Oemof user & developer meeting –
session on Demand Side Management (DSM) / Demand Response (DR)

Progress in demand response modelling

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Agenda

Background and motivation

doctoral thesis on technical and economical potential for demand response in Germany

not considered in the presentation

Macroeconomic scope

- General modelling approach: Using a **power market model** for
  - investment resp.
  - dispatch optimization for Germany

  implemented using oemof

- Need for an appropriate (linearized) **representation of demand response** (portfolios)

- Literature research:
  - Keen on how (slightly) **different modelling approaches** behave
  - → There seems to be no (systematic) comparison yet

Microeconomic case studies

- Assessing demand response potentials for some case studies
  - given load pattern
  - given cost structure

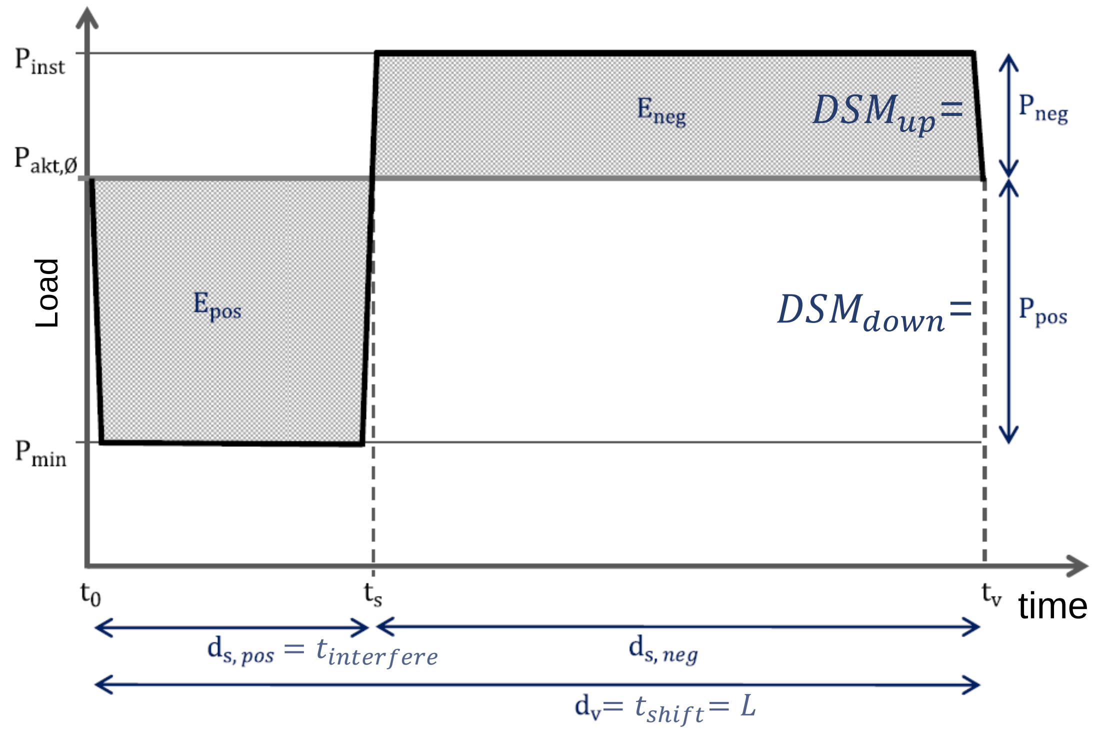
- Need for an appropriate (mixed-integer) **representation of demand response**

Demand response (DR) – small terminology

- Demand response ≈ Demand Side Management*
- Definitions of temporal terms for load shifting
  [according to Steurer (2017, p. 56), Gils (2015, pp. 13-14) as well as Zerrahn and Schill (2015a, p. 845)]

  – 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 $t_{interfere}$:
  Interference time of the load shifting in <u>one direction</u> (parameter)



* DSM often times includes energy efficiency measures in anglo-american context.
DR is limited to load flexibility.

Short Recap: DSM modelling approach currently implemented in the custom SinkDSM component

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

- DSM modelling approach from Zerrahn and Schill (2015):

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

(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 inceases 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

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

(3) Constraint for maximum downwards shift in hour tt

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

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

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

Agenda

Method: Comparison of DR modelling approaches

1. **Choice** of approaches

- used in fundamental models
- storage-alike approach (not price elasticities)
- description (constraints) given

2. **Characterization** of approaches

- identification of central characteristica
- similarities and differences

3. **Implementation** in oemof framework

- implementation as flexible Sinks
- role model: implementation of oemof.solph.custom.SinkDSM

4. **Comparison** of approaches

- Define criteria for comparison
  - formulation, performance, objective value, amount / structure of DR activations
- Steps applied for comparison
  - Set up a highly simplified toy energy system model
  - only once: write .lp-files / pprint model instance (plausibility check / statistics)
  - Visual inspection of DR results plot & compare results (sequences) DataFrames

Toy model architecture*

Stylized example	More realistic setting

Stylized example

- 48 (hourly) timesteps
- stylized „wind“ infeed and coal plant as backup
- Cases
  - Flat demand & constant generation
  - Variations in demand & constant generation
  - Variations in generation & constant demand
  - Variations in both generation and demand

More realistic setting

- 168 (hourly) timesteps
- pv and wind power infeed
- Household consumers and supermarkets in Wittenberg, Anhalt-Bitterfeld and Dessau-Roßlau from Gährs et al. (2020)
- demand data scaled has been scaled down ind Endres & Pleßmann (2020)

** The two notebooks by Julian Endres & Guido Pleßmann stored here has been build upon: https://github.com/windnode/SinkDSM_example*

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

Agenda

DSM modelling approaches evaluated

Modelling approach	Mapping of processes	Symmetric constraints	Capacity limit	Minimum load considered	Energy limit(s)	Balancing variables	DR storage level(s)	Yearly (energy) limit	Fixed shifting cycles
Zerrahn & Schill (2015) DIW	X		X	X					
Gils (2015) DLR		X	X	X	X	X	X (separate up / down)	X	
Steurer (2017) IER		X	X	X	X			X	
Ladwig (2018) TUD		X	X		X		X		X

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

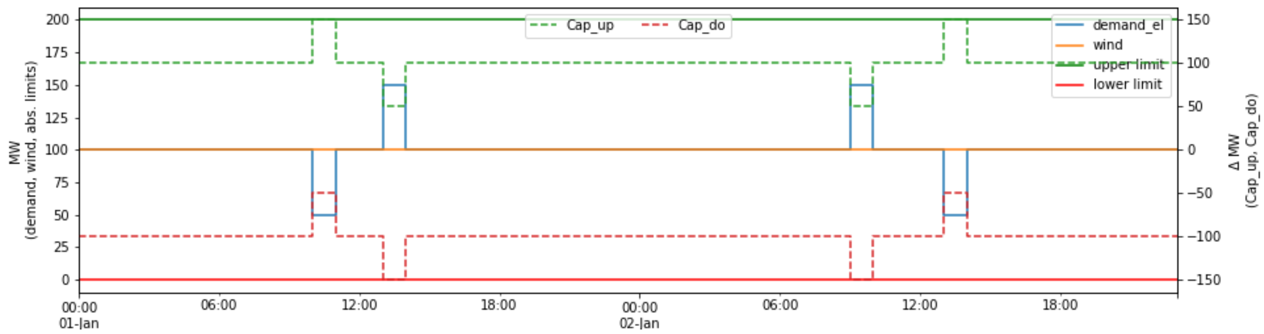
Comparison of modelling approaches: basic parameter settings

- **Overall model settings**
  - timesteps: 48 (hours)
  - Effective costs:
    - Coal plant: 32.5 (€/MWh) [13 €/MWh / 0.4]
    - Wind: 0
    - Excess: 1 (€/MWh)
    - Shortage: 200 (€/MWh)

- **Demand Response**
  - lower capacity limit: 0
  - upper capacity limit: 0
  - delay time: 4 (hours)
  - interference time (if applicable): 2 (hours) up / down
  - Costs (if applicable):
    - Overall: 0.1 (€/MWh)
    - Evenly attributed to upwards resp. downwards shift (each half of overall costs)

Introduction: demand response behaving as one would expect in a toy model with demand variations

- Toy model with demand variations



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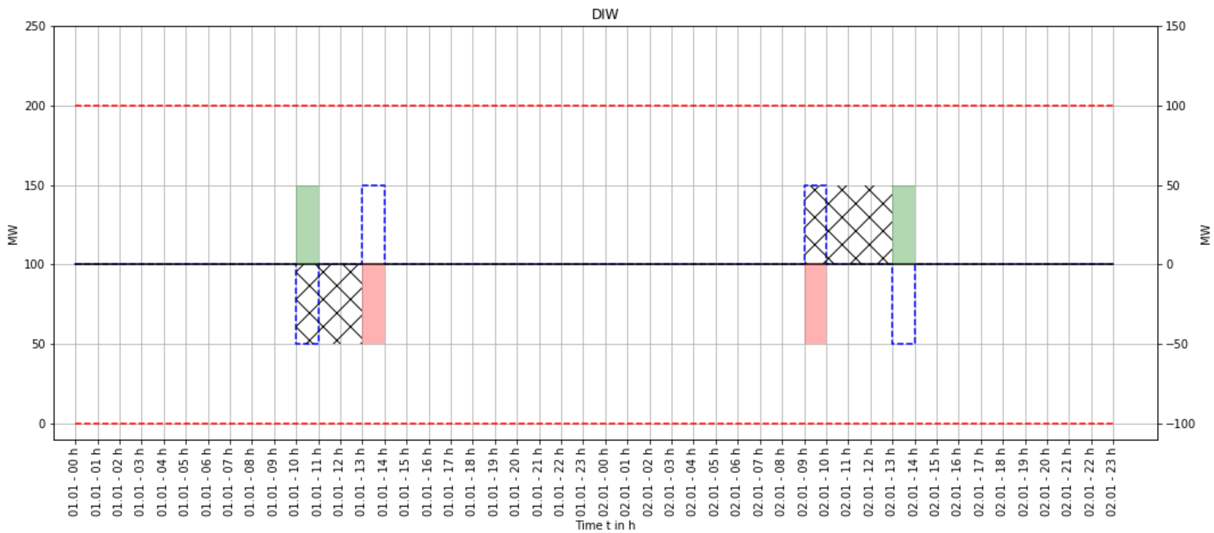
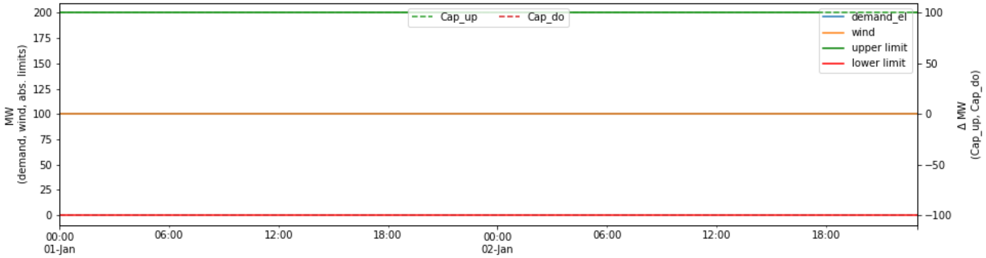


