity	Max. capacity neg. (increase)	Max. capacity pos. (decrease)
Unit	**[$€_{2018}$/kW]**	**[$€_{2018}$/MWh]**	**[$€_{2018}$/kW * a]**	**[MW]**	**[MW]**	**[MW]**
Industry cluster 1	1.3	307.5	0.9	11,983	2,805	6,249
Industry cluster 2	7.1	851.8	18.3	403	38	171
Commerce cluster	82.5	147.1	0.01	4,326	2,897	1,650
Households cluster	121.8	0.01	299.7	163,115	1,833	4,982
Com. & Hoho. cluster	86.0	0.7	24.3	51,038	1,440	3,426

Backup Agenda

1	**Additional results from clustering**
2	**Model formulations of the approaches**
3	**Additional results of the comparison of modeling approaches**

Modeling approaches considered in detail

In the following, detailled formulations for the DR modeling approaches as found in

- Zerrahn and Schill (2015), pp. 842-843) and Zerrahn and Schill (2015b, pp. 12-13)
- Gils (2015, pp. 67-70)
- Steurer (2017, pp. 80-82)
- Ladwig (2018, pp. 90-93)

are layed down.

DR modeling approach in Zerrahn & Schill (2015) (1/2)

Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

- DR modeling approach from Zerrahn and Schill (2015):

$$\boldsymbol{DSM_t^{up}} \cdot \eta = \sum_{tt=t-L}^{t+L} \boldsymbol{DSM_{t,tt}^{do}} \quad \forall t$$

(1) Load increase in hour t equals to the sum of downwards shifts over the shifting timeframe which are effective in hour tt to compensate for load increases in t; L: shifting time

$$\boldsymbol{DSM_t^{up}} \leq C_t^{up} \quad \forall t$$

(2) Constraint for maximum upwards shift in hour t

$$\sum_{t=tt-L}^{tt+L} \boldsymbol{DSM_{t,tt}^{do}} + \boldsymbol{DSM_{tt}^{do,shed}} \leq C_{tt}^{do} \quad \forall tt$$

(3) Constraint for maximum downwards shift in hour tt

$$\boldsymbol{DSM_{tt}^{up}} + \sum_{t=tt-L}^{tt+L} \boldsymbol{DSM_{t,tt}^{do}} + \boldsymbol{DSM_{tt}^{do,shed}} \leq \max\{C_{tt}^{up}, C_{tt}^{do}\} \quad \forall tt$$

(4) Constraint on the sum of upwards and downwards shift in hour tt

source: Zerrahn and Schill (2015a), pp. 842-843; Zerrahn and Schill (2015b), pp. 12-13

DR modeling approach in Zerrahn & Schill (2015) (2/2)

Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

- DR modeling approach from Zerrahn and Schill (2015):

$$\sum_{tt=t}^{t+R-1} \boldsymbol{DSM_{tt}^{up}} = C_t^{up} \cdot L \quad \forall t \qquad (5)$$

Recovery time introduction (optional):
Limit upshifts to the maximum upshift energy of one load shifting cycle

- Parameters:

C_t^{up} :	max. upshift capacity in hour t
C_{tt}^{do}:	max. downshift capacity in hour t
L:	shifting duration (delay time)
R:	recovery duration (time between end of load shift and start of new one)
η:	DR efficiency

- Variables:

$\boldsymbol{DSM_t^{up}}$:	upshift capacity in hour t
$\boldsymbol{DSM_{t,tt}^{do}}$:	downshift effective in hour tt to compensate for load increases in t
$\boldsymbol{DSM_t^{do,shed}}$:	load shedding in hour t

source: Zerrahn and Schill (2015a), pp. 842-844

DR modeling approach in Gils (2015) (1/3)

Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

- Demand response (DR) restrictions (according to Gils 2015, pp. 67-70):
  - Constraints for the compensation of load shifting (DR_1) and (DR_2):

$$\boldsymbol{P}_{\boldsymbol{balanceRed}}^{\boldsymbol{h,t}} = \frac{\boldsymbol{P}_{\boldsymbol{reduction}}^{\boldsymbol{t-t_{shift}^{h}}}}{\eta_{DR}} \quad \forall t \in [t_{shift}..T], h \in H_{DR}$$

$$\boldsymbol{P}_{\boldsymbol{balanceInc}}^{\boldsymbol{h,t}} = \boldsymbol{P}_{\boldsymbol{increase}}^{\boldsymbol{t-t_{shift}^{h}}} \cdot \eta_{DR} \quad \forall t \in [t_{shift}..T], h \in H_{DR}$$

  - Maximum availability for DR measures (DR_3) and (DR_4):

$$\sum_{h=1}^{H_{DR}} \left(\boldsymbol{P}_{\boldsymbol{reduction}}^{\boldsymbol{h,t}} + \boldsymbol{P}_{\boldsymbol{balanceInc}}^{\boldsymbol{h,t}}\right) + \boldsymbol{P}_{\boldsymbol{shed}}^{\boldsymbol{t}} \leq P_{existCap} \cdot s_{flex}^{t} \quad \forall t \in T$$

$$\sum_{h=1}^{H_{DR}} \left(\boldsymbol{P}_{\boldsymbol{increase}}^{\boldsymbol{h,t}} + \boldsymbol{P}_{\boldsymbol{balanceRed}}^{\boldsymbol{h,t}}\right) \leq P_{existCap} \cdot s_{free}^{t} \quad \forall t \in T$$

  - Own addition: Exclusion of DR measures for which compensation is no longer possible in optimization time window (DR_5):

$$\boldsymbol{P}_{\boldsymbol{reduction}}^{\boldsymbol{h,t}} = \boldsymbol{P}_{\boldsymbol{increase}}^{\boldsymbol{h,t}} = 0 \quad \forall t \in [T\text{-}\ t_{shift}..T], \mathrm{h} \in H_{DR}$$

Note: s_{flex}^{t} and s_{free}^{t} are implicitly contained in the formulation from Zerrahn and Schill (2015a).

source: Gils (2015); simplified; own additions; no investments

DR modeling approach in Gils (2015) (2/3)

Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

- Demand response (DR) restrictions (according to Gils 2015, pp. 67-70):
  - Introduction of **fictious DR storage levels** (DR_5) - (DR_7); Storage transition:

$$\boldsymbol{W}_{levelRed}^{t} = \Delta \boldsymbol{t} \cdot \sum_{h=1}^{H_{DR}} \boldsymbol{P}_{reduction}^{h,t} \quad for\ t = 0$$

$$\boldsymbol{W}_{levelRed}^{t} = \Delta \boldsymbol{t} \cdot \sum_{h=1}^{H_{DR}} \boldsymbol{P}_{increase}^{h,t} \quad for\ t = 0$$

$$\Delta \boldsymbol{t} \cdot \sum_{h=1}^{H_{DR}} \left(\boldsymbol{P}_{reduction}^{h,t} - \boldsymbol{P}_{balanceRed}^{h,t} \cdot \eta_{DR}\right) \leq \boldsymbol{W}_{levelRed}^{t} - \boldsymbol{W}_{levelRed}^{t-1} \qquad \forall t \in [1..T]$$

$$\Delta \boldsymbol{t} \cdot \sum_{h=1}^{H_{DR}} \left(\boldsymbol{P}_{increase}^{h,t} \cdot \eta_{DR} - \boldsymbol{P}_{balanceInc}^{h,t}\right) \leq \boldsymbol{W}_{levelInc}^{t} - \boldsymbol{W}_{levelInc}^{t-1} \qquad \forall t \in [1..T]$$

  - Limitation of the **maximum storage levels** (DR_8) and (DR_9):

$$\boldsymbol{W}_{levelRed}^{t} \leq P_{existCap} \cdot \bar{s}_{flex}^{t} \cdot t_{interfere} \quad \forall t \in T$$

$$\boldsymbol{W}_{levelInc}^{t} \leq P_{existCap} \cdot \bar{s}_{free}^{t} \cdot t_{interfere} \quad \forall t \in T$$

DR modeling approach in Gils (2015) (3/3)

Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

- Demand response (DR) restrictions (according to Gils 2015, pp. 67-70):
  - Limit for energy shifted annually (DR_10) and (DR_11) or daily (DR_12) and (DR_13) (optional):

$$\sum_{t=0}^{T}\sum_{h=1}^{H_{DR}} \boldsymbol{P_{reduction}^{h,t}} \le P_{existCap} \cdot \bar{s}_{flex}^{t} \cdot t_{interfere} \cdot n_{yearLimit}$$

$$\sum_{t=0}^{T}\sum_{h=1}^{H_{DR}} \boldsymbol{P_{increase}^{h,t}} \le P_{existCap} \cdot \bar{s}_{free}^{t} \cdot t_{interfere} \cdot n_{yearLimit}$$

$$\sum_{h=1}^{H_{DR}} \boldsymbol{P_{reduction}^{h,t}} \le P_{existCap} \cdot \bar{s}_{flex}^{t} \cdot t_{interfere} \cdot \sum_{t'=1}^{t_{DayLimit}}\sum_{h=1}^{H_{DR}} \boldsymbol{P_{reduction}^{h}(t-t')} \quad \forall t \in [t - t_{DayLimit}..T]$$

$$\sum_{h=1}^{H_{DR}} \boldsymbol{P_{increase}^{h,t}} \le P_{existCap} \cdot \bar{s}_{free}^{t} \cdot t_{interfere} \cdot \sum_{t'=1}^{t_{DayLimit}}\sum_{h=1}^{H_{DR}} \boldsymbol{P_{increase}^{h}(t-t')} \quad \forall t \in [t - t_{DayLimit}..T]$$

- Parameters:

P_{exist}:	existing DR capacity
s_{flex}^{t}:	availability factor downshifts $\in [0; 1]$
s_{free}^{t}:	availability factor upshifts $\in [0; 1]$
η_{DR}:	DR efficiency
$t_{interfere}$:	interference time
h:	shifting time $\in H = \{1, 2, \dots, h_{max}\}$

- Variables:

$\boldsymbol{P_{reduction}^{h,t}}$:	downshift in t with shifting time h
$\boldsymbol{P_{increase}^{h,t}}$:	upshift in t with shifting time h
$\boldsymbol{P_{shed}^{t}}$:	load shedding in t
$\boldsymbol{P_{balanceRed}^{h,t}}$:	balancing of reduction (upshift)
$\boldsymbol{P_{balanceInc}^{h,t}}$:	balancing of increase (downshift)
$\boldsymbol{W_{levelRed}^{t}}$:	DR storage level for downshifts
$\boldsymbol{W_{levelInc}^{t}}$:	DR storage level for upshifts

source: Gils (2015); simplified; own additions; no investments

DR modeling approach in Steurer (2017) (1/3)

- Demand response (DR) restrictions (according to Steurer 2017, pp. 80-82):
  - Potential limit (DR_1a) and (DR_1b):

$$\boldsymbol{P^t_{pos}} + \boldsymbol{P^t_{shed}} \leq P_{max} \cdot f^t_{v,pos} \quad \forall t \in T$$

$$\boldsymbol{P^t_{neg}} \leq P_{max} \cdot f^t_{v,neg} \quad \forall t \in T$$

Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

  - DR balance for each shifting cycle (DR_2):

$$\sum_{t=t_A}^{t_A+d_V} \boldsymbol{P^t_{pos}} = \sum_{t=t_A}^{t_A+d_V} \boldsymbol{P^t_{neg}} \cdot \eta \quad \forall t = t_A \in T_A \subset T$$

  - Limit for the amount of energy that can be shifted in one direction (DR_3a) and (DR_3b):

$$\sum_{t=t_A}^{t_A+d_V} \boldsymbol{P^t_{pos}} \leq d_{S,pos} \cdot P_{max} \quad \forall t = t_A \in T_A \subset T$$

$$\sum_{t=t_A}^{t_A+d_V} \boldsymbol{P^t_{neg}} \leq d_{S,neg} \cdot P_{max} \quad \forall t = t_A \in T_A \subset T$$

Note: Again, f^t_v is already implicitly contained in the formulation from Zerrahn and Schill (2015a).

source: Steurer (2017, pp. 80-82); own modifications; simplified; no investments

DR modeling approach in Steurer (2017) (2/3)

- Demand response (DR) restrictions (according to Steurer 2017, pp. 80-82):
  - Total limit for (annually) shifted amount of energy (DR_4):

$$\sum_{t=0}^{T=8760} \boldsymbol{P_{pos}^t} \leq d_{kum} \cdot P_{max}$$

$$\sum_{t=0}^{T=8760} \boldsymbol{P_{neg}^t} \leq d_{kum} \cdot P_{max}$$

Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

  - Optional addition: DR logic (DR_6) further limiting the shiftable capacity (according to Zerrahn and Schill 2015a, p. 843):

$$\boldsymbol{P_{pos}^t} + \boldsymbol{P_{shed}^t} + \boldsymbol{P_{neg}^t} \leq P_{max} \cdot f_v^t \quad \forall t \in T$$

  - Optional addition: prevent unbalanced shifts (DR_7a and DR_7b):

$$\boldsymbol{P_{pos}^t} = 0 \quad \forall t \in T, t_{A,i} \in T_A \mid t_{A,i} + d_v < t < t_{A,i+1} \vee t > t_{A,|T_A|} + d_v \; mit \; i = \{1,..,|T_A|\}$$

$$\boldsymbol{P_{neg}^t} = 0 \quad \forall t \in T, t_{A,i} \in T_A \mid t_{A,i} + d_v < t < t_{A,i+1} \vee t > t_{A,|T_A|} + d_v \; mit \; i = \{1,..,|T_A|\}$$

source: Steurer (2017, pp. 80-82); own modifications; simplified; no investments
Zerrahn and Schill (2015a, p. 843)

DR modeling approach in Steurer (2017) (3/3)

- Parameters:

P_{max}:	maximum DR capacity
$f_{v,pos}^{t}$:	availability factor downshifts $\in [0; 1]$
$f_{v,neg}^{t}$:	availability factor upshifts $\in [0; 1]$
t_A:	potential start timestep for shifting
T_A:	set of all potential start timesteps
η:	DR efficiency
d_V:	shifting duration
$d_{S,pos}$:	interference duration for downshifts
$d_{S,neg}$:	interference duration for upshifts

- Variables:

$\boldsymbol{P_{pos}^{t}}$:	downshift in hour t
$\boldsymbol{P_{neg}^{t}}$:	upshift in hour t
$\boldsymbol{P_{shed}^{t}}$:	load shedding in hour t

Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

source: Steurer (2017, pp. 80-82); own modifications; simplified; no investments
Zerrahn and Schill (2015a, p. 843)

DR modeling approach in Ladwig (2018) (1/3)

- Demand response (DR) restrictions (according to Ladwig 2018, pp. 90-93):
  - *NOTE: Ladwig (2018, p. 90) introduces a deviating definition for the shifting time!*

