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DRESDEN concept

The value of flexible electricity demand in a future sector-coupled European energy system

Steffi Misconel, Christoph Zöphel, Dominik Möst

1st IAEE Online Conference 7th – 9th June 2021

Concurrent Session 137: European Power Systems, Room: Parallel Room 17

Wednesday, 2021-06-09, 17:00 - 19:00 CEST

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Assessing the value of demand response in a decarbonized energy system – A large-scale model application

ee²

1. **Background:** Increasing need for power system flexibility on supply and demand side
2. **Method:** Scenario framework and main input parameter for the electricity market model ELTRAMOD
3. **Results:** Quantification of the demand response impact on different components in the electricity system
4. **Conclusion:** Underlining the significant value of demand response

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The decarbonization of the energy system leads to an increasing demand for power system flexibility

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1. **EU climate targets** and decarbonization of the whole energy system to achieve climate neutrality in 2050 (European Green Deal)
2. Therefore enforced deployment of **high shares of RES** needed (amongst others)
3. Leads to **high fluctuations** in electricity supply
4. **Electrification of different sectors** leads to increasing electricity demand (e.g. industry, transport sector)
5. Necessitates balancing of electricity supply and demand

   ⇒ **Increasing need for power system flexibility on supply and demand side**

OBJECTIVE

Value assessment of demand response in a system perspective against the background of two strongly contrasting decarbonization pathways (**decentralized** and **centralized** European electricity system) with **100% RES** and **sector coupling**

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A scenario framework describing a decentralized and centralized energy system to assess the value of demand side flexibility

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TODAY

	MORE DECENTRALIZED	MORE CENTRALIZED
Renewable energy sources	**Stronger** deployment of **PV rooftop** and battery systems (100% RES share in 2050)	**Stronger** deployment of **wind offshore** (100% RES share in 2050)
Sector coupling	**PtG** - Decentralized onsite hydrogen production by small-scale electrolysis (389 TWh_{el} in 2050)	**PtG** - Hydrogen production in large-scale electrolysis with distribution by pipelines to consumers (855 TWh_{el} in 2050)
	PtH - Heat supply on individual level (285 TWh_{th} in 2050)	**PtH** - Heat supply on a centralized level (750 TWh_{th} in 2050)
	Individual **small-scale** energy sources	Centralized **large-scale** energy sources
Demand response potentials	**High participation** on local level (DSM, multi-modal transport)	**Lower participation** and **acceptance** on local level (DSM, multi-modal transport)
	Theoretical hourly potential 1,648 GW_{el}	Theoretical hourly potential 370 GW_{el}
	Technical hourly available potential 490 GW_{el}	Technical hourly available potential 140 GW_{el}
	Stronger deployment of battery systems, electro-mobility	

2050

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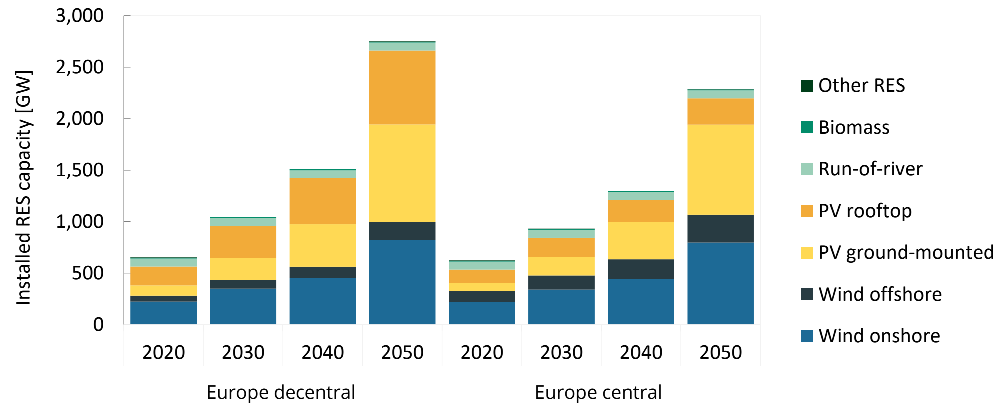
Different combination of RES capacities and electricity demand for the decentralized and centralized scenario framework