Comparison of modelling approaches: demand response patterns

- Toy model with flat demand & generation



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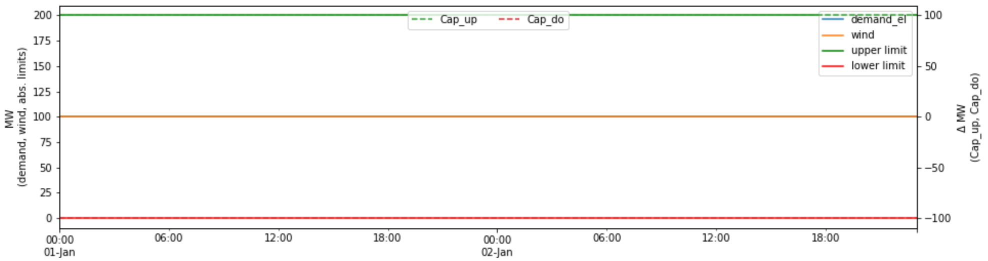

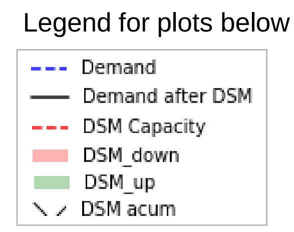

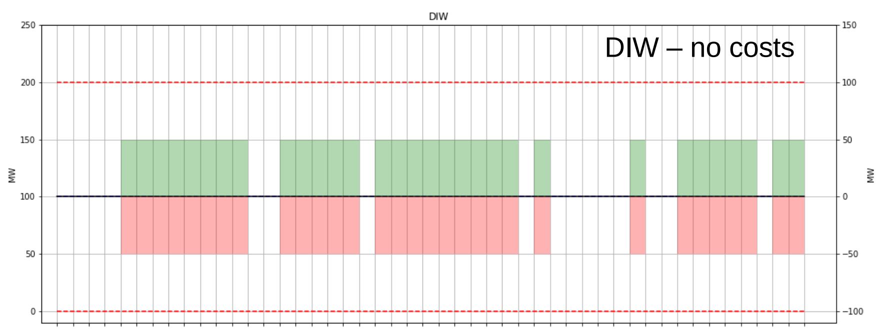

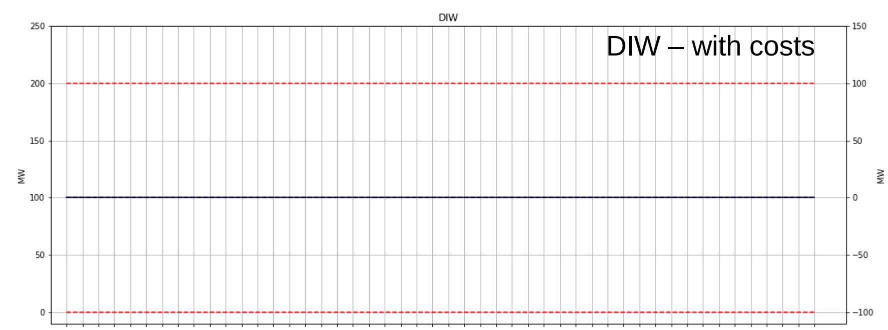

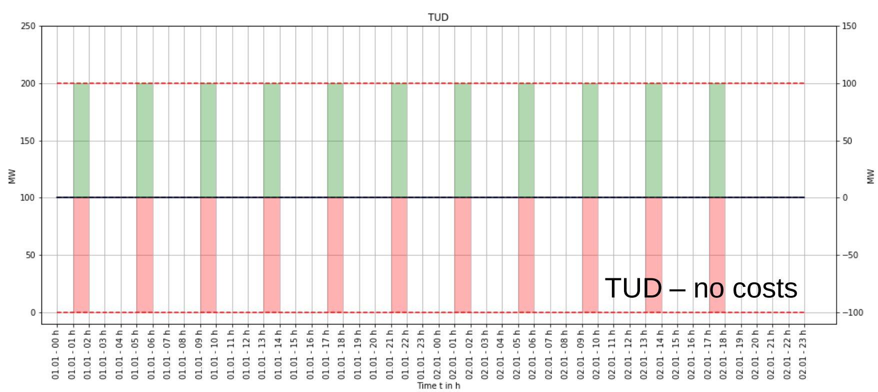

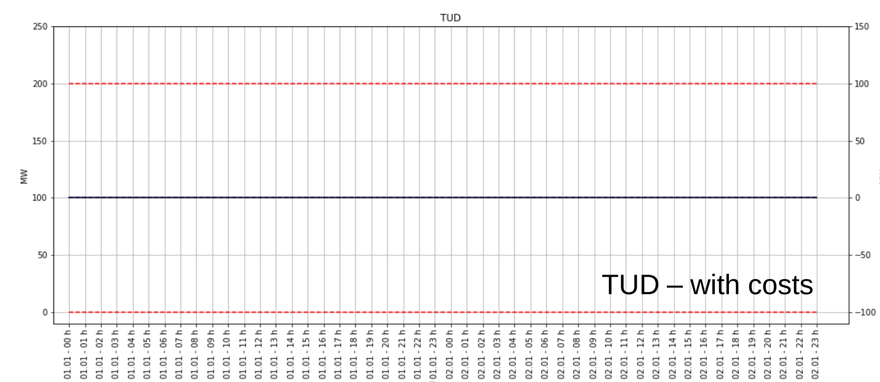

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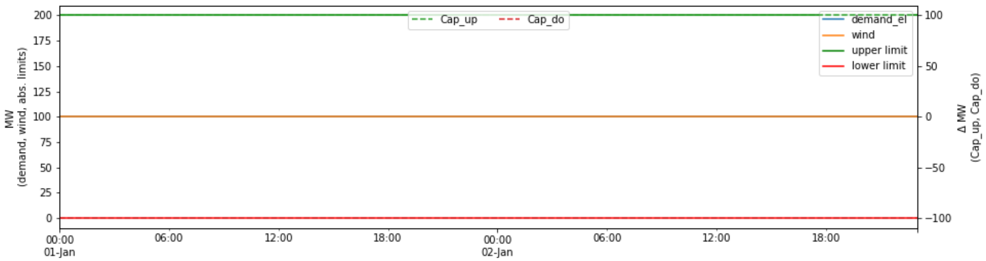

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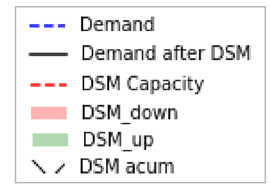
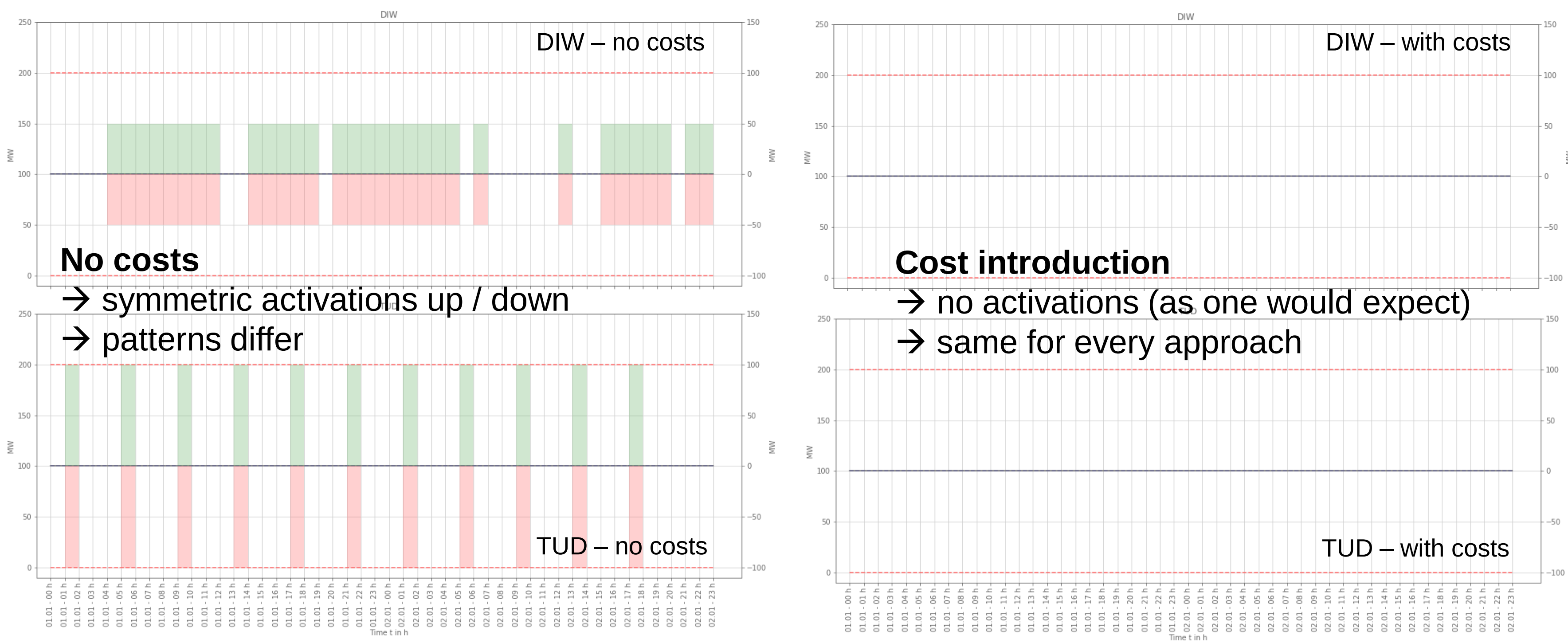