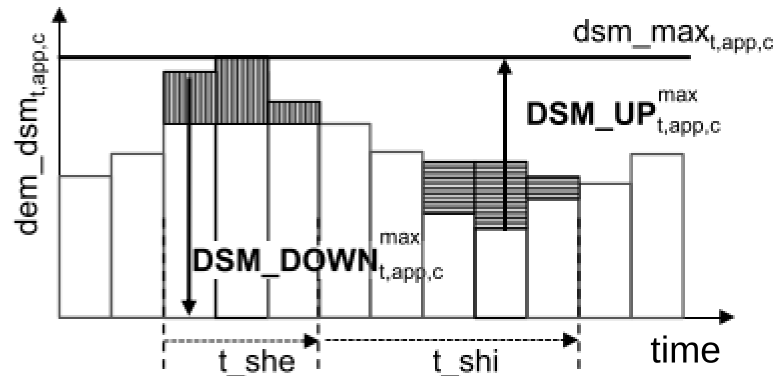
  → $t_{she} + t_{shi} = shifting\ time\ (as\ defined\ above)$*

  - DR_1: potential limit for downwards shift (current demand)

$$\boldsymbol{DSM\_DOWN_t} \leq dem_t \quad \forall t \in T$$

  - DR_PtX: potential limit for PtX applications

$$\boldsymbol{DSM\_DOWN_t^{PTX}} = 0 \quad \forall t \in T$$
$$\boldsymbol{DSM\_UP_t^{PTX}} \leq dsm\_max^{PTX} \quad \forall t \in T$$



*This (+1) in turn is called balancing time in Ladwig (2018, p. 92)

  - DR_LC: potential limit for load shedding units (load curtailment - LC)

$$\boldsymbol{DSM\_UP_t^{LC}} = 0 \quad \forall t \in T$$
$$\boldsymbol{DSM\_DOWN_t^{LC}} \leq dsm\_max^{LC} - dem_t^{LC} \quad \forall t \in T$$

Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

  - DR_2: Introduction of a fictious DR storage level (which may take negative values as well)

$$\boldsymbol{DSM\_SL_t^{LS}} = \boldsymbol{DSM\_SL_{t-1}^{LS}} + \boldsymbol{DSM\_UP_t^{LS}} - \boldsymbol{DSM\_DOWN_t^{LS}} \qquad \forall t \in T \backslash \{0\}$$

source: Ladwig (2018), pp. 90-93; simplified

DR modeling approach in Ladwig (2018) (2/3)

- Demand response (DR) restrictions (according to Ladwig 2018, pp. 90-93):
  - DR_3: Energy balancing constraint and balancing timesteps

$$\boldsymbol{DSM\_SL_t^{LS}} = 0 \quad \forall t \in t_{bal}$$

with $t_{bal} = y \cdot (t_{she} + t_{shi}) + 1$ and

$y \in \{0,1,\dots,f_a - 1\}$ where f_a: number of feasible acitvations per year

  - DR_4: Daily limit for load shifting (optional)

$$\sum_{t_{start}}^{t_{start}+23} \boldsymbol{DSM\_DOWN_t^{LS}} \leq \frac{1}{24} \cdot \sum_{t_{start}}^{t_{start}+23} dem_t^{LS} \cdot t\_she \cdot f_d \qquad \forall t \in T, \mathrm{t_{start}} = \mathrm{d} \cdot 24 + 1$$

  - DR_5: Further limit for downward shifts based on prior activation

$$\boldsymbol{DSM\_DOWN_t^{LS}} \leq dem_{t-1} - \boldsymbol{DSM\_DOWN_{t-1}^{LS}} \qquad \forall t \in T\{0\}$$

Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

  - DR_6a and DR_6b: Overall annual / daily limit for load shedding

$$\sum_{t_1}^{t_{8760}} \boldsymbol{DSM\_DOWN_t^{LC}} \leq f_a \cdot t_{she} \cdot dsm\_pot \ \forall t \in T$$

$$\sum_{t_{start}}^{t_{start}+23} \boldsymbol{DSM\_DOWN_t^{LC}} \leq t_{she} \cdot dsm\_pot \quad \forall t \in T$$

source: Ladwig (2018), pp. 90-93; simplified

DR modeling approach in Ladwig (2018) (3/3)

- Parameters:

dem_t:	demand in hour t
dsm_max^{LC}:	maximum demand of load curtailment (shedding) unit
t_{she}:	time for a downshift ($= t_{interference}$)
t_{shi}:	time between end of upshift and balancing of load shift
f_a :	maximum activations per year
f_d:	maximum activations per day
$d_{S,neg}$:	interference duration for upshifts

- Variables:

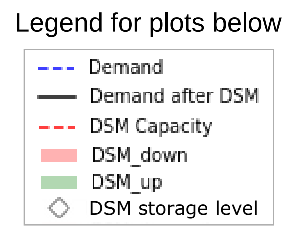
$\boldsymbol{DSM\_DOWN_t}$:	downshift in hour t
$\boldsymbol{DSM\_UP_t^{LS}}$:	upshift in hour t
$\boldsymbol{DSM\_DOWN_t^{LC}}$:	load shedding in hour t
$\boldsymbol{DSM\_SL_t^{LS}}$:	DR storage level in hour t

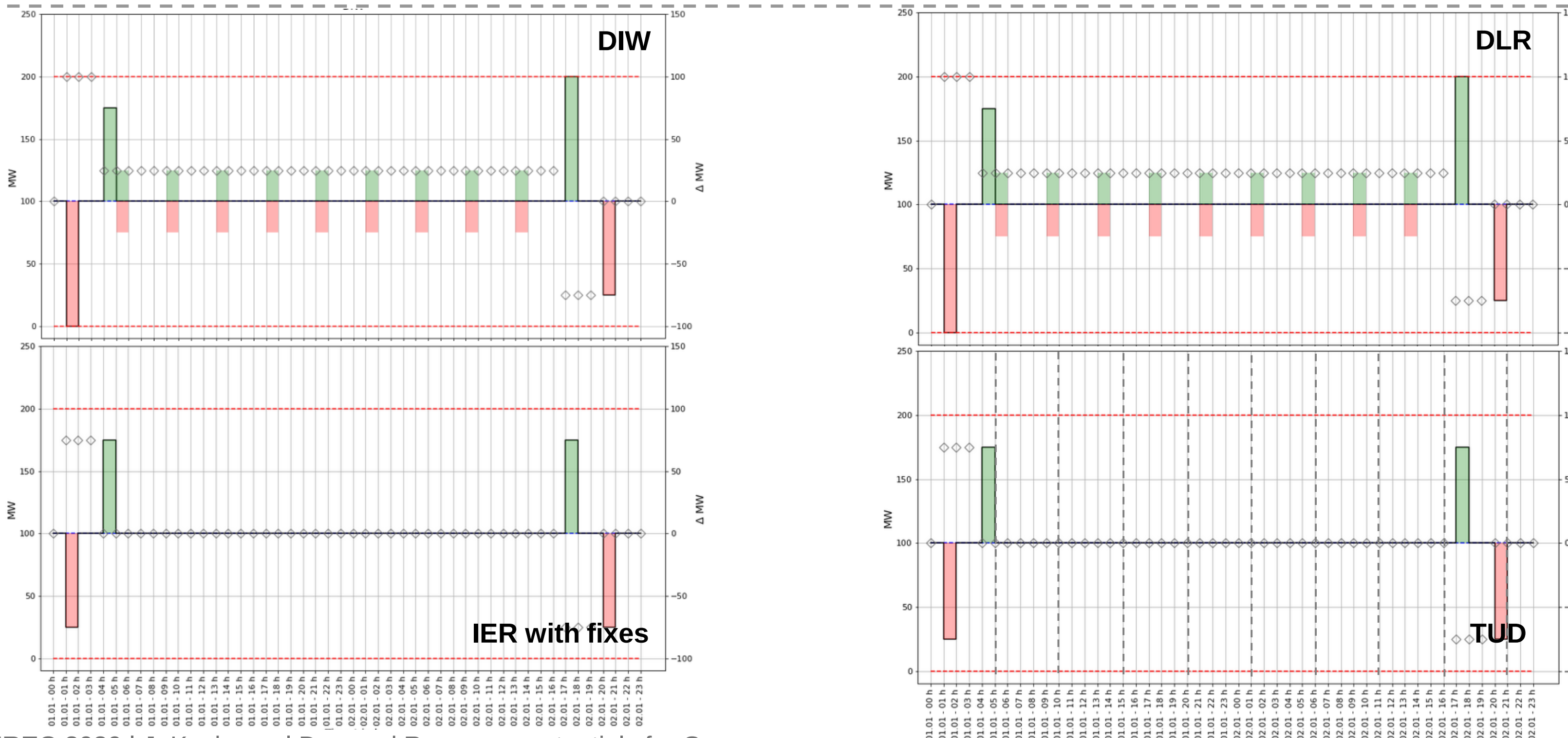
Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

source: Ladwig (2018), pp. 90-93; simplified

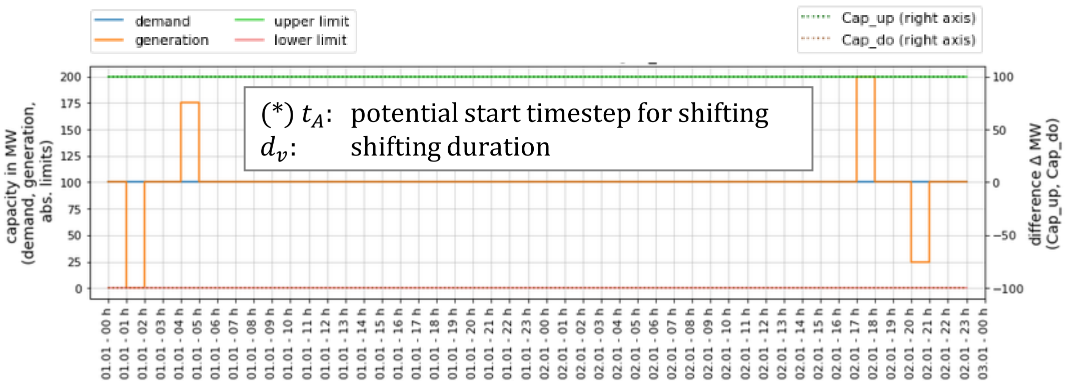
Backup Agenda

Comparison of modeling approaches:
DR utilization – Case: generation variations - **asymmetric**



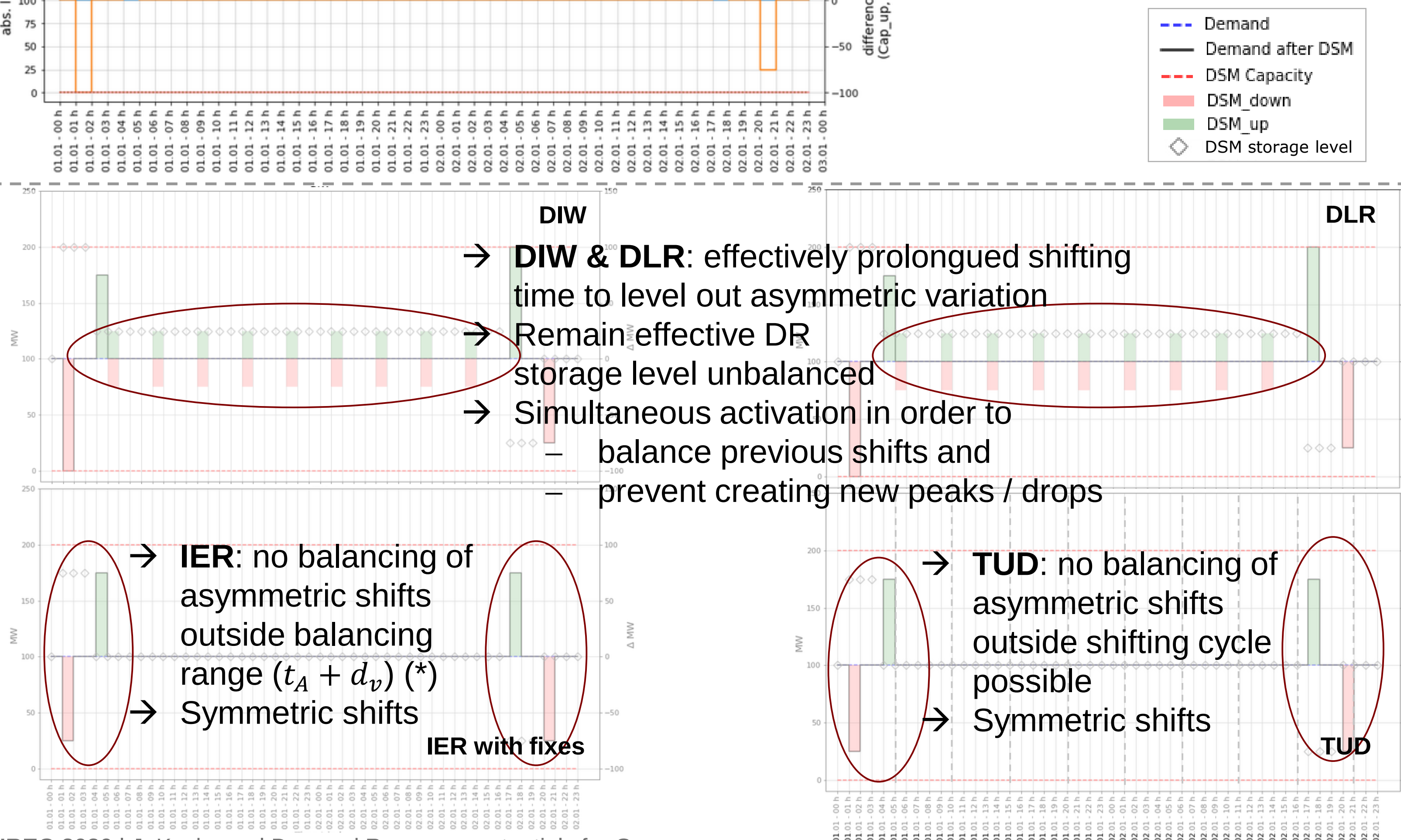


Comparison of modeling approaches: DR utilization – Case: generation variations - **asymmetric**



(*) t_A: potential start timestep for shifting
d_v: shifting duration

Legend for plots below



→ **DIW & DLR**: effectively prolongued shifting time to level out asymmetric variation

→ Remain effective DR storage level unbalanced

→ Simultaneous activation in order to
- balance previous shifts and
- prevent creating new peaks / drops

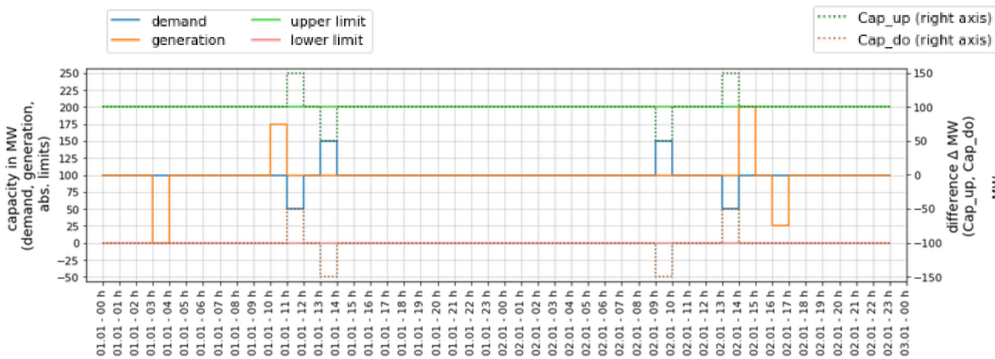
→ **IER**: no balancing of asymmetric shifts outside balancing range $(t_A + d_v)$ (*)

