oemof developer meeting –
session on Demand Side Management (DSM)

Plans on further development for the oemof DSM component(s)

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Background and motivation

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

Macroeconomic scope	Microeconomic case studies
▪ General modelling approach: Using a **power market model** for – investment resp. – dispatch optimization for Germany implemented using oemof	▪ Assessing demand response potentials for some case studies – given load pattern – given cost structure
▪ Need for an appropriate (linearized) **representation of demand response** (portfolios)	▪ Need for an appropriate (mixed-integer?) **representation of demand response** (using oemof for this purpose?)
▪ Literature research: – Keen on how (slightly) different modelling approaches behave – → There seems to be no (systematic) comparison yet	

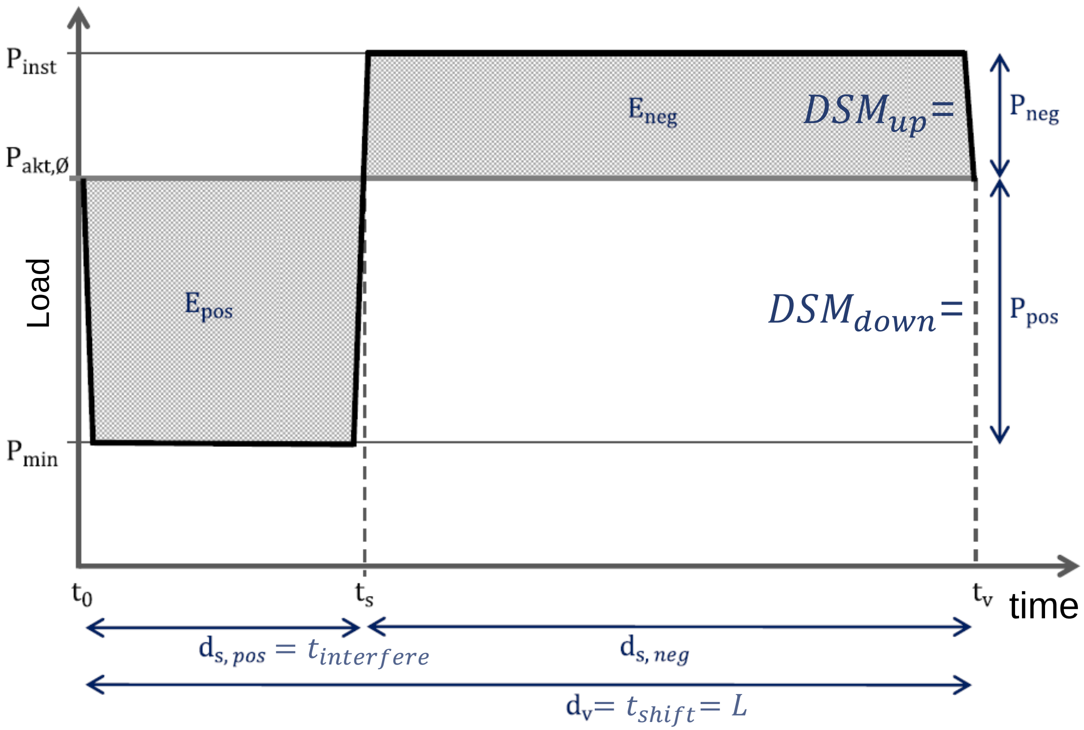
Demand response – small terminology

- 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)

  – Accumulated interference time d_{kum} (not shown):
    Number of hours in one year for which load shiftings can be performed (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 DSM component

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- 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

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

(2) Constraint for maximum upwards shift

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

(3) Constraint for maximum downwards shift

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

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

source: Zerrahn und Schill (2015a)

Planned contributions (1) – investment in DSM and distinction of load shifting and load shedding