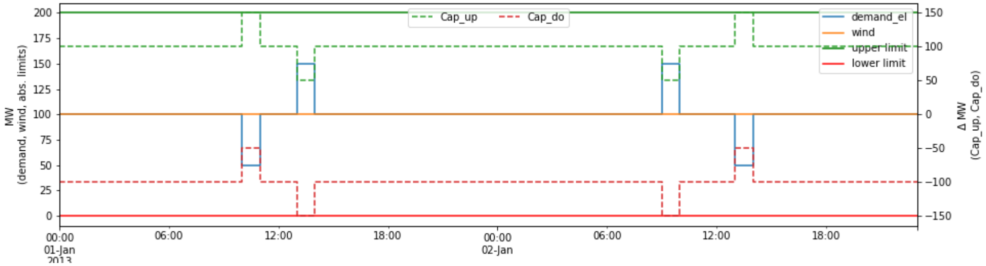


No costs
→ symmetric activations up / down
→ patterns differ

Cost introduction
→ no activations (as one would expect)
→ same for every approach

Comparison of modelling approaches: demand response patterns

- Toy model with demand variations



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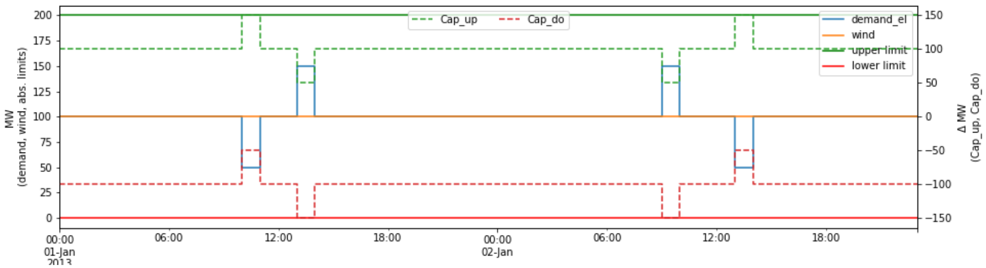

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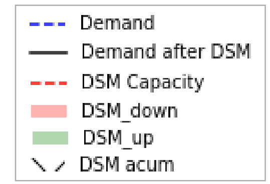

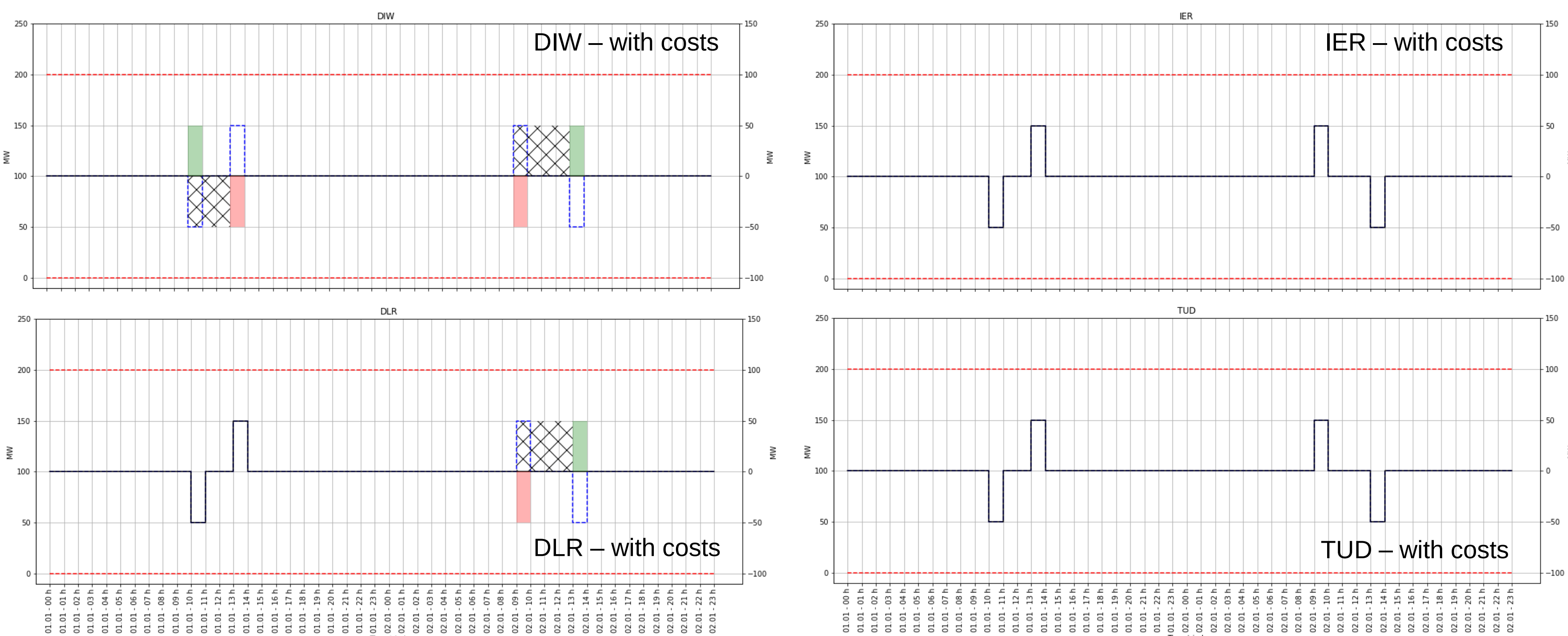

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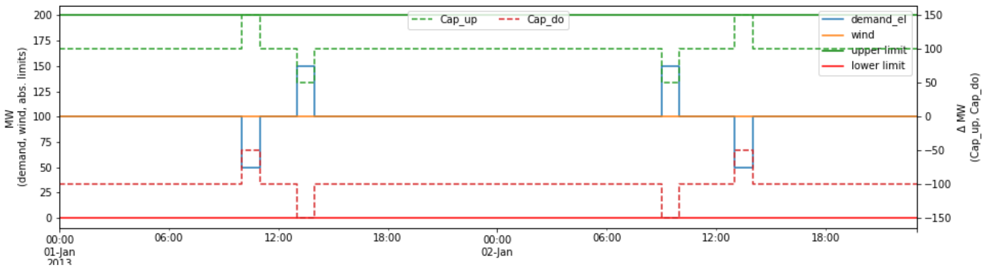

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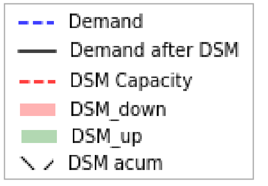

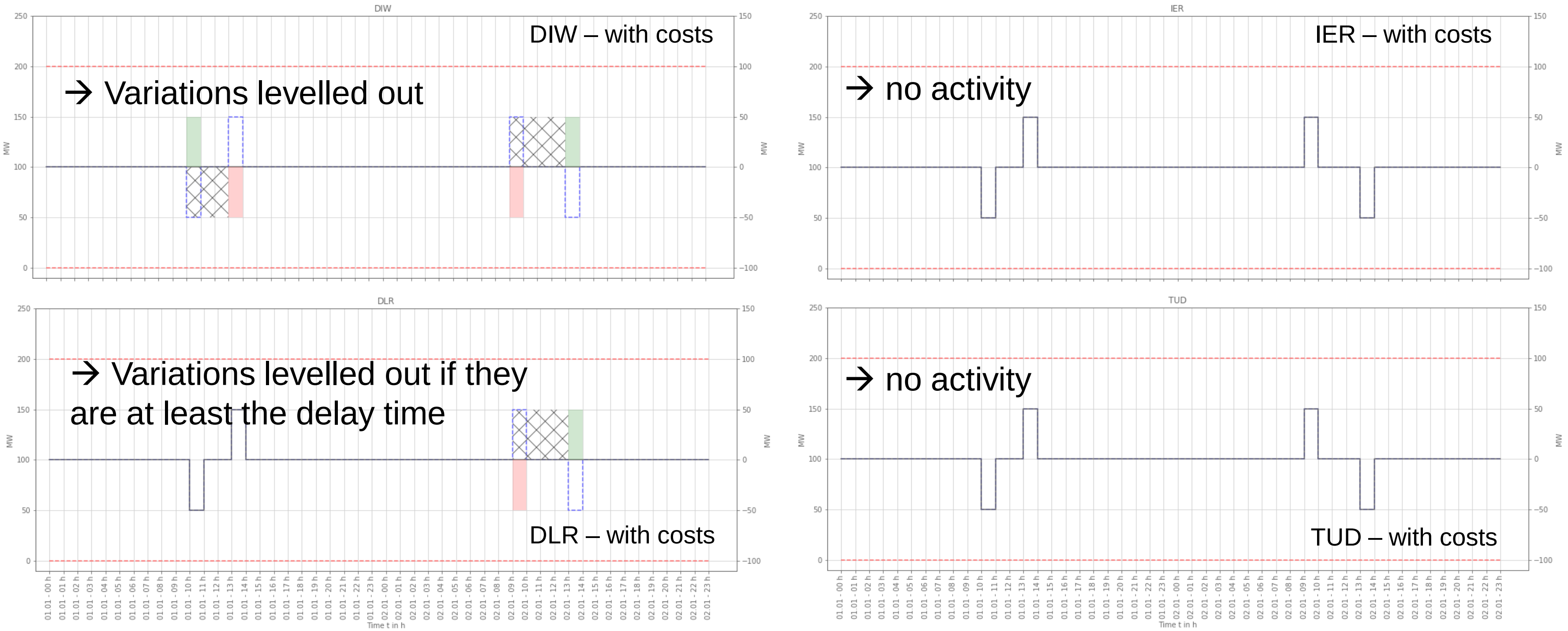

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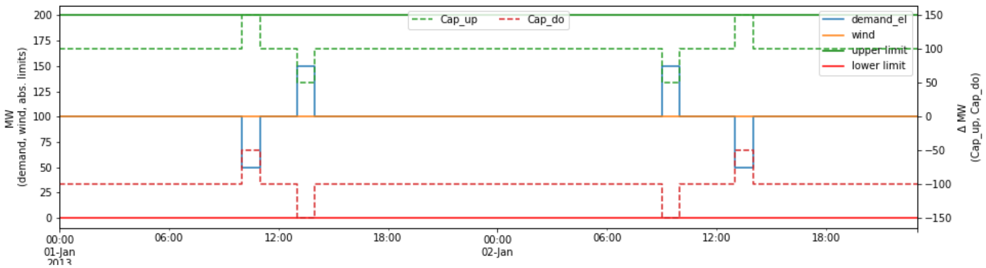