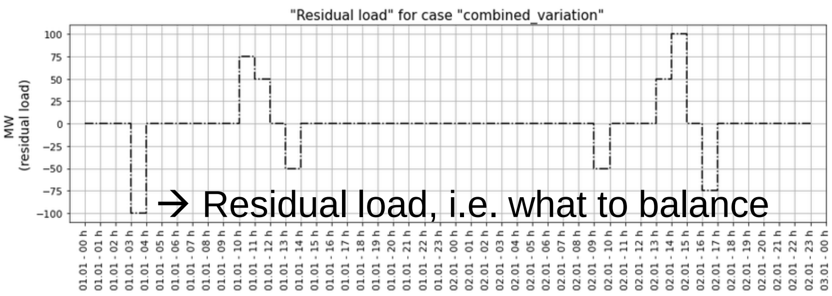
→ Symmetric shifts

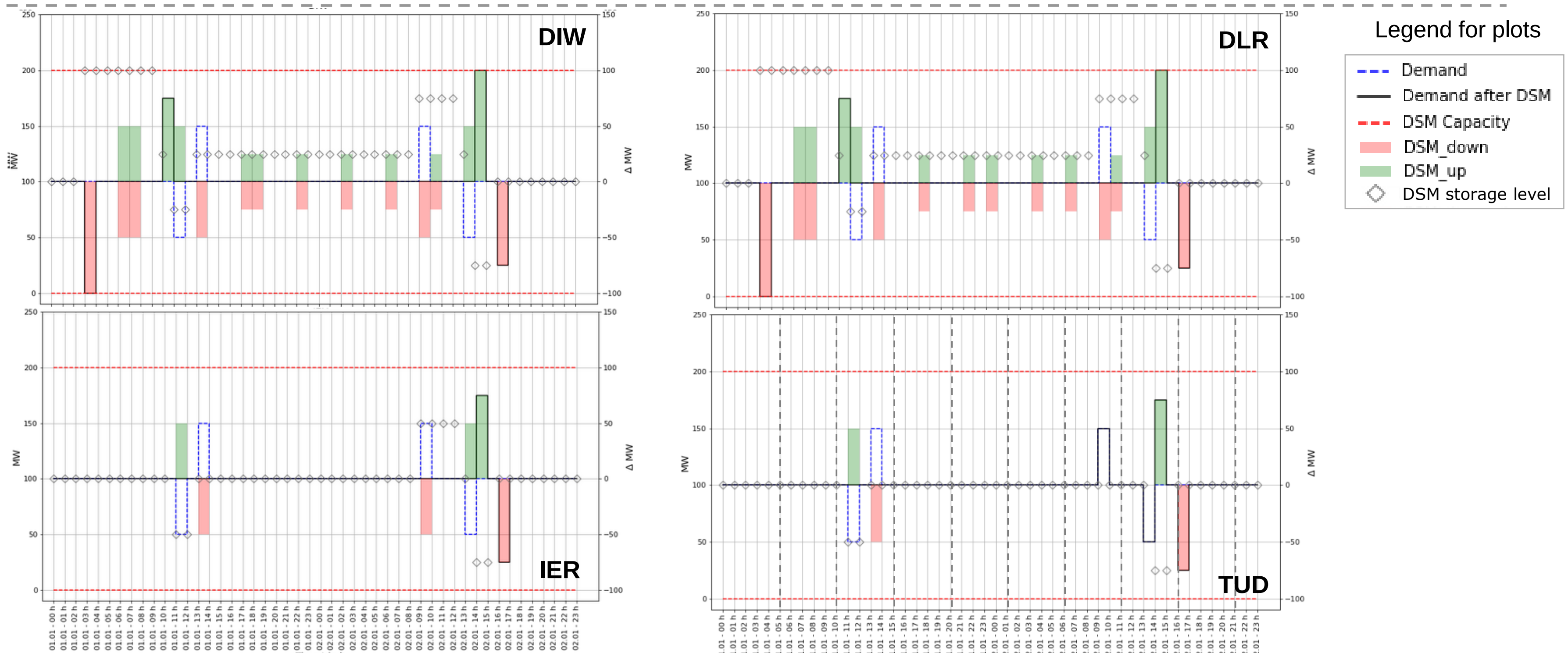
→ **TUD**: no balancing of asymmetric shifts outside shifting cycle possible

→ Symmetric shifts

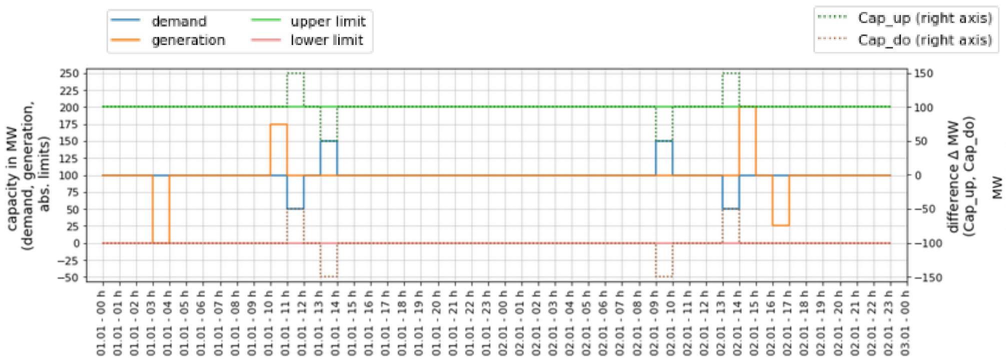
Comparison of modeling approaches: DR utilization – Case: **combined variations**

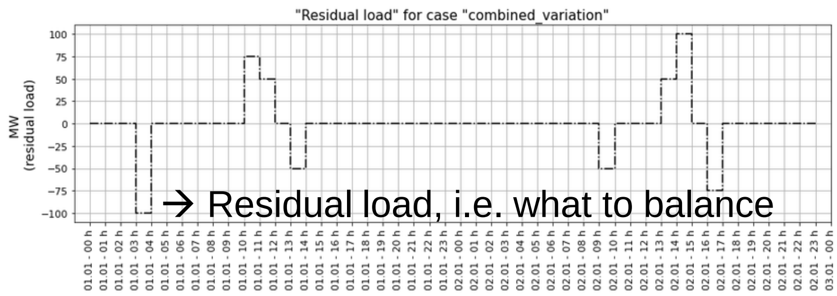




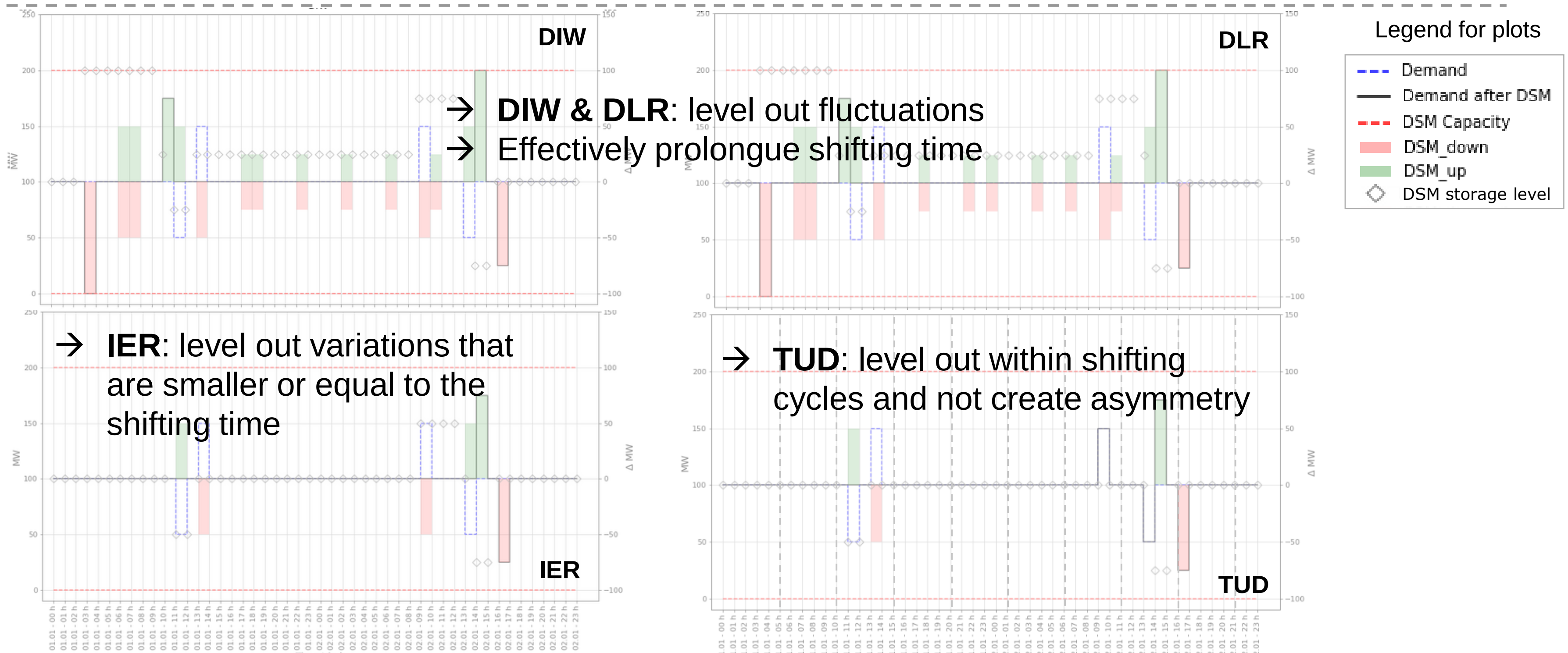


Comparison of modeling approaches: DR utilization – Case: **combined variations**





→ Residual load, i.e. what to balance



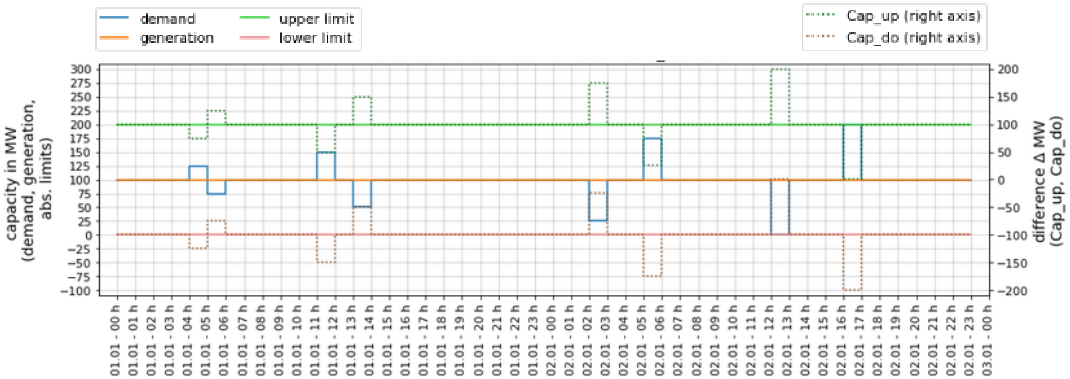
→ **DIW & DLR**: level out fluctuations

→ Effectively prolongue shifting time

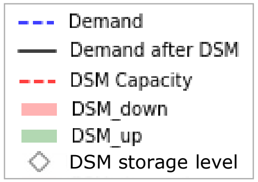
→ **IER**: level out variations that are smaller or equal to the shifting time

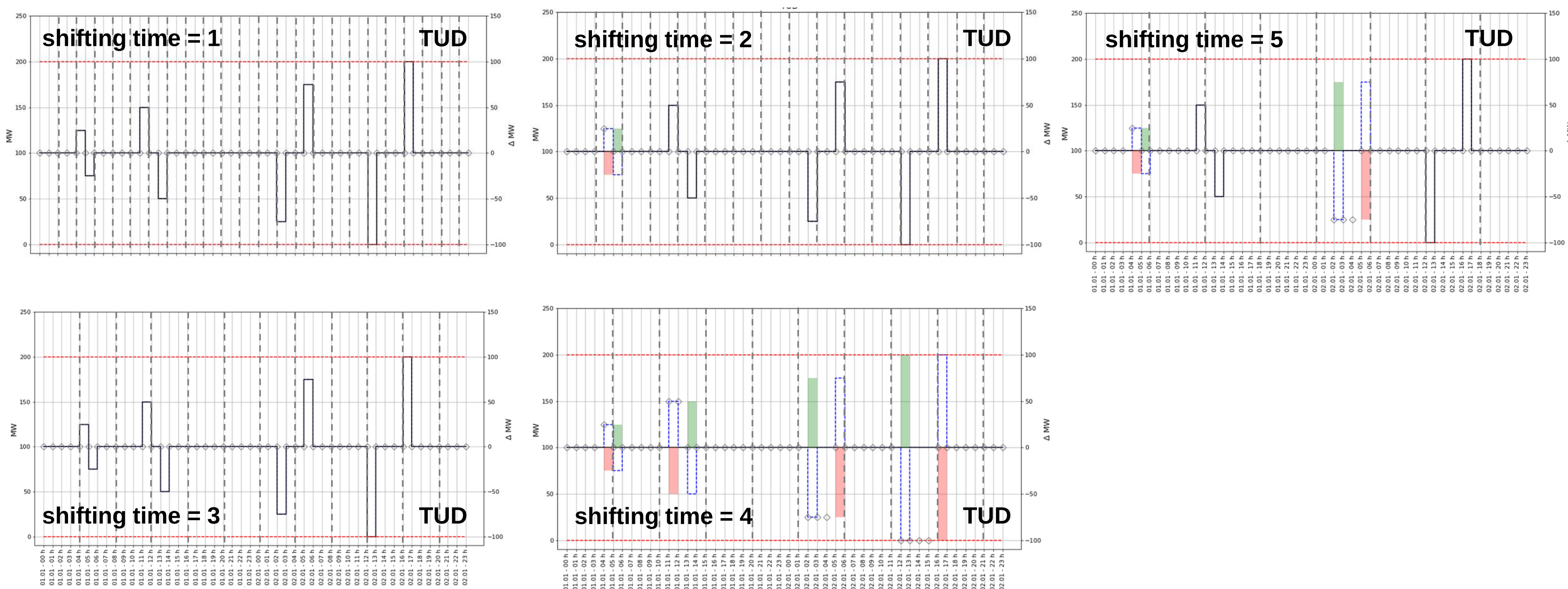
→ **TUD**: level out within shifting cycles and not create asymmetry

Comparison of modeling approaches: Parameter variations: **shifting time** (delay time)