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- Extending the new oemof DSM component (based on Zerrahn and Schill 2015a) by **investment** consideration and introducind a distinction between load shifting and load shedding
  - Implementation described for the energy system model DIETER (Zerrahn and Schill 2015b)
  - Basically add a target function term:

$$+\sum_{lc}\left(c_{lc}^{inv}+c_{lc}^{fix}\right)\cdot \boldsymbol{DSM_{lc}^{cap}}+\sum_{ls}\left(c_{ls}^{inv}+c_{ls}^{fix}\right)\cdot \boldsymbol{DSM_{ls}^{cap}}$$

lc: set of load shedding units (load curtailment)
ls: set of load shifting units

Exemplary / work in progress!

```python
def _objective_expression(self):
    r""" Objective expression with fixed and investement costs.
    """
    if not hasattr(self, 'INVESTDR'):
        return 0

    investment_costs = 0

    for n in self.INVESTDR:
        if n.investment.ep_costs is not None:
            investment_costs += self.invest[n] * n.investment.ep_costs
        else:
            raise ValueError("Missing value for investment costs!")

    self.investment_costs = Expression(expr=investment_costs)

    return investment_costs
```

  - Modelling **load shedding**:
    - No upwards shifts
    - No balance constraints
    - Recovery time may be introduced (same as for load shifting)

source: Zerrahn and Schill (2015b)

Planned contributions (2) – comparing (slightly) different demand response implementations

- Modelling approaches given in
  - Zerrahn and Schill (2015a) → baseline (given in the current custorm DSM component)
  - Gils (2015) → introducing a **fictious DR storage levels (for both directions)**; considering an **energy shift limit per year**
  - Steurer (2017) → very similar to Zerrahn and Schill (2015a), but not mapping processes to another (constraint for every direction); considering an energy shift limit per year
  - Ladwig (2018) → similar to Gils (2015); only one **DR storage level**; **load increase (PtX)** modelled in addition

- Question: Do these different modelling approaches lead to…
  - …significant differences in model complexity / solution times?
  - …significant differences in model outcomes using the same parametrization?

- Approach
  - Implementing the different approaches in the same way as the existing DSM component has been (work in progress)
  - Testing them in a toy power system (work in progress)
  - Testing them in a „real“ power system (planned)

Planned contributions (2) – comparing (slightly) different demand response implementations

```
class SinkDrShift(solph.Sink):
    """..."""

    def __init__(self, demand, P_exist, s_flex, s_free, t_shift, t_interfere,
                 *args, **kwargs):
        super().__init__(*args, **kwargs)

        self.P_exist = P_exist
        self.s_flex = solph_sequence(s_flex)
        self.s_free = solph_sequence(s_free)
        self.t_shift = t_shift
        self.t_interfere = t_interfere
        self.efficiency = kwargs.get('efficiency', 1.0)
        self.demand = solph_sequence(demand)
```

Exemplary / work in progress!

```
# Equation 4.8
def energy_balance_red_rule(block):
    """
    Load reduction must be balanced by load increase within t_shift
    """
    for t in m.TIMESTEPS:
        for g in group:

            if t >= g.t_shift:
                # balance load reduction
                lhs = self.P_balanceRed[g, t]
                # load reduction (efficiency considered)
                rhs = self.P_reduction[g, t - g.t_shift] / g.efficiency
                # add constraint
                block.energy_balance_red.add((g, t), (lhs == rhs))
```

```
#  ************* SETS *********************************

# Set of DR Components
self.DR = Set(initialize=[n for n in group])

#  ************* VARIABLES ******************************

# Variable load shift down (MW)
self.P_reduction = Var(self.DR, m.TIMESTEPS, initialize=0, within=NonNegativeReals)

# Variable load shift up (MW)
self.P_increase = Var(self.DR, m.TIMESTEPS, initialize=0, within=NonNegativeReals)
```

Rough timeline:
- finish implementation until Jan or Feb/2020
- Do first tests in Jan and Feb/2020
- Tests in a more realistic setting from Feb/2020 on

source: some code snippets of own implementation for modelling apporach from Gils (2015)