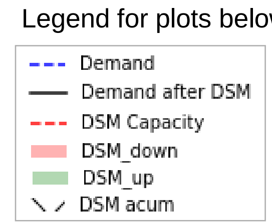

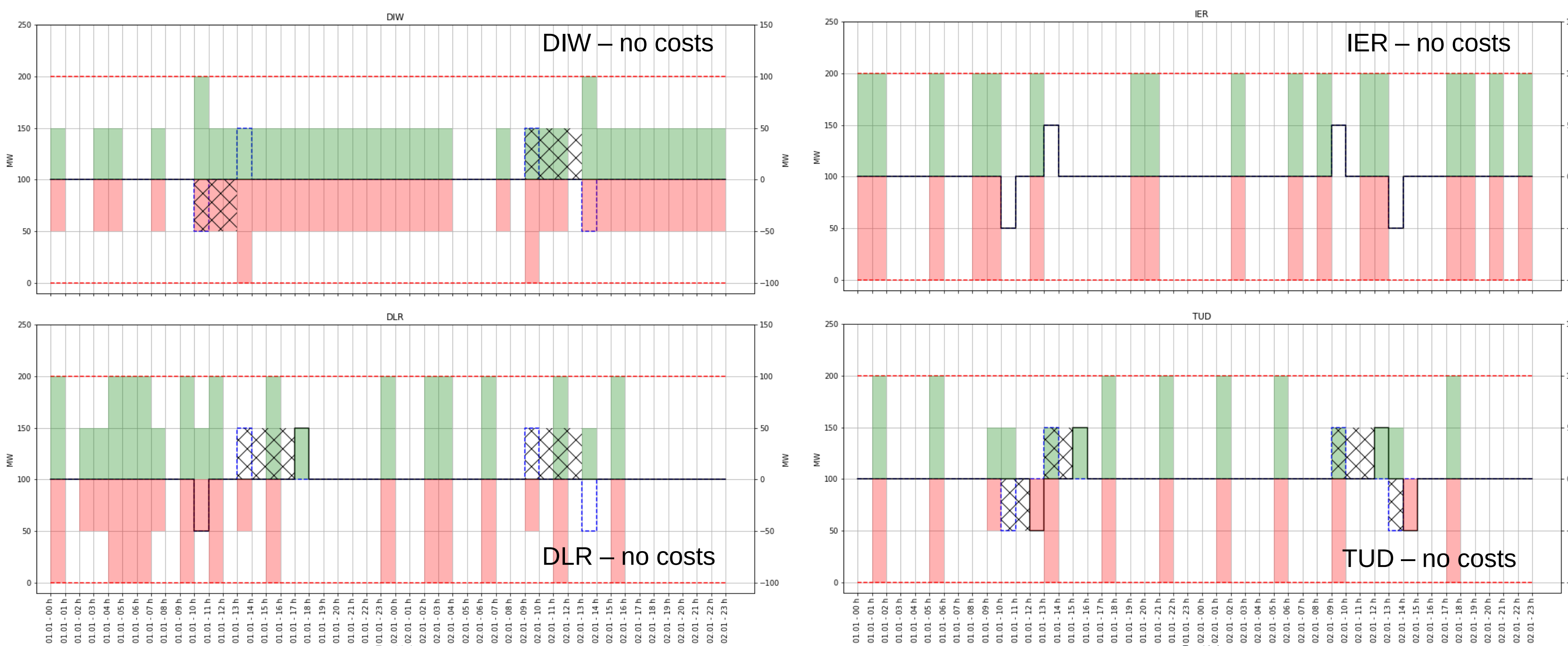

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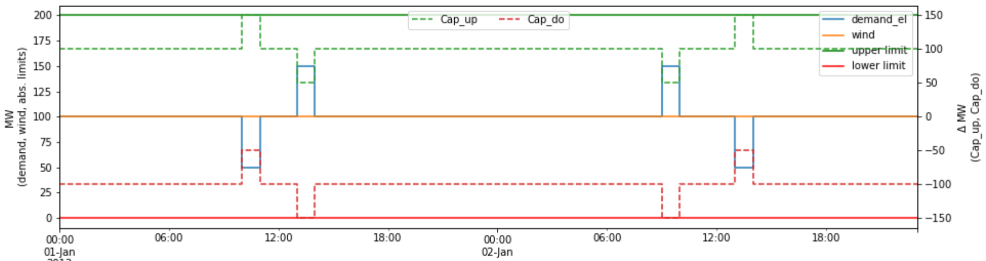

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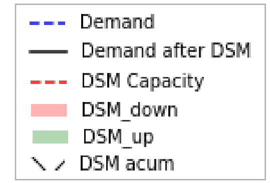
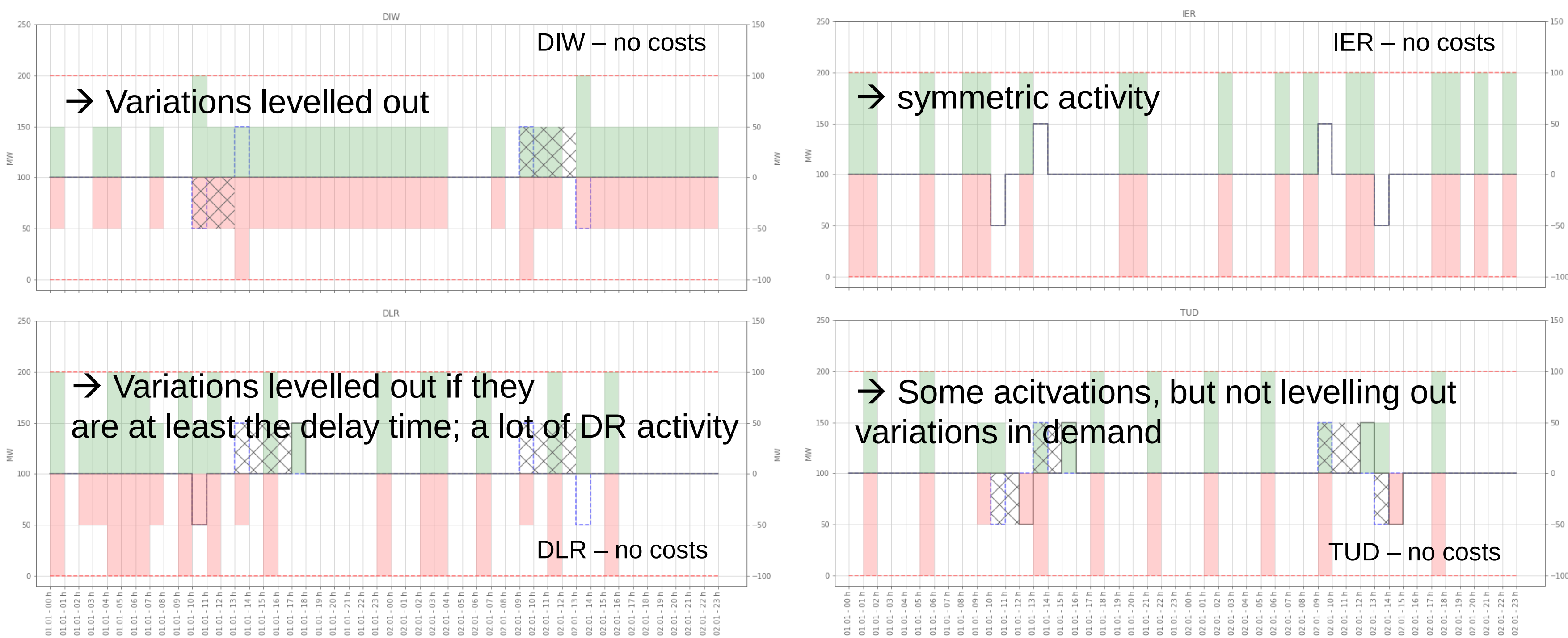
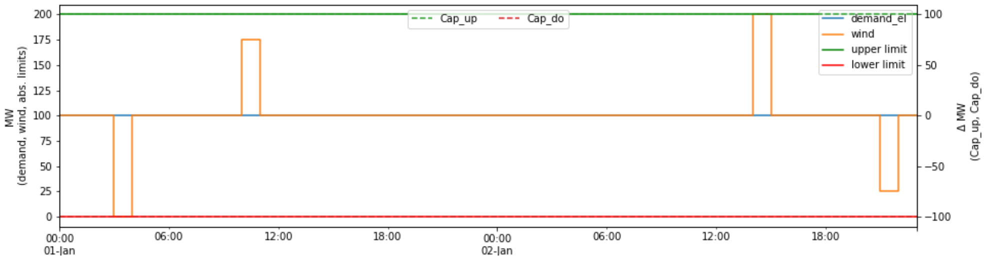




Comparison of modelling approaches: demand response patterns

- Toy model with generation variations



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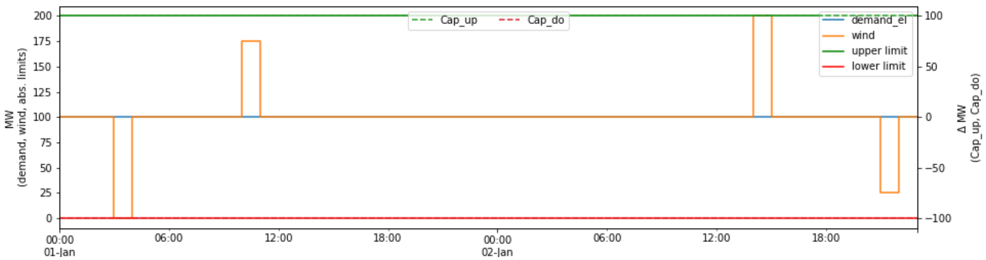

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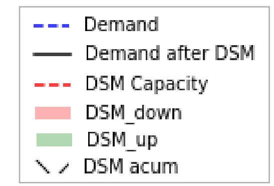