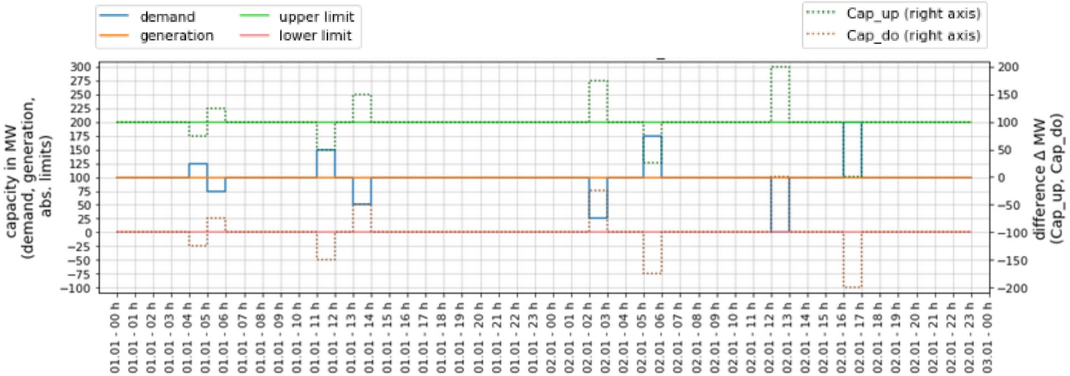


Legend for plots below



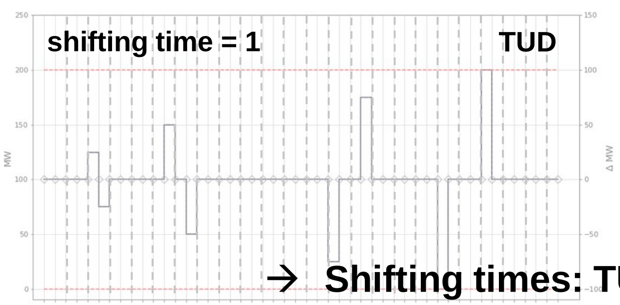


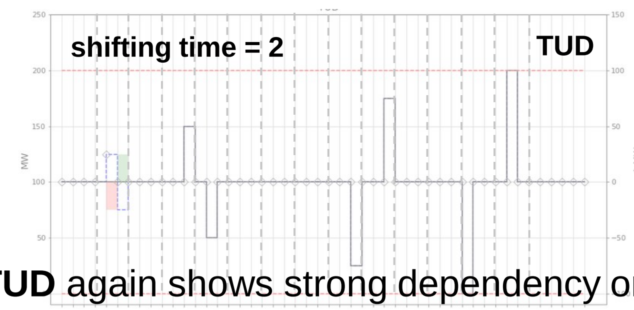
Comparison of modeling approaches:
Parameter variations: **shifting time** (delay time)

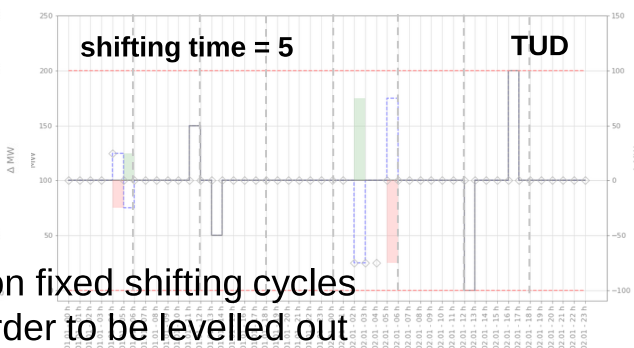


Legend for plots below

- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level

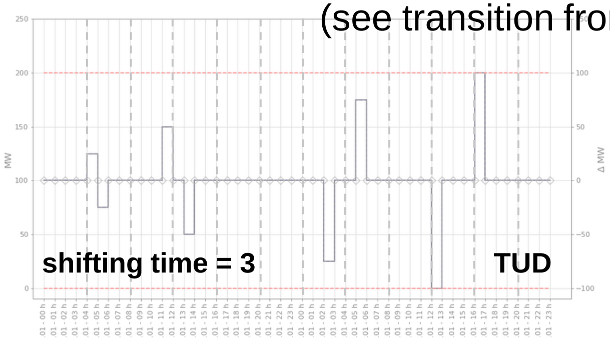


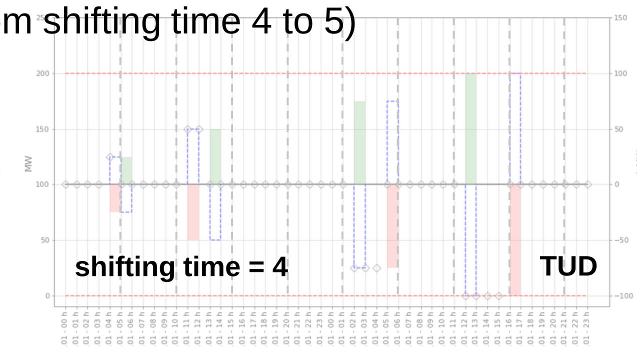




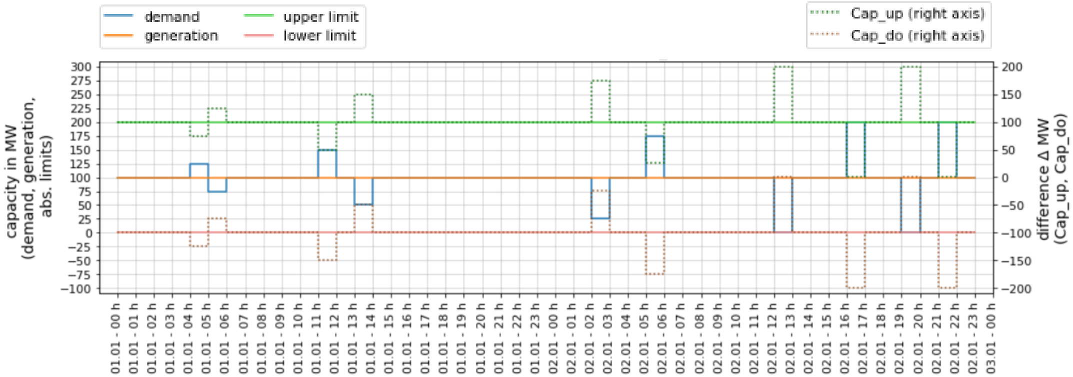
→ **Shifting times: TUD** again shows strong dependency on fixed shifting cycles

→ Starts and stops of processes have to match these in order to be levelled out (see transition from shifting time 4 to 5)



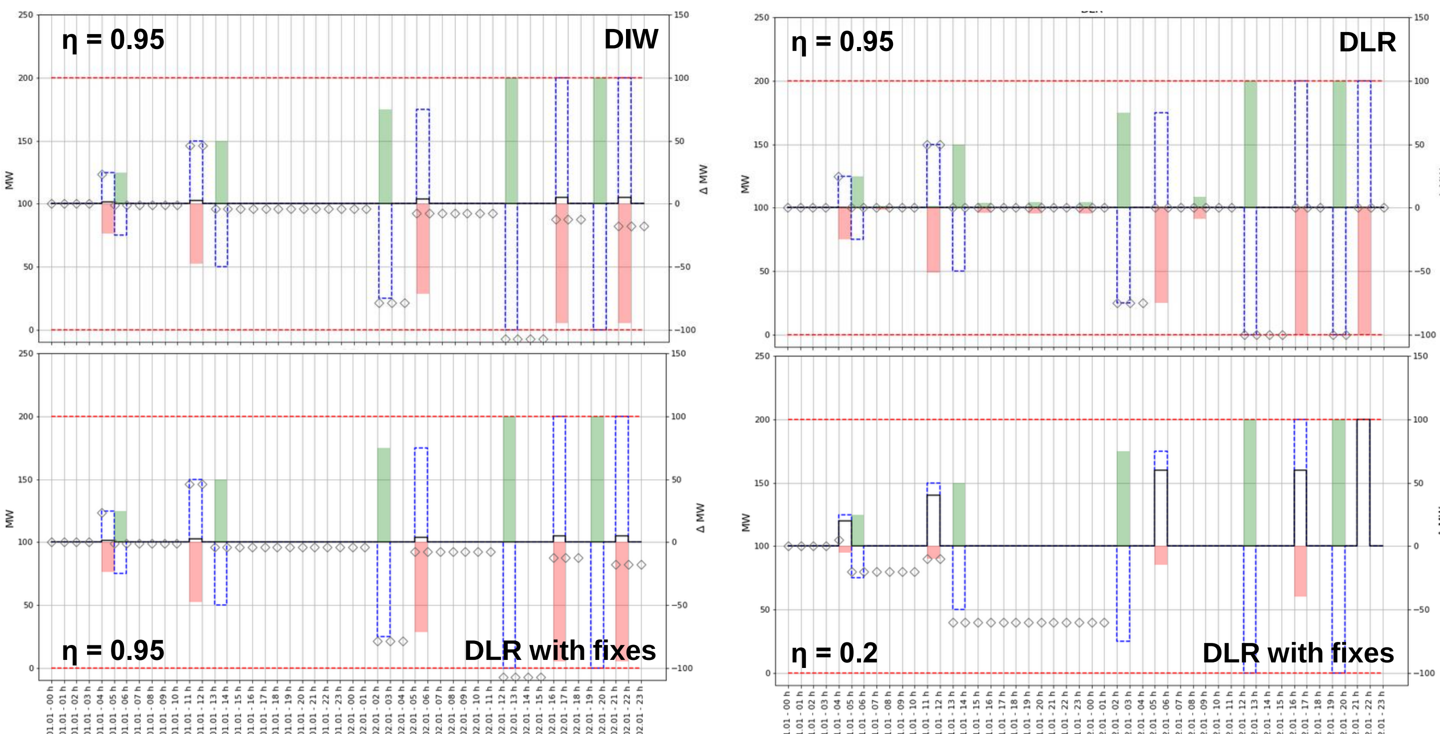


Comparison of modeling approaches: Parameter variations: **efficiency**



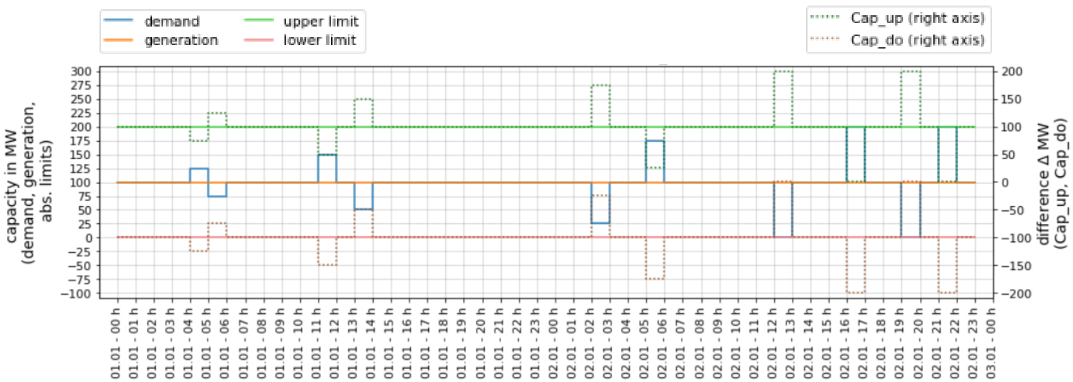
Legend for plots below

- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level

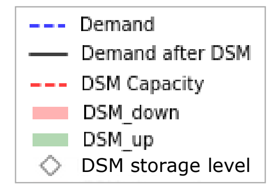


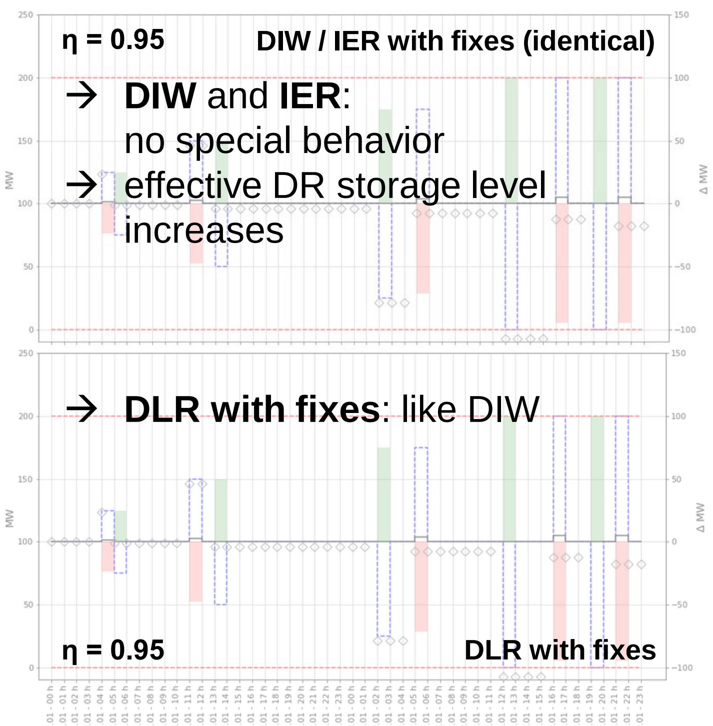
Efficiency losses are associated with **upshifts**

Comparison of modeling approaches: Parameter variations: **efficiency**



Legend for plots below





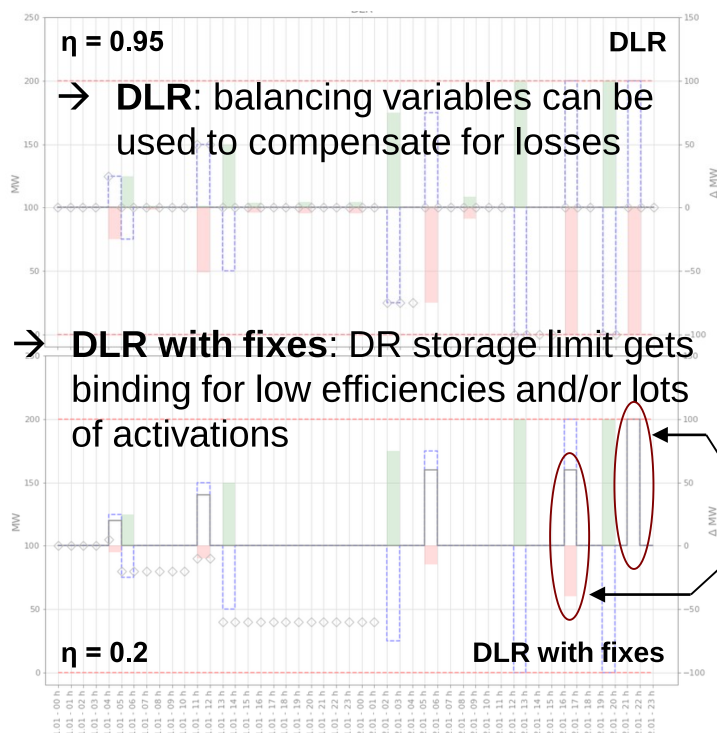
$\eta = 0.95$ **DIW / IER with fixes (identical)**

→ **DIW** and **IER**: no special behavior

→ effective DR storage level increases

→ **DLR with fixes**: like DIW

$\eta = 0.95$ **DLR with fixes**



$\eta = 0.95$ **DLR**

→ **DLR**: balancing variables can be used to compensate for losses

→ **DLR with fixes**: DR storage limit gets binding for low efficiencies and/or lots of activations