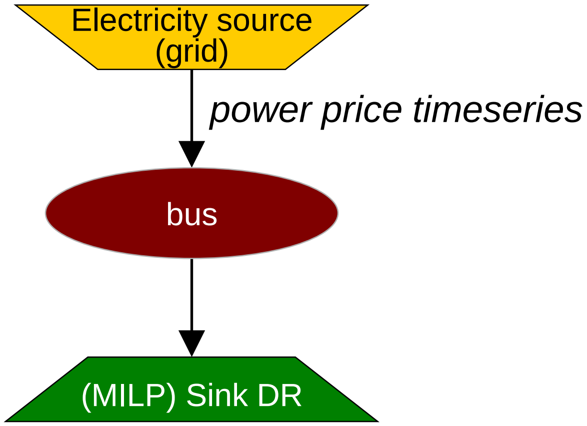
Discussion and outlook

Discussion: Macroeconomic scope

- Shortcoming of all linear DR modelling approaches
  - Activation of positive and negative power at a time is not forbidden → i.e. modelling DR portfolios
  - Drawback: Might be not suitable for every specific modelling task
- General discussion
  - *Do you see a benefit in a benchmarking of existing approaches?*
  - *What aspect should be focussed on / especially be taken into account?*

Outlook: Microeconomic scope

- Possible simple modelling setting in oemof



  - *MILP modelling approach yet to be developed (possible approach described in Gartner 2018)*
  - *Do you see a benefit in having such a MILP DR component in principle?*

source: Gartner (2018)

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.

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

$$\boldsymbol{P}^{t}_{\boldsymbol{balanceRed}} = \begin{cases} \dfrac{\boldsymbol{P}^{t-t_{shift}}_{\boldsymbol{reduction}}}{\eta_{DR}} & \forall t \in [t_{shift}..T] \\ 0 & \forall t \in [0..t_{shift}] \end{cases}$$

$$\boldsymbol{P}^{t}_{\boldsymbol{balanceInc}} = \begin{cases} \boldsymbol{P}^{t-t_{shift}}_{\boldsymbol{increase}} \cdot \eta_{DR} & \forall t \in [t_{shift}..T] \\ 0 & \forall t \in [0..t_{shift}] \end{cases}$$

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

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

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

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

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

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

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:

$$\boldsymbol{W}_{\boldsymbol{levelRed}}^{\boldsymbol{t}} = \boldsymbol{W}_{\boldsymbol{levelInc}}^{\boldsymbol{t}} = 0 \; for \; t = 0$$

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

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

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

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

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

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

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

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

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

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

Legend:
- **Variables: bold font**
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- 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).

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

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):

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

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

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

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

source: Steurer (2017, pp. 80-82); own modifications; Zerrahn und Schill (2015a, p. 843)

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

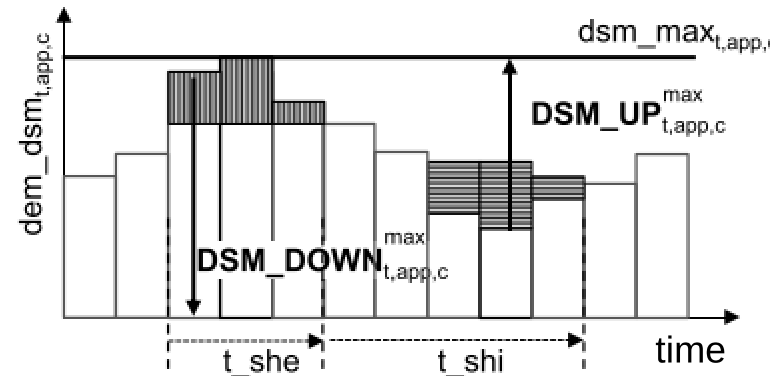
Legend:
- **Variables: bold font**
- Parameters, Sets: normal font

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

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

  - 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

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

  - 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)

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

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

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

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

Legend:
- **Variables: bold font**
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- 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 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

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

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

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