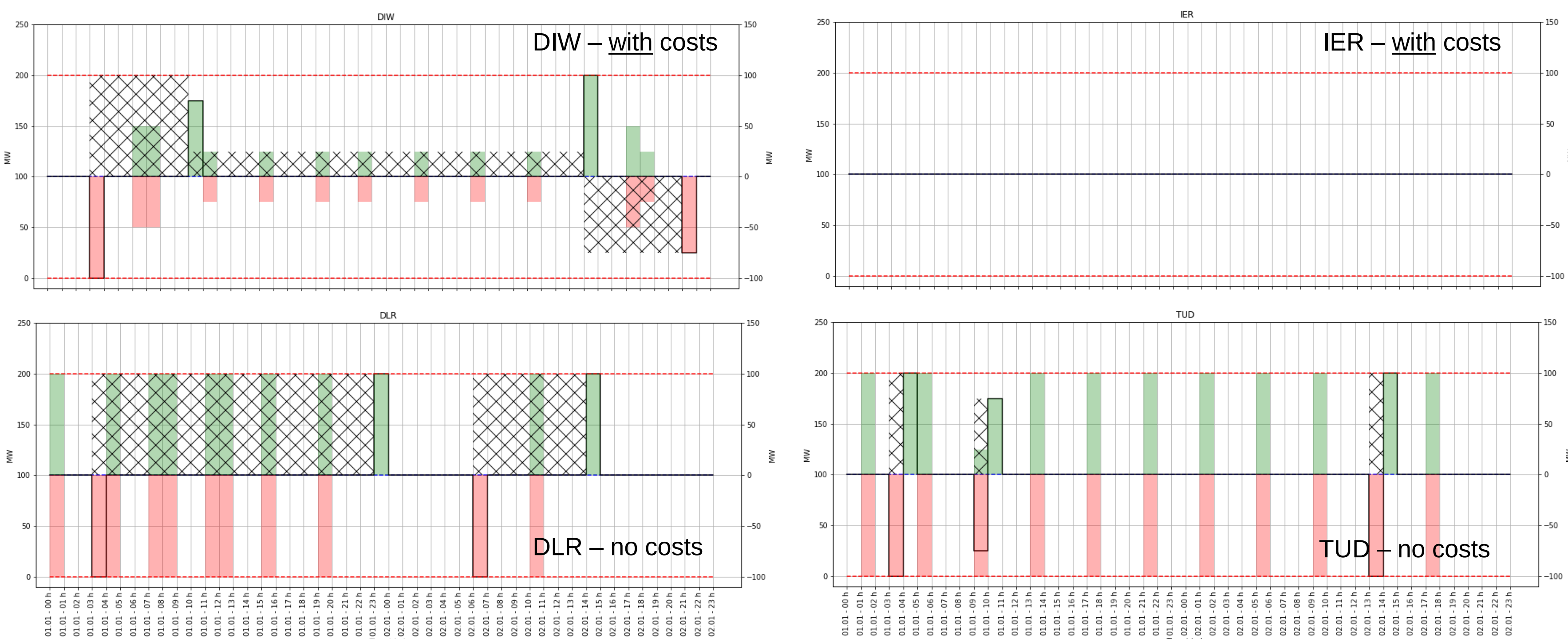

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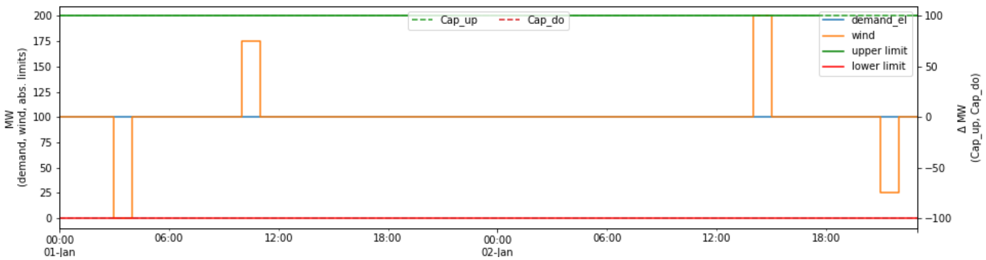

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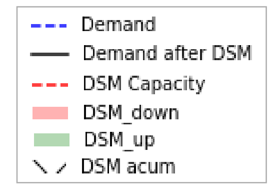

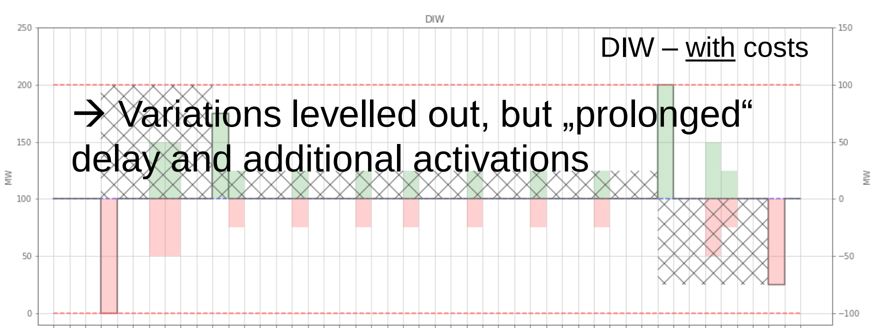

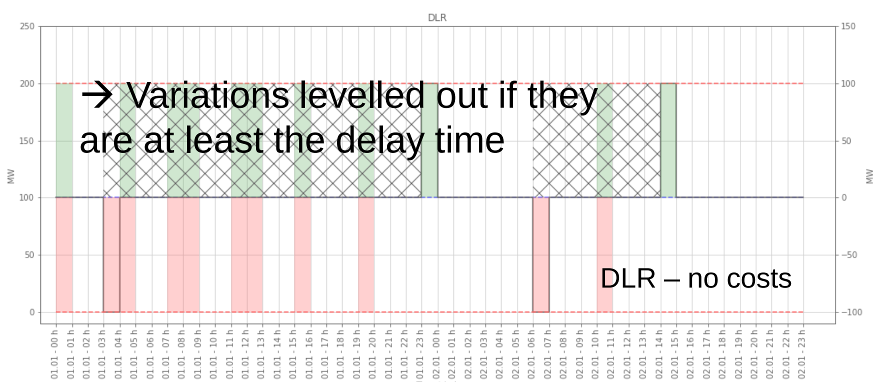

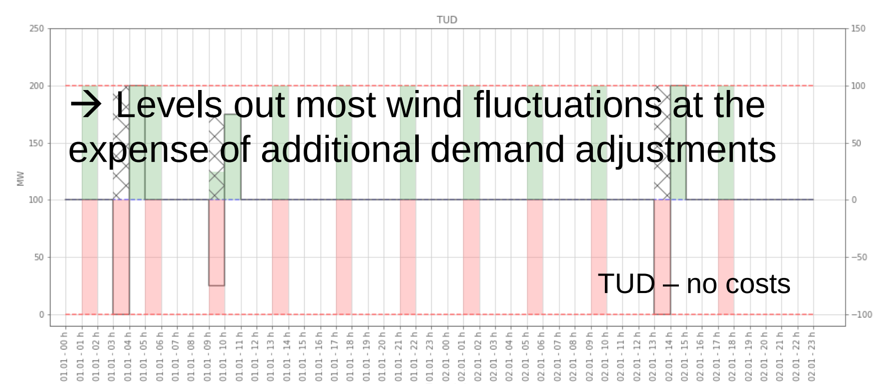

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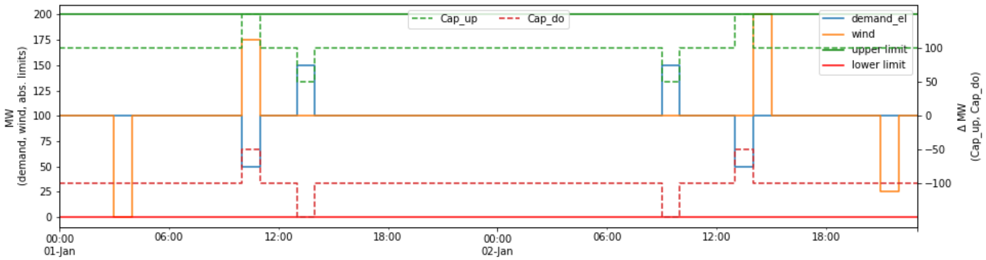

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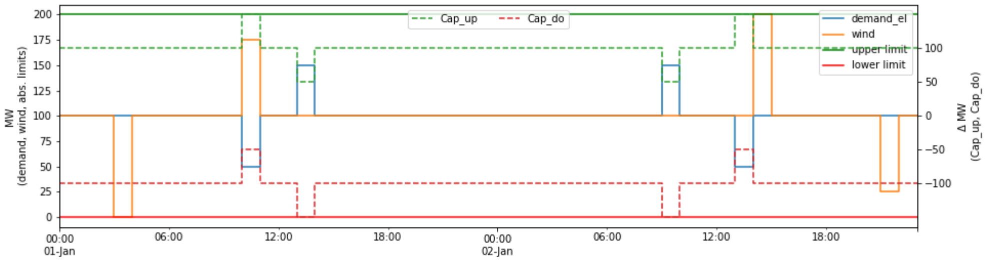

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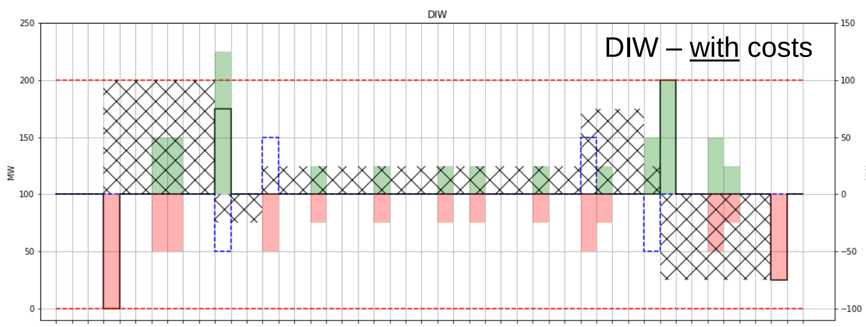