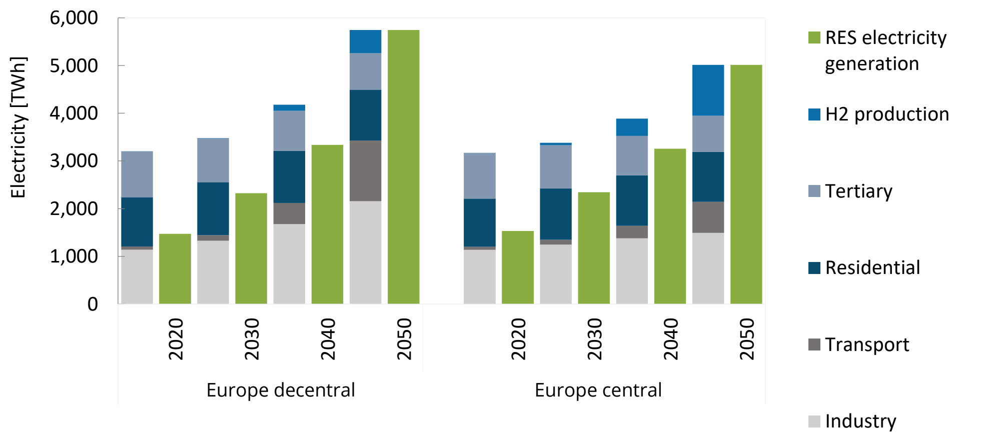
RES expansion pathways

- Geographically highly resolved data on land availability
- Hourly time series of vRES generation based on weather data
- Theoretical share of 100% RES generation at future´s electricity demand in 2050



Electricity demand

- Increasing electricity demand due to electrification of other sectors
- Hourly electricity demand profiles from eLOAD (open-access data set*)



* Source: https://data.esa2.eu/tree/REFLEX

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Higher demand response potentials in the decentralized scenario due to higher acceptance on local level

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Demand response (DR) potentials

- Max. available DR potential (max. load) from eLOAD
- 15 DR processes of four different sectors

Demand response (DR) profiles

- Max. hourly available DR potentials from eLOAD (open-access data set*)
- Country-specific and process-aggregated DR profiles

Sector	Demand response processes	Demand response potential [GW] Europe decentral 2050		Demand response potential [GW] Europe central 2050		Act. costs [EUR/ MWh]
Industry	*Cement grinding*	**0.2**	0%	**0.1**	0%	100
	Electric arc furnace	**10.6**	0.6%	**6.4**	1.7%	100
	Aluminum (primary)	**0.0**	0%	**1.5**	0.4%	100
	Copper (primary)	**0.0**	0%	**0.1**	0%	100
	Mechanical pulp	**1.1**	0.1%	**0.7**	0.2%	100
	Hydrogen electrolysis (feedstock)	**185.7**	11.3%	**---***	---*	60
Tertiary	*Circulation pumps*	**11.0**	0.7%	**7.4**	2.0%	20
	Heat pumps (space heating)	**23.5**	1.4%	**7.1**	1.9%	10
	Refrigeration	**13.0**	0.8%	**8.8**	2.4%	10
	Ventilation and air-conditioning	**3.6**	0.2%	**2.3**	0.6%	10
Residential	*Heat pumps (space heating)*	**105.2**	6.4%	**74.8**	20.2%	0
	Refrigerators	**10.4**	0.6%	**0.0**	0.0%	0
	Battery Storage	**234.7**	14.2%	**0.0**	0.0%	0
Transport	*Hydrogen electrolysis*	**170.9**	10.4%	**---***	---*	60
	E-mobility - passenger cars	**878.0**	53.3%	**260.7**	70.5%	0
Max. DR potential [GW]		**1,648**	100%	**370**	100%	
Max. hourly available DR potential [GW]		**490**	30%	**140**	38%	

**Model-endogenous result from ELTRAMOD*

Source: Demand response data according to REFLEX project 2019; activation costs based on own assumptions, Ladwig 2018, Gils 2015, McKenna et al. 2018.