$\eta = 0.2$ **DLR with fixes**

Efficiency losses are associated with **upshifts**

- Last demand peak cannot be levelled out
- Last downshift: mixture of balancing previous upshift and initial downshift which is balanced afterwards

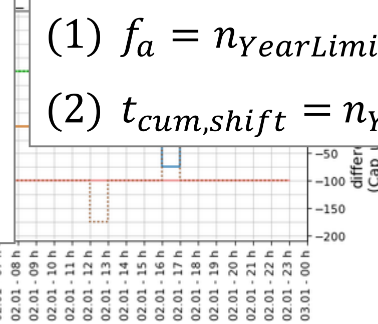
Comparison of modeling approaches: Parameter variations: **recovery time / max. activations**

(*) f_a:	max. amount of activations per year / optimization time frame ($f_a = n_{YearLimit}$)
T:	optimization time frame
$t_{cum,shift}$:	max. cumulative interference duration
$t_{shifting}$:	shifting duration
$t_{interference}$:	interference duration
$t_{recovery}$:	recovery duration (time between end of load shift and start of new one)

Interrelation of limits: (*)

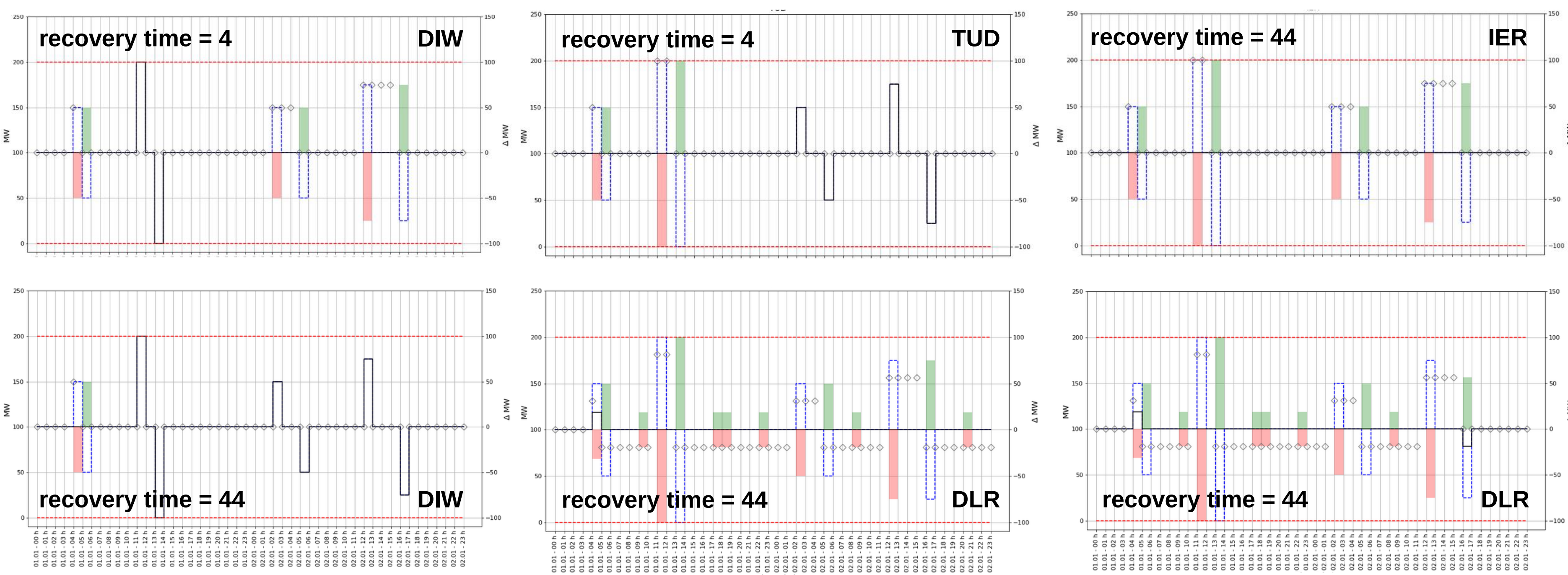
$$(1)\quad f_a = n_{YearLimit} = \frac{T}{t_{shifting} + t_{recovery}}$$

$$(2)\quad t_{cum,shift} = n_{YearLimit} \cdot t_{interference}$$



Legend for plots below

- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level



Comparison of modeling approaches:
Parameter variations: **recovery time / max. activations**

(*) f_a:	max. amount of activations per year / optimization time frame ($f_a = n_{YearLimit}$)
T:	optimization time frame
$t_{cum,shift}$:	max. cumulative interference duration
$t_{shifting}$:	shifting duration
$t_{interference}$:	interference duration
$t_{recovery}$:	recovery duration (time between end of load shift and start of new one)

Interrelation of limits: (*)

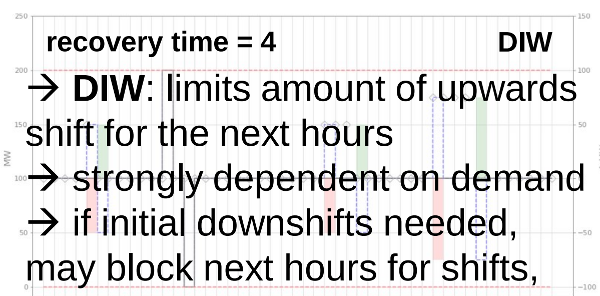
$$(1)\quad f_a = n_{YearLimit} = \frac{T}{t_{shifting} + t_{recovery}}$$

$$(2)\quad t_{cum,shift} = n_{YearLimit} \cdot t_{interference}$$

(**) $\boldsymbol{DSM_{tt}^{up}}$:	DR upshift in hour tt
R:	recovery time
L:	shifting time (delay time)
C_t^{up}:	maximum capacity for upshifts in hour t

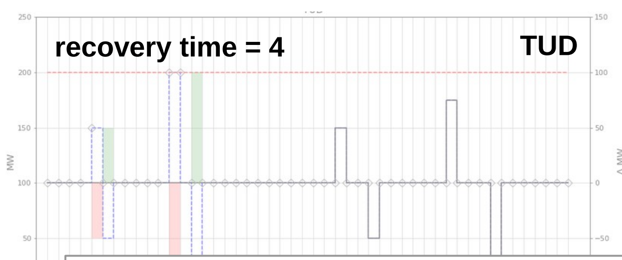
Legend for plots below

- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level

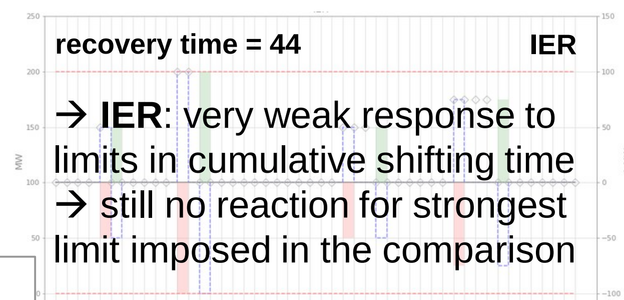


recovery time = 4 **DIW**

→ **DIW**: limits amount of upwards shift for the next hours
→ strongly dependent on demand
→ if initial downshifts needed, may block next hours for shifts, but no effect on initial upshifts



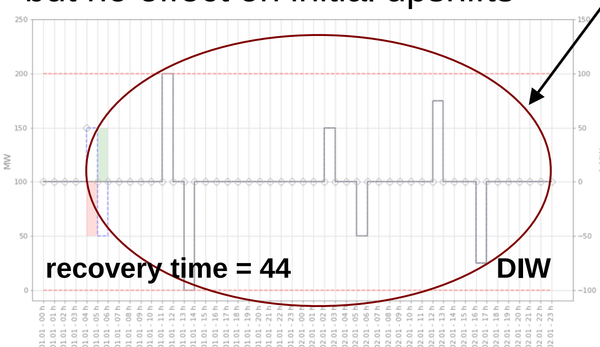
recovery time = 4 **TUD**



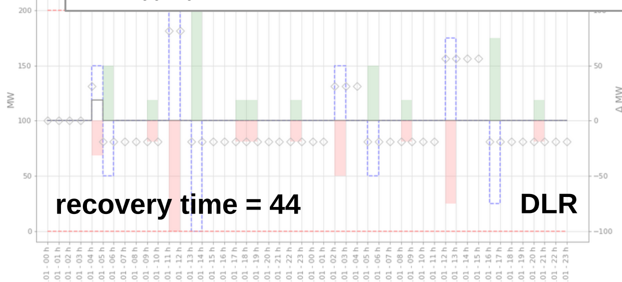
recovery time = 44 **IER**

→ **IER**: very weak response to limits in cumulative shifting time
→ still no reaction for strongest limit imposed in the comparison

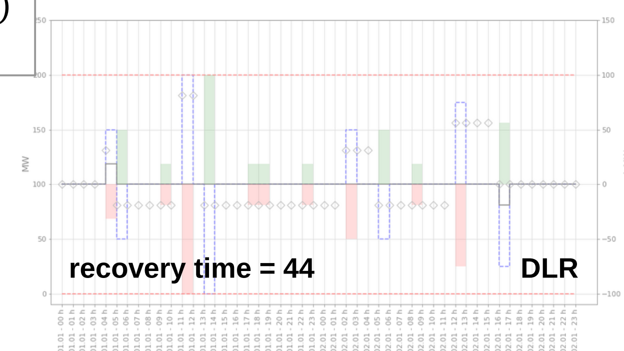
$$\sum_{tt=t}^{t+R-1} \boldsymbol{DSM_{tt}^{up}} \leq C_t^{up} \cdot L \quad \forall t \quad (**)$$



recovery time = 44 **DIW**



recovery time = 44 **DLR**



recovery time = 44 **DLR**

Comparison of modeling approaches: Parameter variations: **recovery time / max. activations**

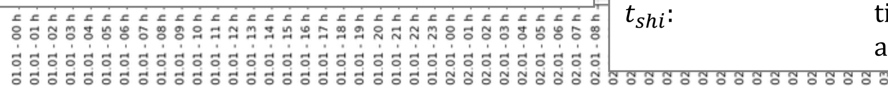
(*) f_a: max. amount of activations per year / optimization time frame ($f_a = n_{YearLimit}$)
T: optimization time frame
$t_{cum,shift}$: max. cumulative interference duration
$t_{shifting}$: shifting duration
$t_{interference}$: interference duration
$t_{recovery}$: recovery duration (time between end of load shift and start of new one)

Interrelation of limits: (*)

$$(1)\quad f_a = n_{YearLimit} = \frac{T}{t_{shifting} + t_{recovery}}$$

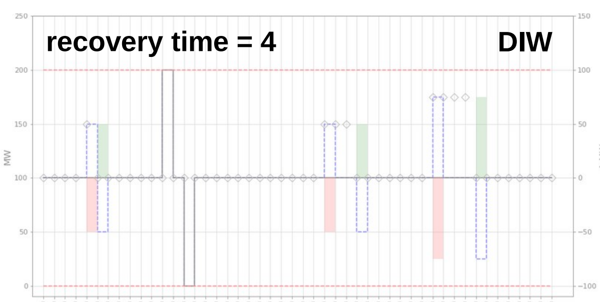
$$(2)\quad t_{cum,shift} = n_{YearLimit} \cdot t_{interference}$$

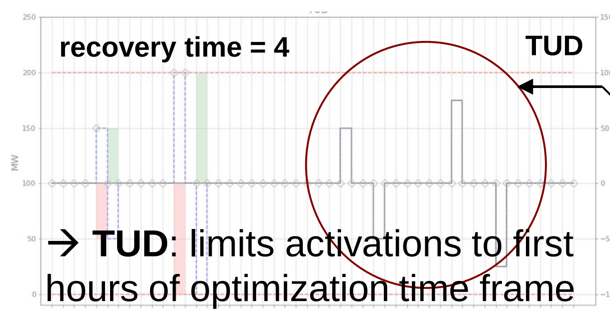
(**) $\boldsymbol{DSM\_SL_t^{LS}}$: DR storage level in hour t
t_{she}: time for a downshift ($= t_{interference}$)
t_{shi}: time between end of upshift and balancing of load shift



Legend for plots below

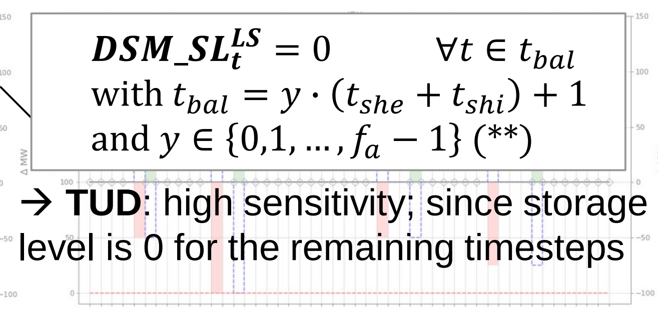
- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level



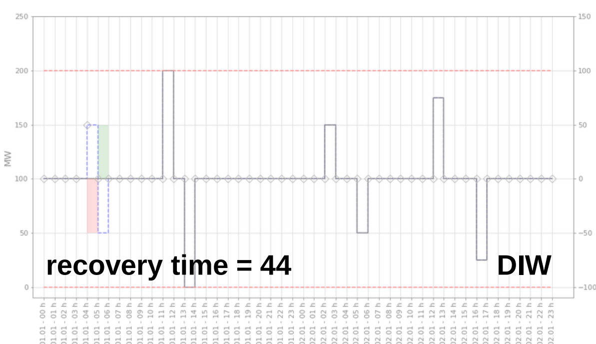


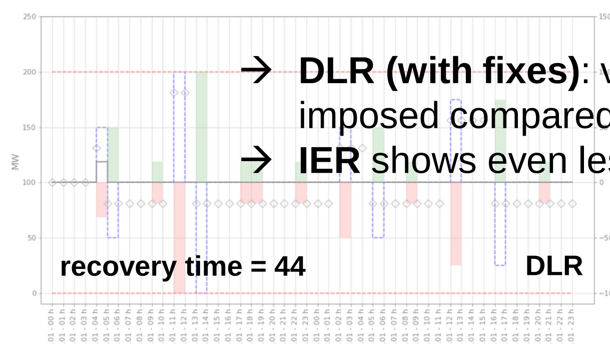
→ **TUD**: limits activations to first hours of optimization time frame

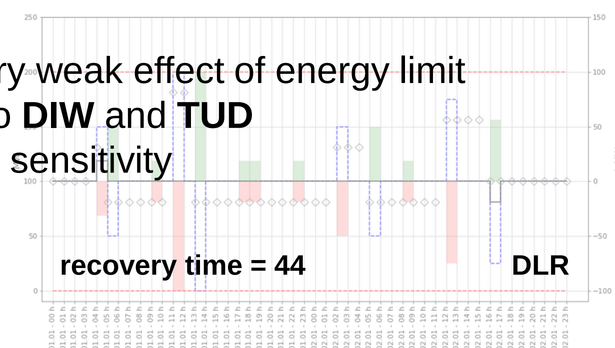
$$\boldsymbol{DSM\_SL_t^{LS}} = 0 \qquad \forall t \in t_{bal}$$
with $t_{bal} = y \cdot (t_{she} + t_{shi}) + 1$
and $y \in \{0,1,\dots,f_a - 1\}$ (**)