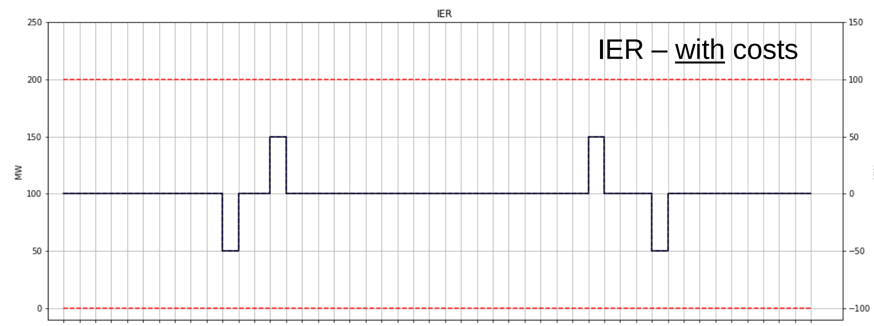

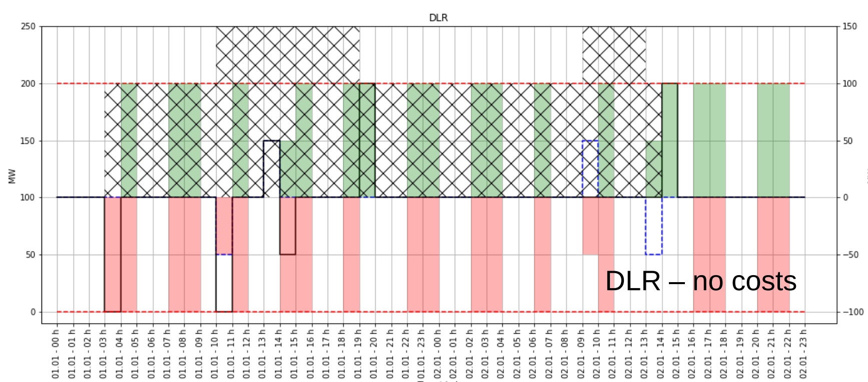

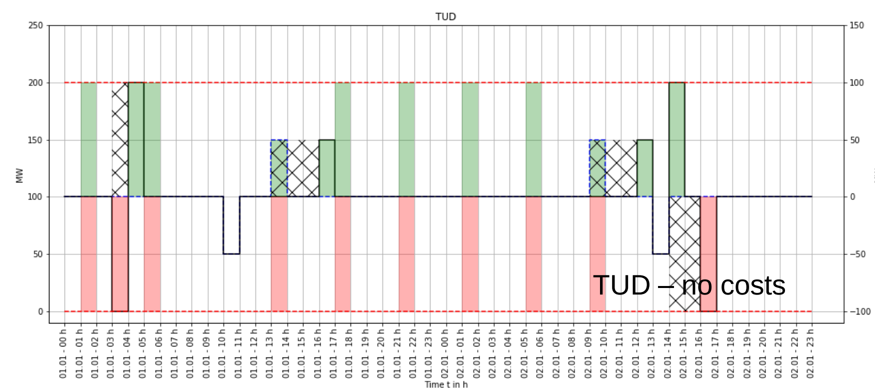

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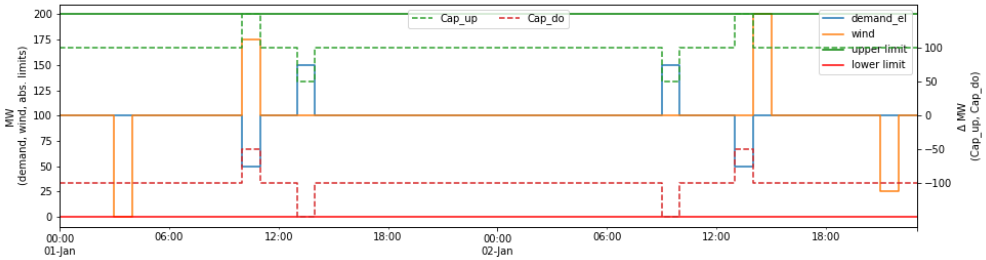

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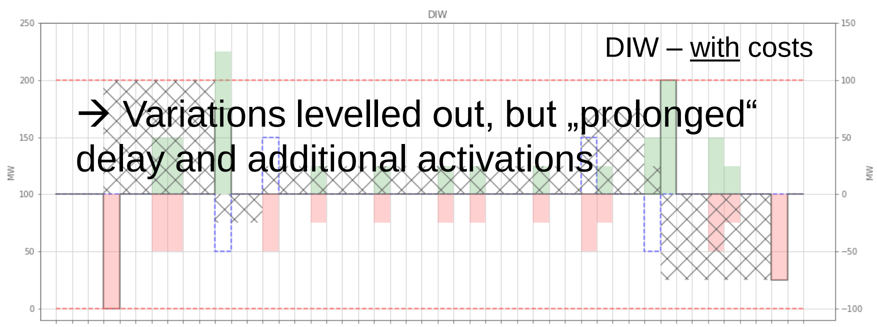
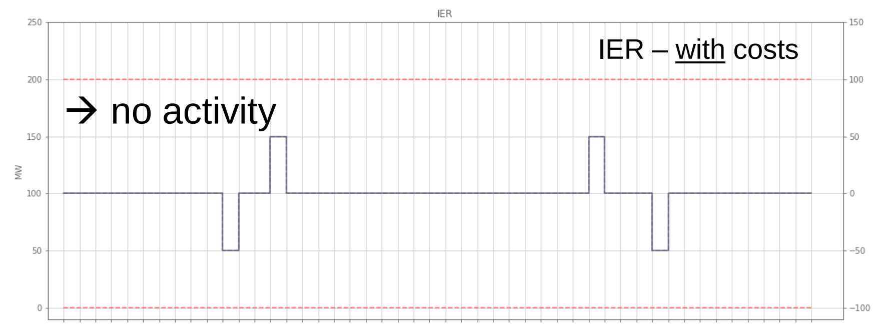
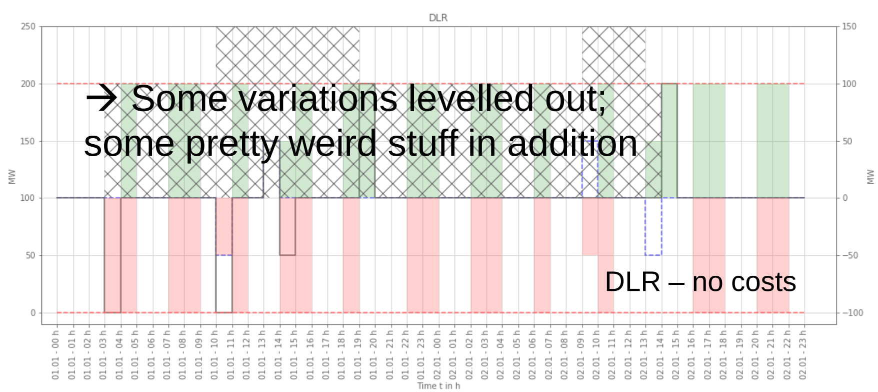
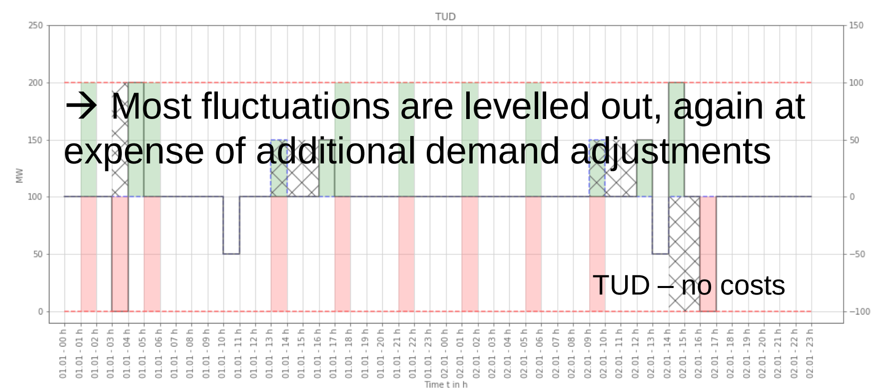
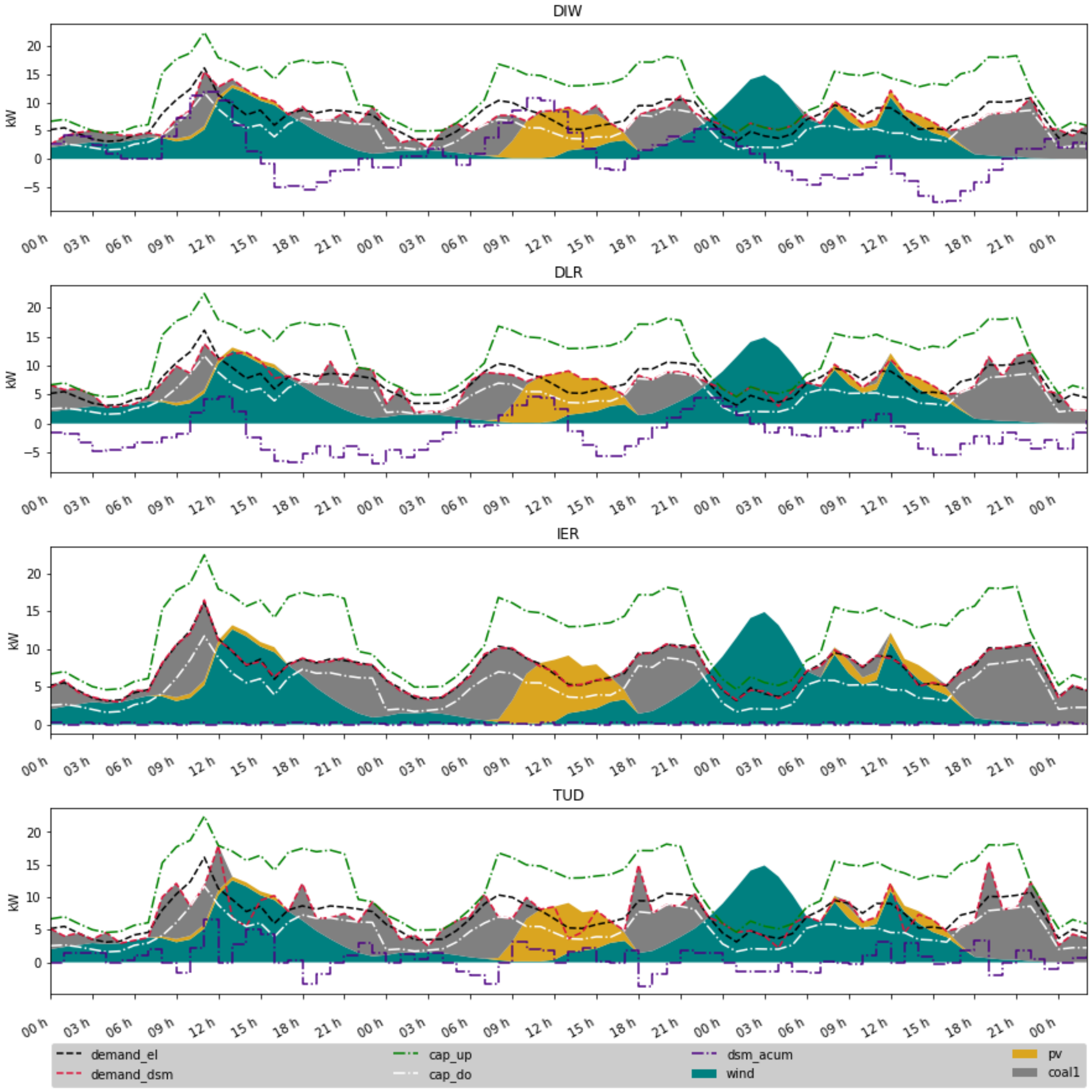








Comparison of modelling approaches: A more realistic setting (no costs for DR)



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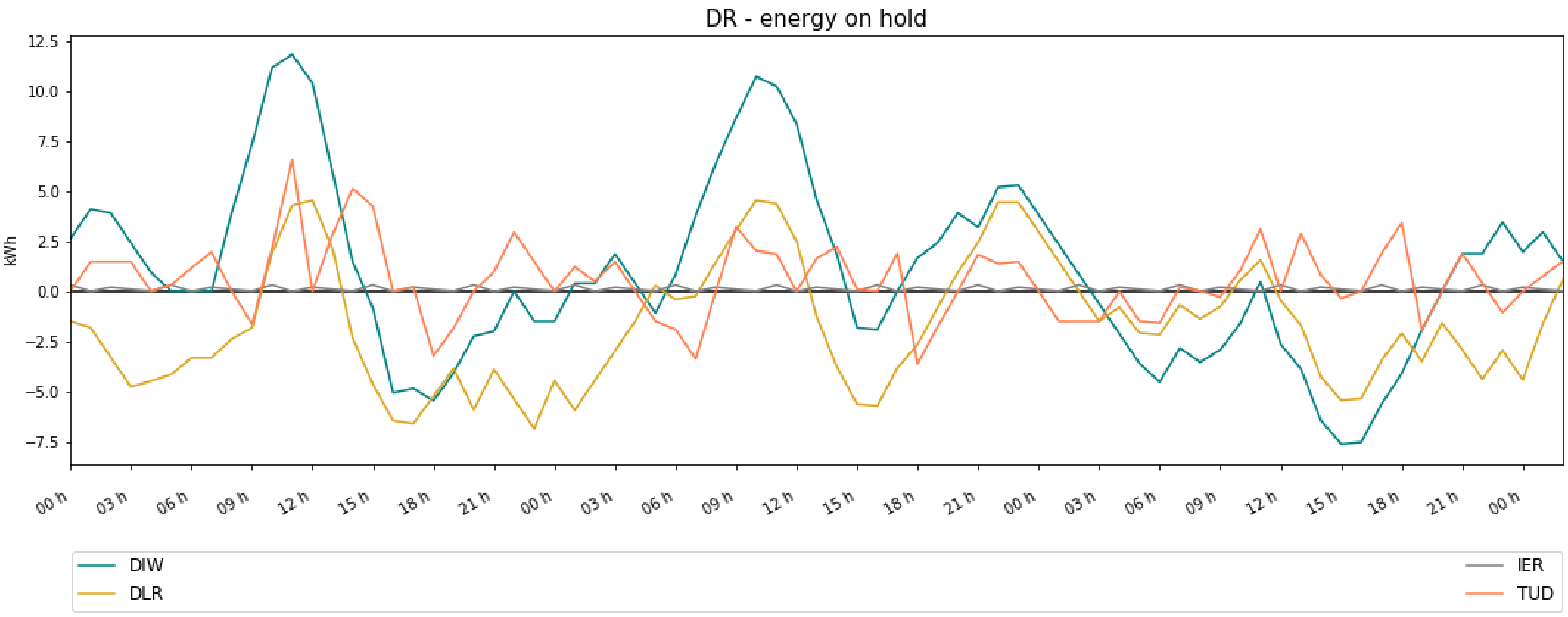


→ Similar patterns for DIW / DLR
→ Shorter cycles and lower peaks for TUD
→ Cycles with barely notable amplitude for IER

Comparison of modelling approaches: overall amount of activations

- Toy model with 48 timesteps & different configurations + realistic example

Approach	Costs	Toy Model - Demand variation	Toy Model - Generation variation	Toy Model - Combined variation	Realistic example
DIW	Yes	**200**	**350**	**550**	**222**
	No	200	350	550	309
DLR	Yes	100	0	100	163
	No	200	400	500	231
IER	Yes	0	0	0	23
	No	0	0	0	36
TUD	Yes	0	0	0	37
	No	**400**	**550**	**600**	**315**

Total amount: difference of downwards and upwards shift per timestep, summed up over all timesteps

→ No costs: DIW approach shows most activations
→ costs: TUD approach shows most activations

Comparison of modelling approaches: optimal objective

- Toy model; delay time = 4; (interference time = 2, if applicable); wind and generation varied at once
- Optimal objective values:

Approach	12 timesteps	24 timesteps	36 timesteps	48 timesteps
DIW	10,225	15,362.5	15,025	16,300
	100%	100%	100%	100%
DLR	10,225	15,362.5	15,862.5	19,650
	100%	100%	106%	121%
IER	15,200	22,900	27,587.5	40,587.5
	149%	149%	184%	249%
TUD	15,250	22,900	27,587.5	37,237.5
	149%	149%	184%	228%

– → DIW approach delivers best results; DLR is close to that
– → no activations for IER; barely any for TUD, though high savings could be achieved
– → further research needed here …

Comparison of modelling approaches: problem formulation

- Toy model with 24 timesteps; delay time = 4; (interference time = 2, if applicable)
- Number of demand response variables & constraints:

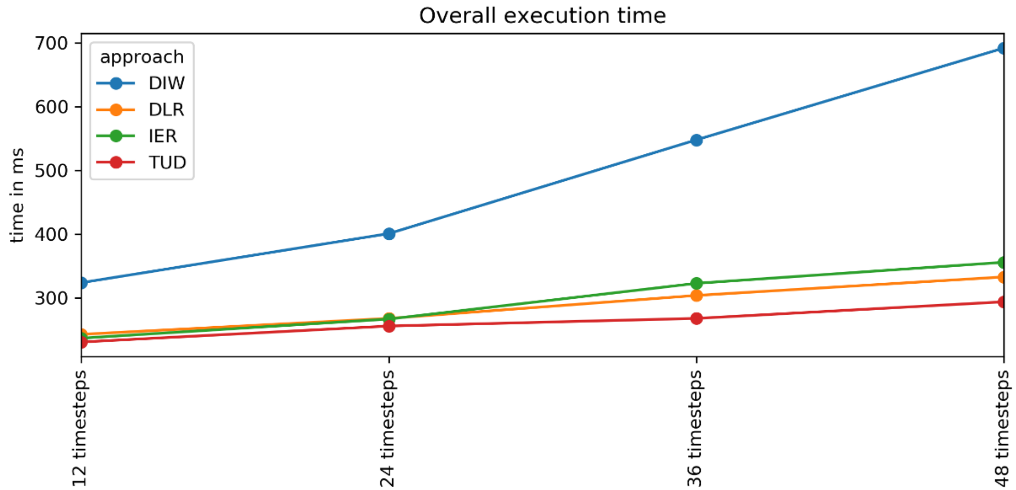
Approach	Variables	Constraints	Interlinkage (time)
DIW	2 Vars (1 * 24, 1 * 24 * 24)	5 Constraints (5 * 24)	Lots of interlinking sums
DLR	6 Vars (6 * 24)	11 Constraints (7 * 24, 2 * 20, 2 * 4)	Very few interlinking sums
IER	2 Vars (2 * 24)	8 Constraints (3 * 24, 2 * 20, 2 * 1)	Lots of interlinking sums
TUD	3 Vars (3 * 24)	7 Constraints (3 * 24, 2 * 23, 1 * 24/4, 1 * 1)	Few interlinking sums

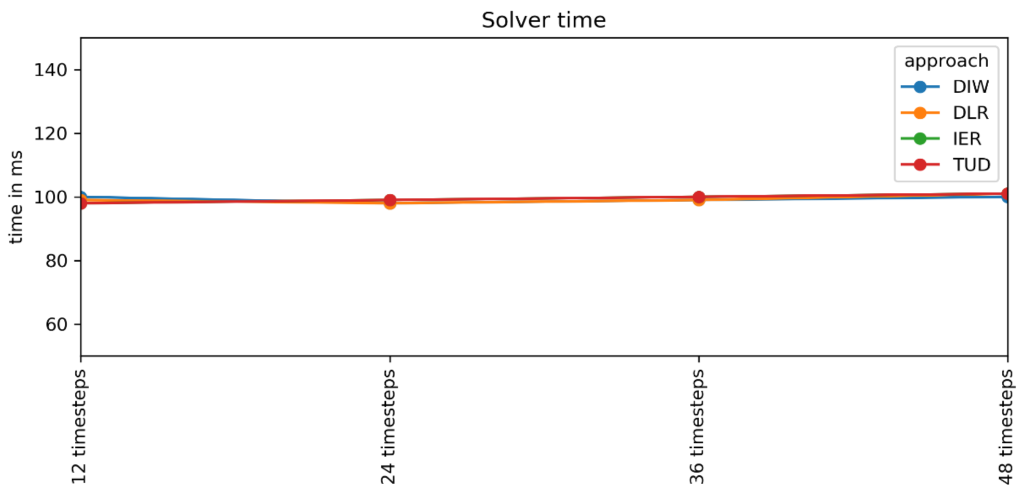
- Length of LP-files:
  - DIW: 2.144
  - DLR: 1.994
  - IER: 1.678
  - TUD: 1.395

Comparison of modelling approaches: model performance

- Toy model; delay time = 4; (interference time = 2, if applicable)

- Time for execution:
  - Processing is quite different
  - No noteable differences in solver time (very small examples)





Solver: solver time only (100 runs)

Overall: Build up, solve, dump/restore model and extract / process results (10 runs, 10 loops each)

Agenda

Preliminary Conclusion

Caution: Preliminary!

- Limitation
  - All that was shown is **work in progress**!
  - There are some effects which deserve some **more research**

- It is hard to interprete the results of highly stylized toy model configurations.
  - Some effects can clearly be seen
    - → e. g. the tendency to level out fluctuations in demand & generation
  - Some other effects seem „pretty random“.
    - → Such as extending delay times and shifts in the opposite direction one would expect.