→ **TUD**: high sensitivity; since storage level is 0 for the remaining timesteps



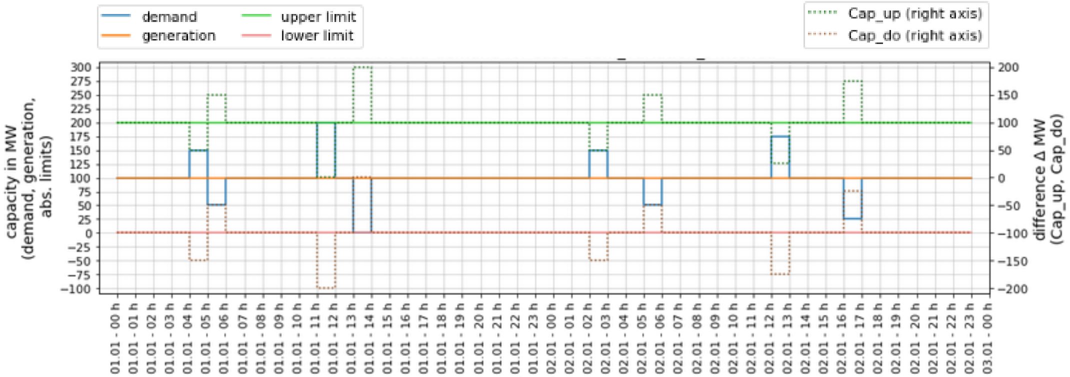




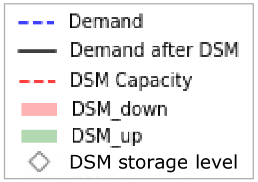
→ **DLR (with fixes)**: very weak effect of energy limit imposed compared to **DIW** and **TUD**

→ **IER** shows even less sensitivity

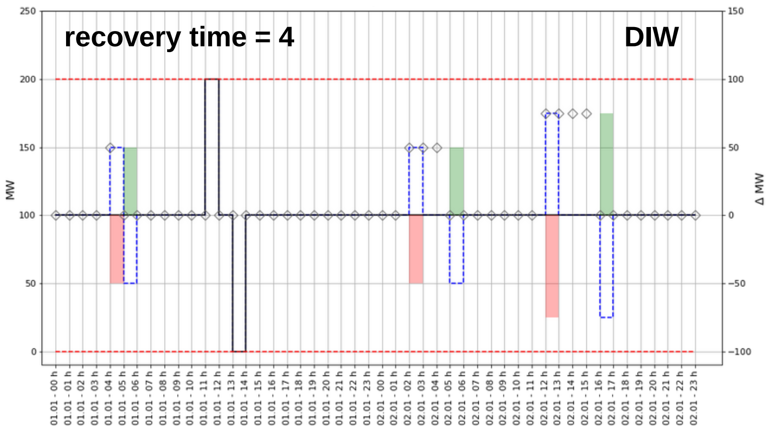
Comparison of modeling approaches: Parameter variations: **short-term energy limits**

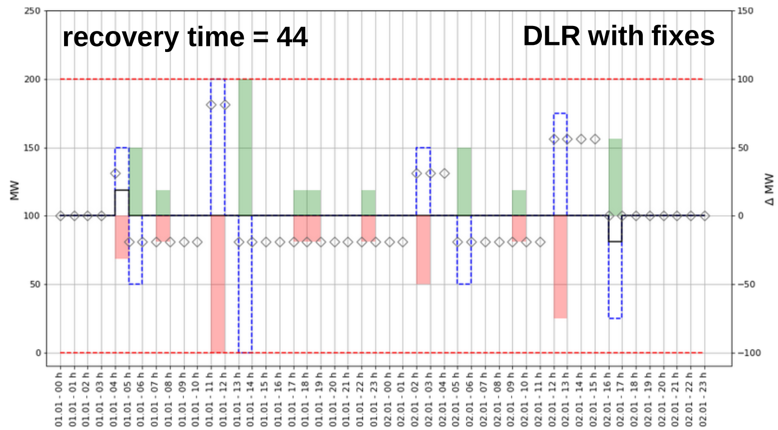


Legend for plots below

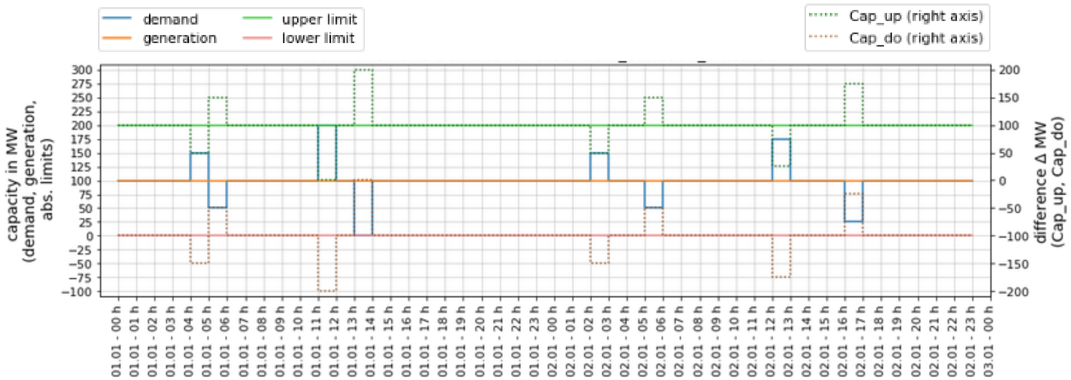


$$t_{recovery} = t_{DayLimit}$$





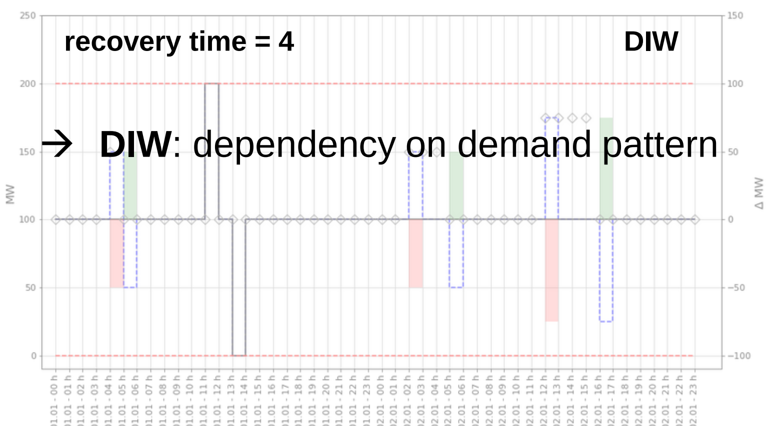
Comparison of modeling approaches: Parameter variations: **short-term energy limits**



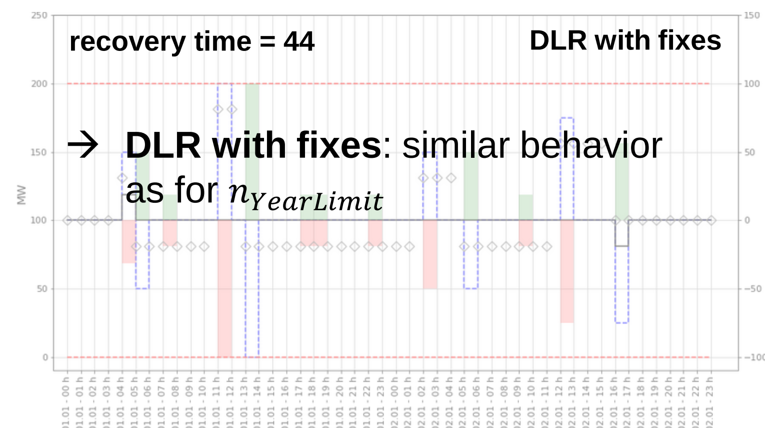
Legend for plots below

- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level

$$t_{recovery} = t_{DayLimit}$$

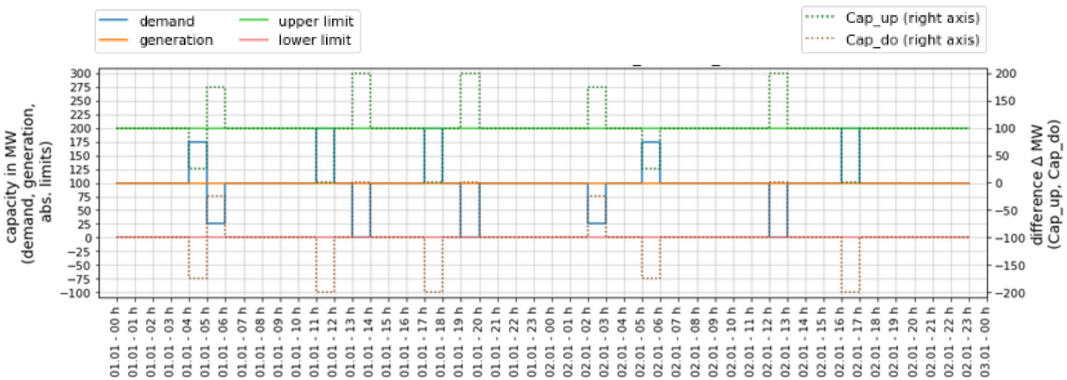


→ **DIW**: dependency on demand pattern

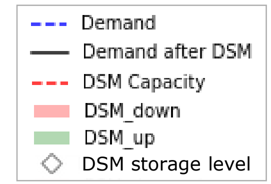


→ **DLR with fixes**: similar behavior as for $n_{YearLimit}$

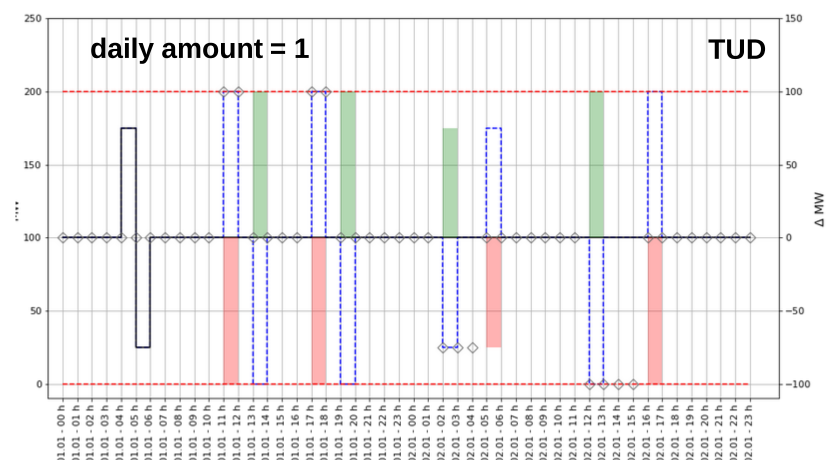
Comparison of modeling approaches: Parameter variations: **daily energy limits**

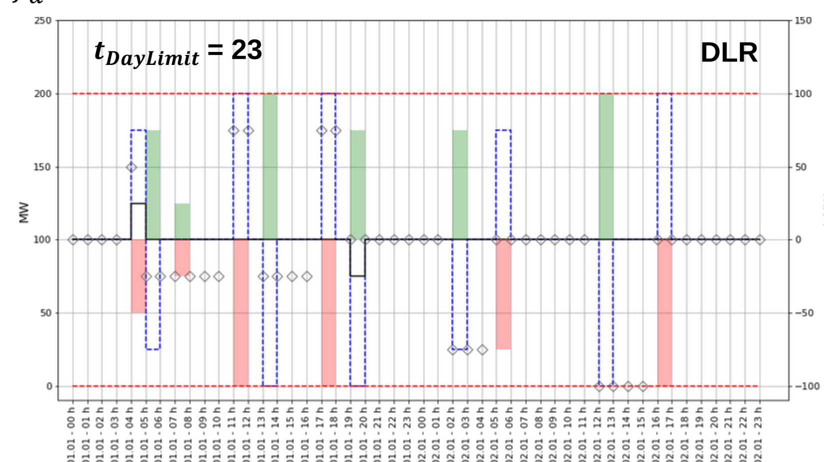


Legend for plots below



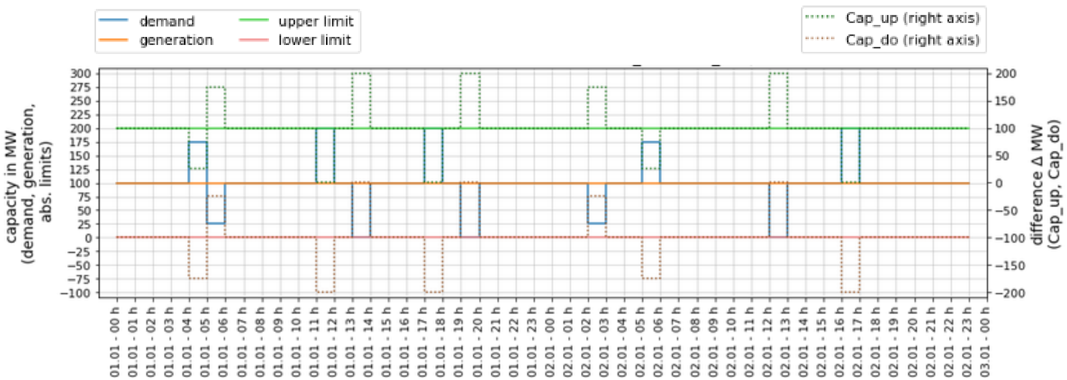
$$t_{DayLimit} = \frac{24}{f_d} - 1 \quad (*)$$





(*) $t_{DayLimit}$:	limit shiftable energy for the next $t_{DayLimit}$ hours
f_d:	max. activations per day
t_{she} :	time for downshift in Ladwig (2018)

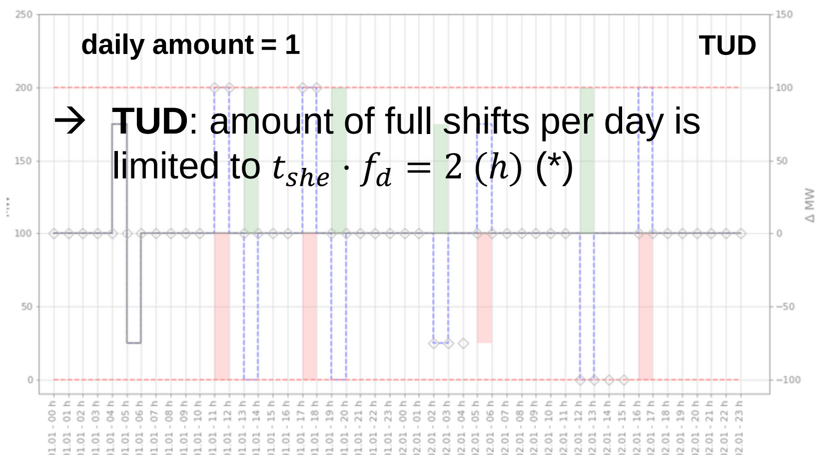
Comparison of modeling approaches: Parameter variations: **daily energy limits**