- Quite hard to derive central tendencies since in general <u>all</u> approaches behave very sensitive to changes in parameterization, e.g. costs or delay time.
- But the following preliminary can be stated for the **approaches**:
  - **DIW approach** seems to be the most suitable / fits intuity best.
  - **DLR approach** leads to similar results than DIW approach if no costs are introduced.
  - **IER approach** shows barely any activations of demand response.
  - **TUD approach** shows some shifting cycles and manages to level out some fluctuations at the expense of additional peaks / reductions

Preliminary Conclusion

Caution: Preliminary!

- Shortcoming of all approaches: No information on how to deal with „special“ timesteps, i. e. usually the first resp. last ones.
  - → Finding appropriate solutions was quite some work and seems important for models with few timesteps.

- Additionally, some **general effects** can be identified:
  - Structural problem with setting time restrictions
    - → Ignore (DIW) or impose energy limits instead (all except for DIW)
  - Introduction of (at least small amounts of) variable costs seems to make sense in order to prevent an „overactivation“ of demand response measures, but here, the sensitivity of some approaches has to be taken care of.
  - Limiting overall DR capacity utilized seems to make sense
    - → e.g. equation 10 from Zerrahn & Schill (2015) (DIW) limiting the sum of up- and downwards shifts
    - → Reason: Elsewhise, the whole portfolio could be shifted in both directions simultaneously which does not make sense

Discussion

- **Architecture** of Components
  - (Planned) architecture in the first place:
    - Main component holding parameters
    - Load Shedding Block
    - Load Shifting Block → Inherits from Shedding Block; potentially overwrites
    - Load Shedding Investment Block
    - Load Shifting Investment Block
  - Difficulty / need for another approach:
    - One unit might be eligible for load shifting and load shedding at a time
    - A decision for one decreases the capacity for the other one
    - How to depict that? → Seems to only be properly adressed when everything is formulated in one block and different variables are used …
  - <u>Separate</u> (custom) component for each approach
    - → Expanding the methods attribute of existing solph.custom.SinkDSM would blow up the DSM component (in my opinion)
    - → not every single implementation has to be integrated into solph.custom since this might harm one oemof policy („*There is only one thing for a special purpose.*“)

Agenda

Outlook

- Next steps
  - **Continue benchmark**
    - Have a closer look at parameter sensitivities
    - Examine additional / optional constraints

  - **Integrate load shedding** measures
    - Constraints are given
    - architecture has to be defined (see discussion slide)
    - Basic difference to load shifting:
      - No upwards shifts
      - No balancing constraints

  - **Integrate investments** in demand response → Existing components will serve as a role model.

- Parameterization and tests in a broader setting
  - Demand response measures will be evaluated in an overall German power market model.
  - Therefore, a parameterization of demand response will be used which is based on the results of a meta-analysis (Kochems 2020)

Source: Kochems (2020)

Sources

- Gartner, Mathias (2018): Entwicklung eines monetären Bewertungsverfahrens für Einsparungen durch Nachfrageflexibilisierung im Stromsektor, Freie wissenschaftliche Arbeit zur Erlangung des Grades Master of Science am Fachgebiet Energie- und Ressourcenmanagement der TU Berlin, Berlin.
- Gils, Hans Christian (2015): Balancing of Intermittent Renewable Power Generation by Demand Response and Thermal Energy Storage. Dissertation. Universität Stuttgart, Stuttgart.
- 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; 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.
- Zerrahn, Alexander; Schill, Wolf-Peter (2015b): A Greenfield Model to Evaluate Long-Run Power Storage Requirements for High Shares of Renewables. In: *SSRN Journal*. DOI: 10.2139/ssrn.2591303.

Technische Universität Berlin

Oemof user & developer meeting –
session on Demand Side Management (DSM) / Demand Response (DR)

Progress in demand response modelling - Appendix

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14 May 2020

E&R Energie und Ressourcen

Comparison of modelling approaches: performance

- Toy model; delay time = 4; (interference time = 2, if applicable)
- Time for execution:

Approach	Time	12 timesteps	24 timesteps	36 timesteps	48 timesteps
DIW	Solver	100 ms ± 17.51 ms	98 ms ± 14.39 ms	99 ms ± 13.37 ms	100 ms ± 13.18 ms
	Overall	324 ms ± 19.4 ms per loop	401 ms ± 5.68 ms per loop	548 ms ± 22.2 ms per loop	692 ms ± 10.3 ms per loop
DLR	Solver	99 ms ± 15.75 ms	98 ms ± 13.99 ms	99 ms ± 13.35 ms	101 ms ± 12.99 ms
	Overall	243 ms ± 25.1 ms per loop	268 ms ± 20.4 ms per loop	304 ms ± 26.4 ms per loop	333 ms ± 9.24 ms per loop
IER	Solver	98 ms ± 15.75 ms	99 ms ± 13.95 ms	100 ms ± 13.03 ms	101 ms ± 12.69 ms
	Overall	237 ms ± 11 ms per loop	267 ms ± 17.4 ms per loop	323 ms ± 16.8 ms per loop	356 ms ± 9.96 ms per loop
TUD	Solver	98 ms ± 15.24 ms	99 ms ± 13.91 ms	100 ms ± 13.38 ms	101 ms ± 12.61 ms
	Overall	231 ms ± 16.6 ms per loop	256 ms ± 10.4 ms per loop	268 ms ± 6.47 ms per loop	294 ms ± 5.42 ms per loop

Solver: solver time only (100 runs)
Overall: Build up, solve, dump/restore model and extract / process results (10 runs, 10 loops each)

Appendix: Modelling approaches considered in detail

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

- Gils (2015, pp. 67-70)
- Steurer (2017, pp. 80-82)
- Ladwig (2018, pp. 90-93)

are layed down.

DR modelling approach in Gils (2015) (1/2)

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):

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

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

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

$$\boldsymbol{P^{t}_{reduction}} + \boldsymbol{P^{t}_{balanceInc}} \leq P_{existCap} \cdot s^{t}_{flex} \quad \forall t \in T$$

$$\boldsymbol{P^{t}_{increase}} + \boldsymbol{P^{t}_{balanceRed}} \leq P_{existCap} \cdot s^{t}_{free} \forall t \in T$$

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

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

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

source: Gils (2015); simplified / own additions; no investments, no shifting sets

DR modelling approach in Gils (2015) (2/2)

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:

$$\boldsymbol{W^t_{levelRed}} = \Delta \boldsymbol{t} \cdot \left(\boldsymbol{P^t_{reduction}} - \boldsymbol{P^t_{balanceRed}} \cdot \eta_{DR}\right) \quad for\ t = 0$$

$$\boldsymbol{W^t_{levelInc}} = \Delta \boldsymbol{t} \cdot \left(\boldsymbol{P^t_{increase}} \cdot \eta_{DR} - \boldsymbol{P^t_{balanceInc}}\right) \quad for\ t = 0$$

$$\Delta \boldsymbol{t} \cdot \left(\boldsymbol{P^t_{reduction}} - \boldsymbol{P^t_{balanceRed}} \cdot \eta_{DR}\right) \leq \boldsymbol{W^t_{levelRed}} - \boldsymbol{W^{t-1}_{levelRed}} \quad \forall t \in [1..T]$$

$$\Delta \boldsymbol{t} \cdot \left(\boldsymbol{P^t_{increase}} \cdot \eta_{DR} - \boldsymbol{P^t_{balanceInc}}\right) \leq \boldsymbol{W^t_{levelInc}} - \boldsymbol{W^{t-1}_{levelInc}} \quad \forall t \in [1..T]$$

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

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

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

  - Limit for the total amount of energy shifted annually (DR_10) and (DR_11) (optional):

$$\sum_t \boldsymbol{P^t_{reduction}} \leq P_{existCap} \cdot \bar{s}^t_{flex} \cdot t_{interfere} \cdot n_{yearLimit} \quad \forall t \in T$$

$$\sum_t \boldsymbol{P^t_{increase}} \leq P_{existCap} \cdot \bar{s}^t_{free} \cdot t_{interfere} \cdot n_{yearLimit} \quad \forall t \in T$$

source: Gils (2015); simplified / own additions; no investments, no shifting sets

DR modelling approach in Steurer (2017) (1/2)

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

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

$$\boldsymbol{P_{pos}^{t}} \leq P_{max} \cdot f_{v,pos}^{t} \quad \forall t \in T$$

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

  - DR balance for each shifiting cycle (DR_2):

$$\sum_{t}^{t+d_V} \boldsymbol{p_{pos}^{t}} = \sum_{t}^{t+d_V} \boldsymbol{p_{neg}^{t}} \cdot \eta \quad \forall t \in [0..T-d_v]$$

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

$$\sum_{t}^{t+d_V} \boldsymbol{P_{pos}^{t}} \leq d_S \cdot P_{max} \quad \forall t \in [0..T-d_v]$$

$$\sum_{t}^{t+d_V} \boldsymbol{P_{neg}^{t}} \leq d_S \cdot P_{max} \quad \forall t \in [0..T-d_v]$$

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

DR modelling approach in Steurer (2017) (2/2)

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

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

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

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

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

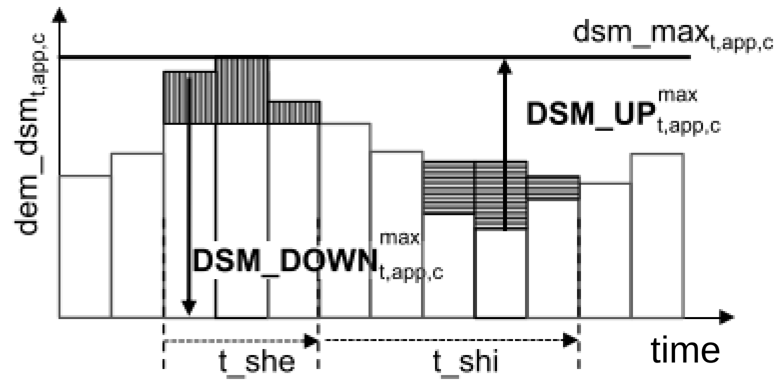
$$\boldsymbol{p_{pos}^{t}} + \boldsymbol{p_{neg}^{t}} \leq P_{max} \cdot f_{v}^{t} \quad \forall t \in T$$

DR modelling approach in Ladwig (2018) (1/2)

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

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

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



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

  - 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

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

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

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

  - 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 modelling approach in Ladwig (2018) (2/2)

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

- 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

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

  - DR_4: Daily limit for load shedding (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

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

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

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

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