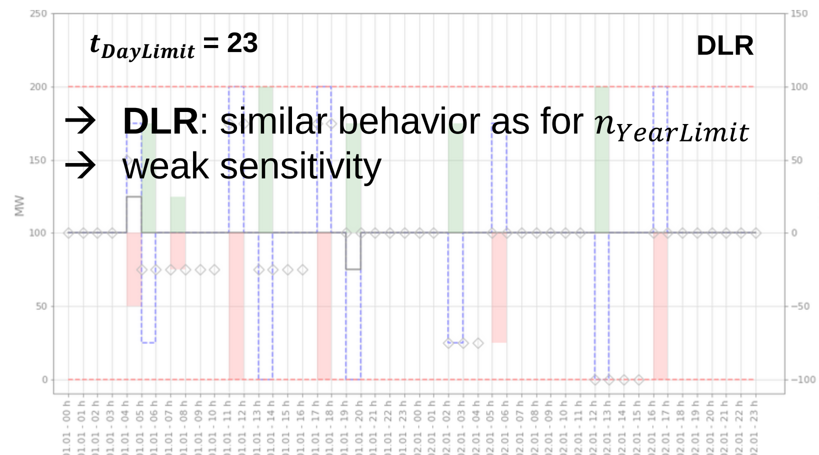


Legend for plots below

- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level

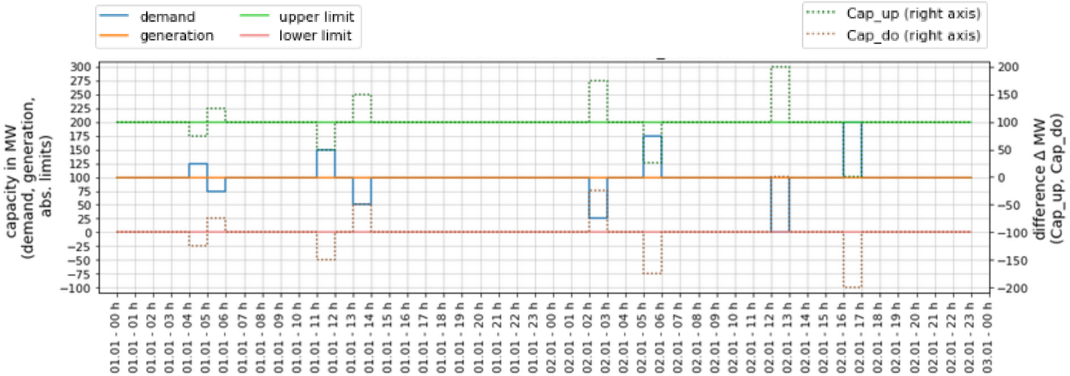
$$t_{DayLimit} = \frac{24}{f_d} - 1 \ (*)$$

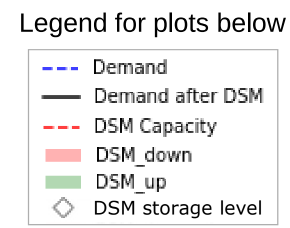


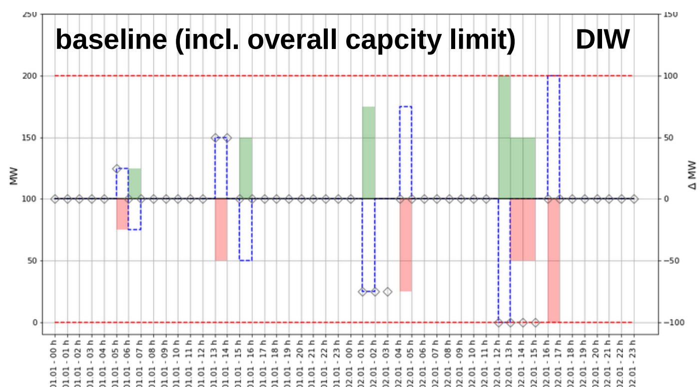


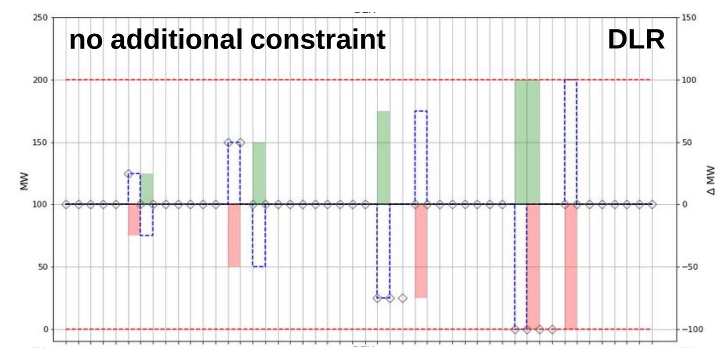
(*) $t_{DayLimit}$:	limit shiftable energy for the next $t_{DayLimit}$ hours
f_d:	max. activations per day
t_{she} :	time for downshift in Ladwig (2018)

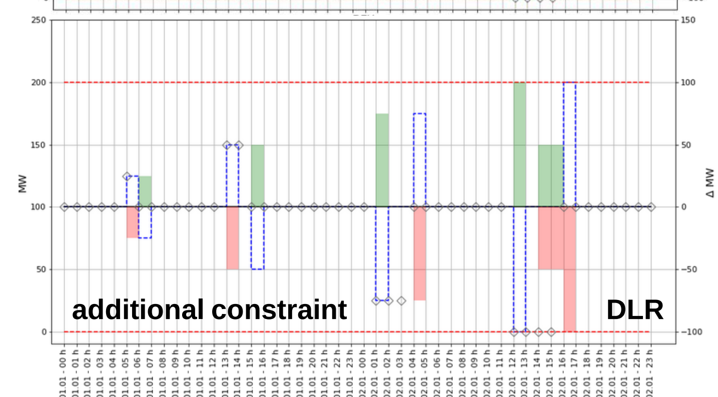
Comparison of modeling approaches: Constraint variations: **overall capacity limit constraint**



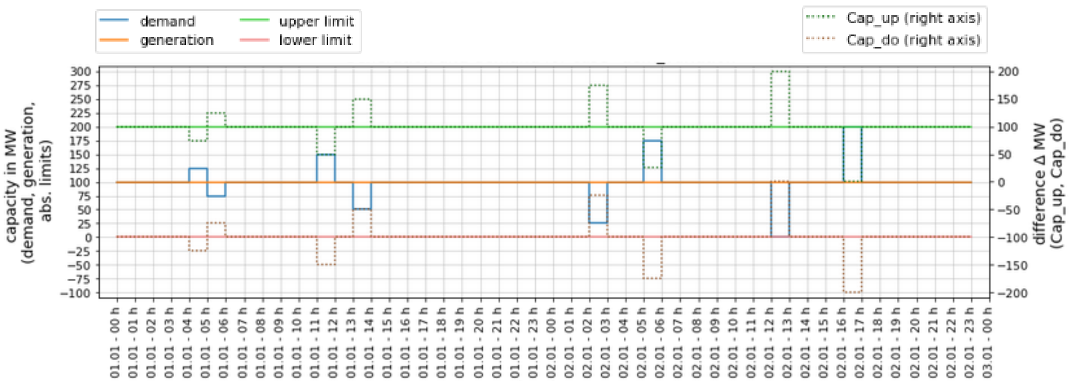




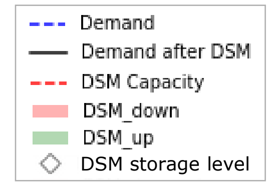


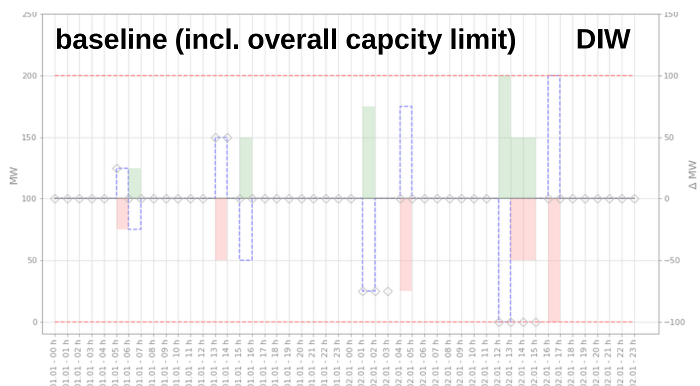


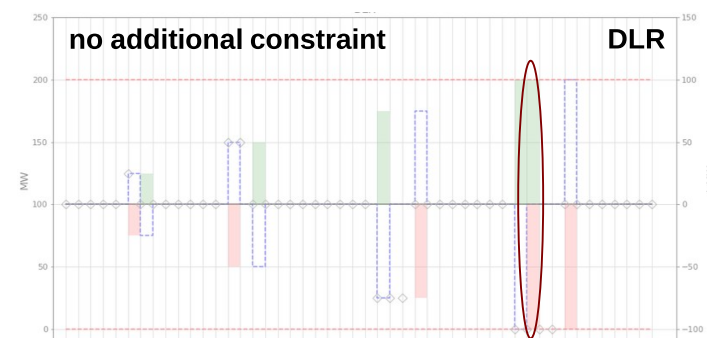
Comparison of modeling approaches: Constraint variations: **overall capacity limit constraint**

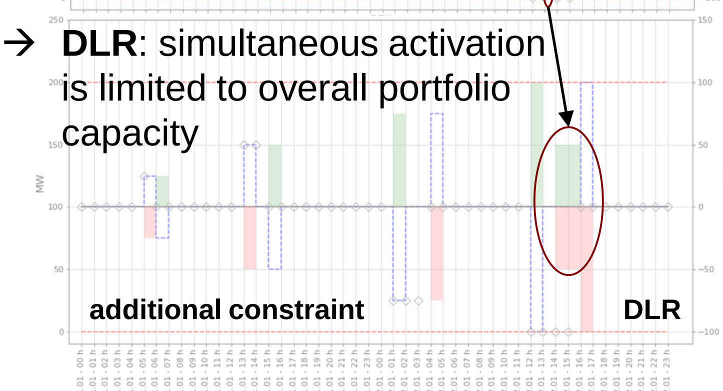


Legend for plots below





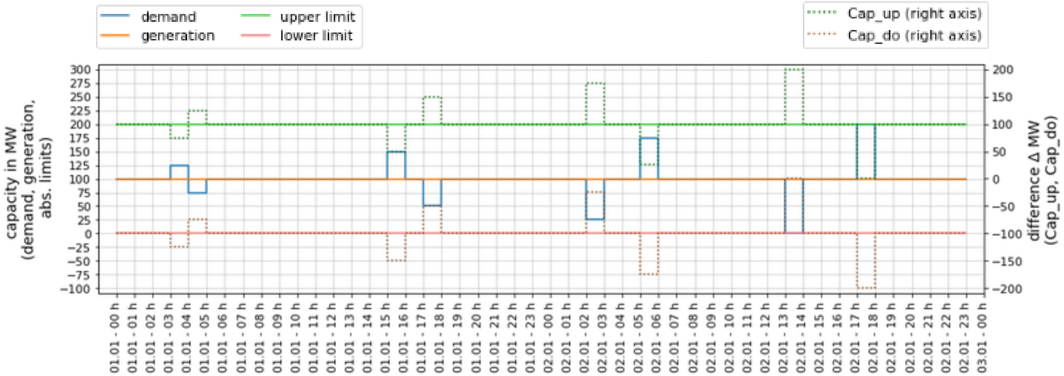




→ **DLR**: simultaneous activation is limited to overall portfolio capacity

→ **IER** (not depicted): no effect since there are no simultaneous activations to prolongue the shifting time

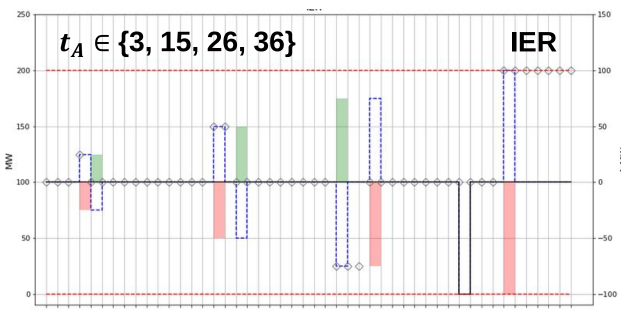
Comparison of modeling approaches: Parameter variations: **start timesteps for IER approach**

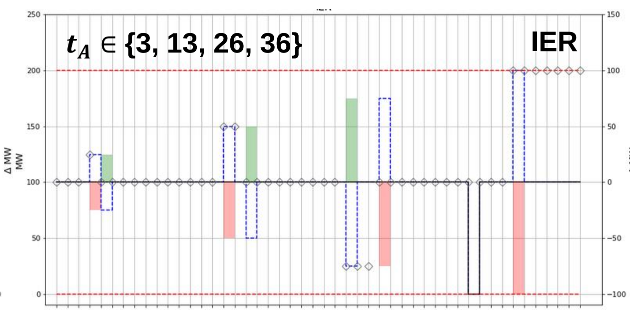


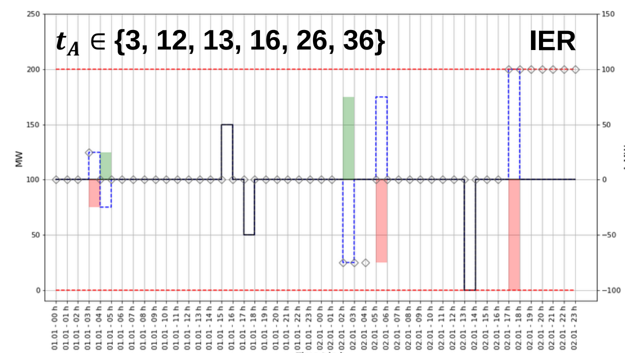
t_A: potential start timestep for shifting

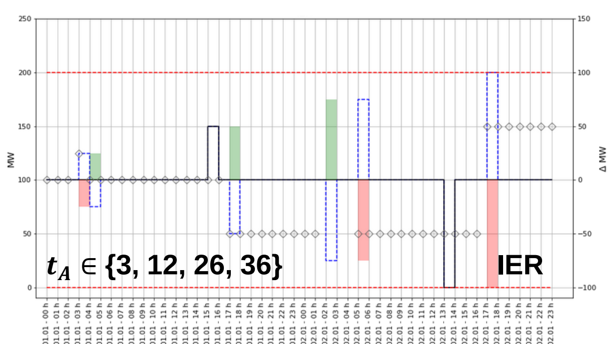
Legend for plots below

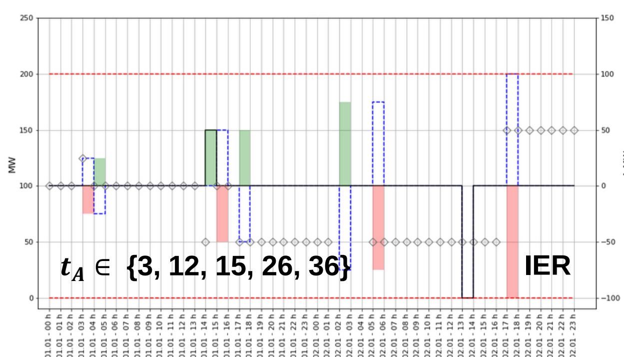
- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level





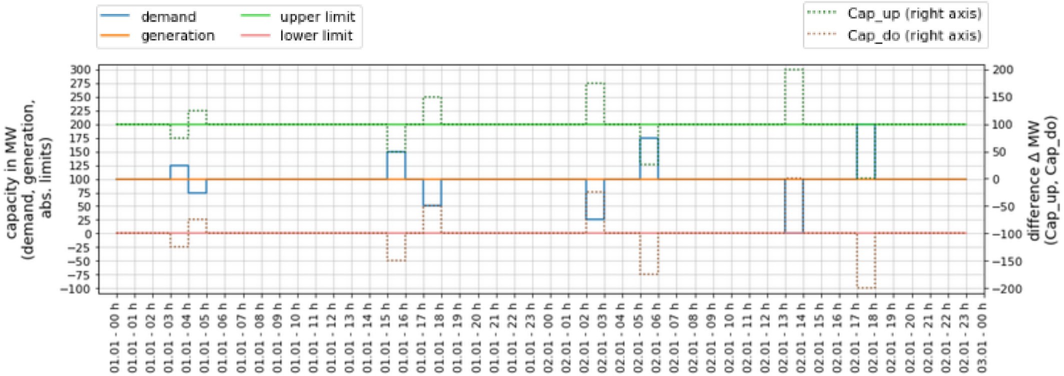






Starts of demand variations at $t_{start} \in \{3, 15, 26, 37\}$

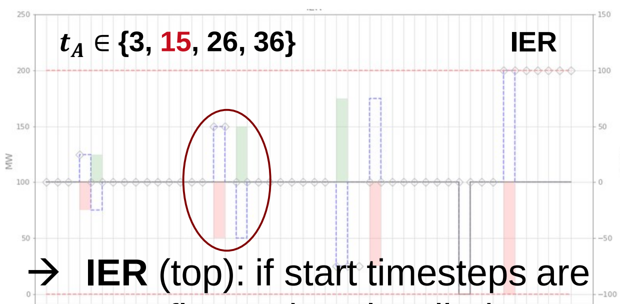
Comparison of modeling approaches: Parameter variations: **start timesteps for IER approach**

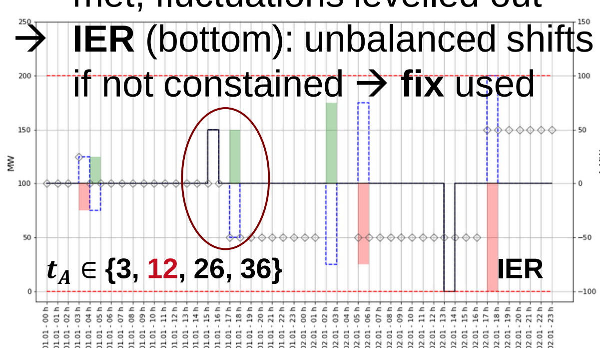


t_A: potential start timestep for shifting

Legend for plots below

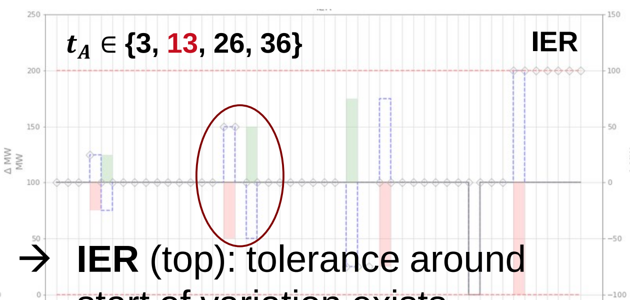
- Demand
- Demand after DSM
- DSM Capacity
- DSM_down
- DSM_up
- DSM storage level

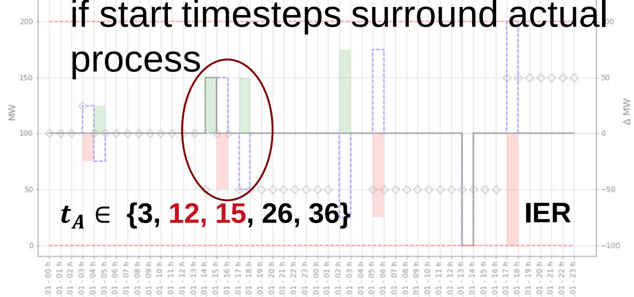




→ **IER** (top): if start timesteps are met, fluctuations levelled out

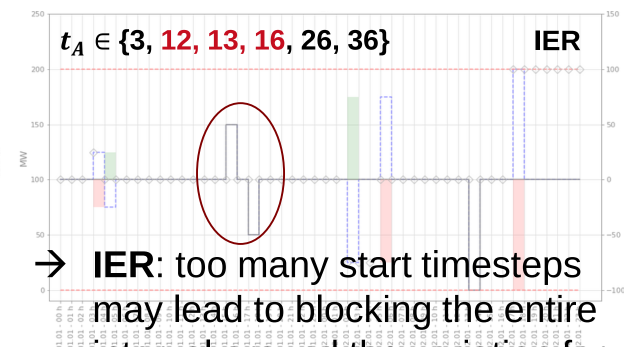
→ **IER** (bottom): unbalanced shifts if not constained → **fix** used





→ **IER** (top): tolerance around start of variation exists

→ **IER** (bottom): additional activation if start timesteps surround actual process



→ **IER**: too many start timesteps may lead to blocking the entire interval around the variation for shifts

Starts of demand variations at $t_{start} \in \{3, 15, 26, 37\}$

Comparison of modeling approaches: **realistic example – settings**

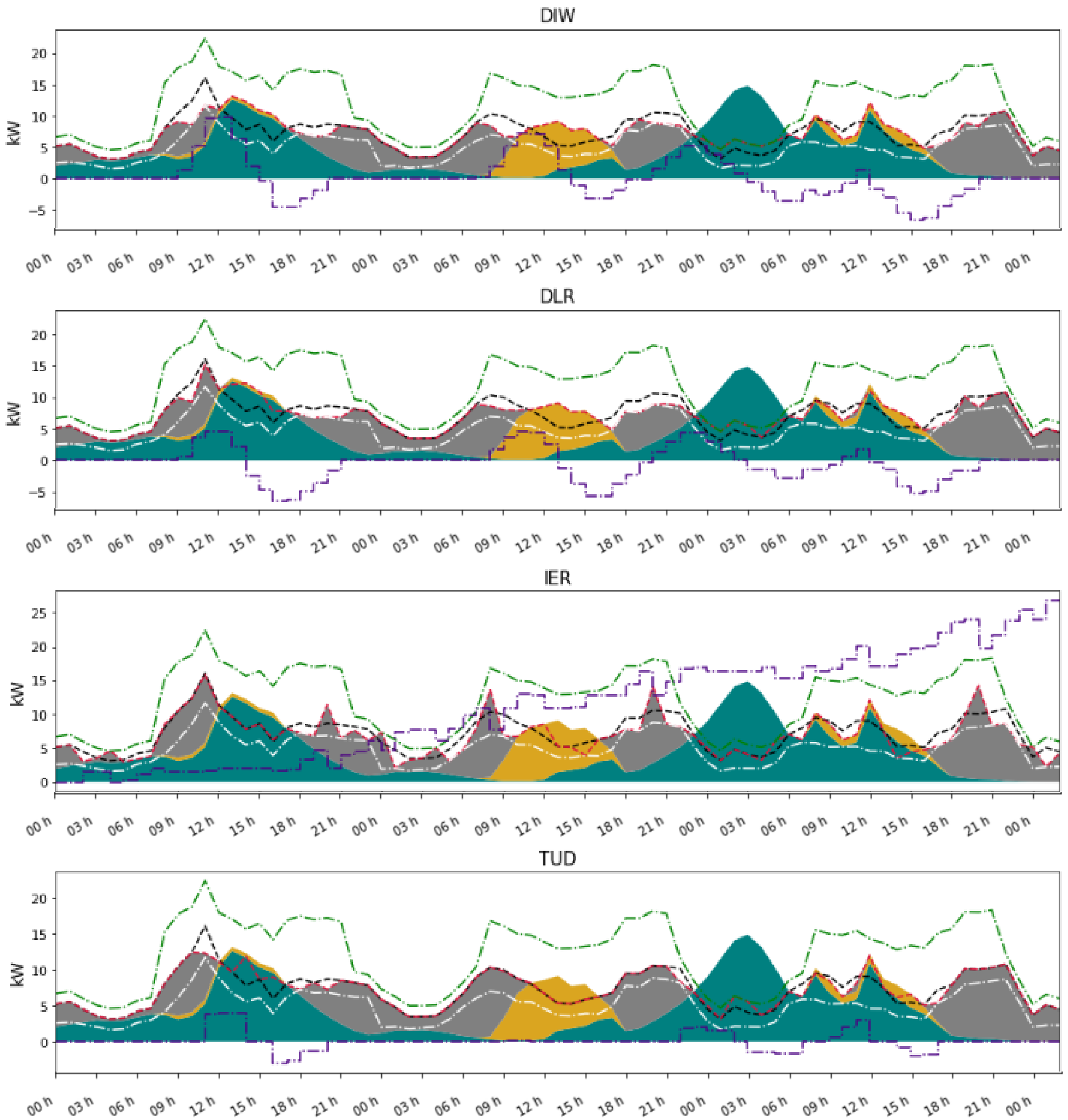
- **168** (hourly) **timesteps**

- **Realistic input data**
  - Fixed PV and wind infeed
  - Household consumers and supermarkets
    in the regions Anhalt-Bitterfeld and Dessau-Roßlau, Germany, taken from Gährs et al. (2020)
  - Demand is scaled done and taken from Endres & Pleßmann (2020)

- **Demand Response** parameterization
  - **Availability**
    - time series information from Gährs et al. (2020)
  - **Times**
    - shifting time (delay time): 4 (hours)
    - interference time (if applicable): 2 (hours) up / down
  - **Costs**
    - Overall: 0.1 (€/MWh)
    - Evenly attributed to upwards resp. downwards shift (each half of overall costs)

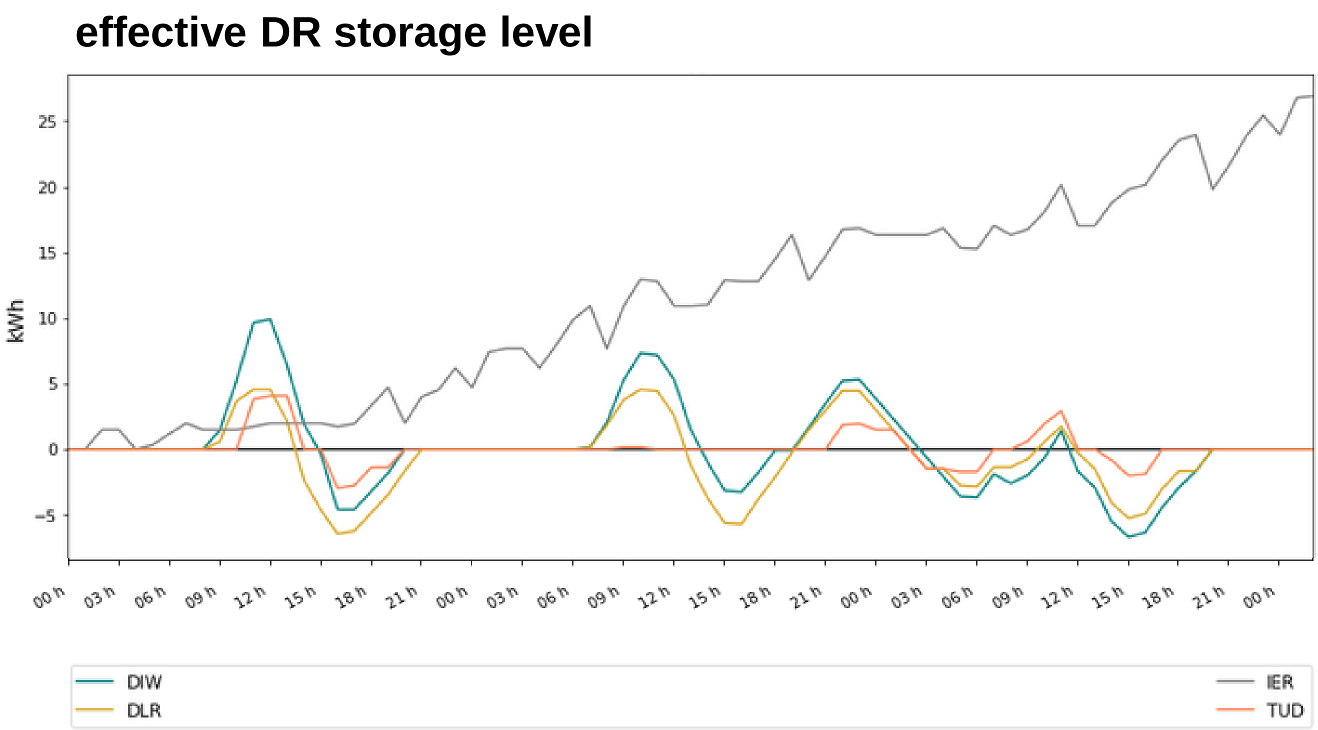
data sources: Gährs et al. (2020); Endres & Plessmann (2020)

Comparison of modeling approaches: **realistic example – dispatch results**



data sources: Gährs et al. (2020); Endres & Plessmann (2020)

Comparison of modeling approaches: **realistic example – DR utilization**



→ Similar pattern for **DIW** and **DLR**
→ **DIW** shows most activations
→ Smaller amplitude and fixed cycles for **TUD**
→ Constantly rising storage level for **IER** due to lacking an overall balancing requirement

data sources: Gährs et al. (2020); Endres & Plessmann (2020)

Conclusion on comparison of modeling approaches: **overall evaluation of approaches**

modeling approach	advantages	drawbacks
Zerrahn & Schill (2015) DIW	▪ parsimonious ▪ levels out almost all variations ▪ performs best as for objective value ▪ overall capacity limit	▪ no interference times & no further energy / storage level limit → overestimation on tendency ▪ behaviour of (optional) recovery constraint depends on demand pattern ▪ high computation times
Gils (2015) DLR	▪ explicitly shows balancing / mapping ▪ distinction between initial increase / decrease capability possible ▪ further restriction via energy limits / storage level limits ▪ sensitivity to additional energy limits low	▪ complexity of formulation ▪ missing overall capacity limit
Steurer (2017) IER	▪ parsimonious ▪ further restriction via energy limits ▪ computation is quite fast	▪ starting time points for load shifts needed → sensitive behavior; no overall balancing ▪ unbalanced shifts may occur → fixes used
Ladwig (2018) TUD	▪ limits within one day possible ▪ only one storage level ▪ further restriction via energy limits / storage level limits ▪ computationally efficient	▪ no levelling out of longer-term variations ▪ fixed storage cycles may prevent shifts → underestimation of potentials ▪ limits shifts to lie within the first timesteps

source: own collocation based on Zerrahn and Schill (2015a), pp. 842-844; Gils (2015), pp. 67-70; Steurer (2017), pp. 80-82; Ladwig (2018), pp. 90-93