* Source: https://data.esa2.eu/tree/REFLEX

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ELTRAMOD – A fundamental linear optimization and electricity market model (NTC-based)

MODEL INPUT

TECHNO-ECONOMIC DATA

- Technology specific power **plant characteristics** (e.g. capacities, efficiencies, fuel types, emission factors, availabilities etc.)
- **Economic parameter** (e.g. load-change costs, hourly **fuel and CO_2 price** profiles)
- European transmission capacity (**NTC**)
- **No** congestion within one market zone (copper plate)

SUPPLY SIDE

- **17 conventional generation technologies**
- **RES capacities** and hourly generation **profiles**

DEMAND SIDE

- Hourly **electricity demand** per country
- Country-specific aggregated **demand response profiles**

LINEAR OPTIMIZATION

Target function:

Cost-optimal investment and dispatch

$$Min \sum_t TOTAL\ SYSTEM\ COSTS$$

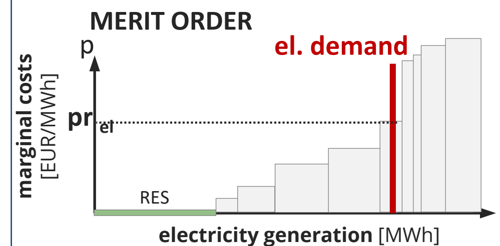
$$t \in T\ [8760\ h]$$

Member states of EU28*

Norway, Switzerland and Balkan countries*

Existing lines

MODEL ENDOGENOUS ELECTRICITY PRICE CALCULATION



$ENERGY\ BALANCE:$

$$electricity\ demand = electricity\ supply$$

$$t \in T\ [8760\ h], p \in P$$

$$ENERGY\ BALANCE\ .\ Marginal = pr_{el}$$

FURTHER MODEL OUPUT

- Power plant investment and dispatch
- Cost-minimal (optimal) dispatch of flexibility options
- CO_2 emissions
- Export-import flows
- Integrated/curtailed RES
- Dispatch costs/total system costs

* with technology-specific aggregated power plants representation

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Modeling the impact of demand response with the electricity market model ELTRAMOD

$$DR_{t,c}^{OPT} \leq dr_{t,c}^{MAX} \cdot \boxed{dr^{SHARE}} \tag{1}$$

0% / 25% / 50% / 75% / 100% OF MAX. AVAILABLE POTENTIAL

$$DR_{t,c}^{OPT} \geq dr_{t,c}^{MIN} \cdot dr^{SHARE} \tag{2}$$

$$\sum_{t=1}^{T} DR_{t,c}^{OPT} = 0 \tag{3}$$

$$\boxed{RESDEM_{t,c}^{OPT}} = resdem_{t,c} - \boxed{DR_{t,c}^{OPT}}$$

DR ACTIVATION COSTS -> TARGET FUNCTION

$$DR_{t,c}^{OPT} \cdot co_{DR_{y,c}}$$

OPTIMIZED RESIDUAL LOAD -> ENERGY BALANCE

$DR_{t,c}^{OPT}$	Optimal hourly dispatch of demand response
$dr_{t,c}^{MAX}$	Maximal positive hourly demand response potential (for residual load reduction)
$dr_{t,c}^{MIN}$	Minimal negative hourly demand response potential (for residual load increase)
dr^{SHARE}	Share of activated demand response potential
$RESDEM_{t,c}^{OPT}$	Optimized residual load (smoothed)
$resdem_{t,c}$	Residual load (unsmoothed)
$t \in T$	Hour of a year
$c \in C$	Country of considered geographical scale (EU-27, United Kingdom, Norway, Switzerland, Balkan countries)

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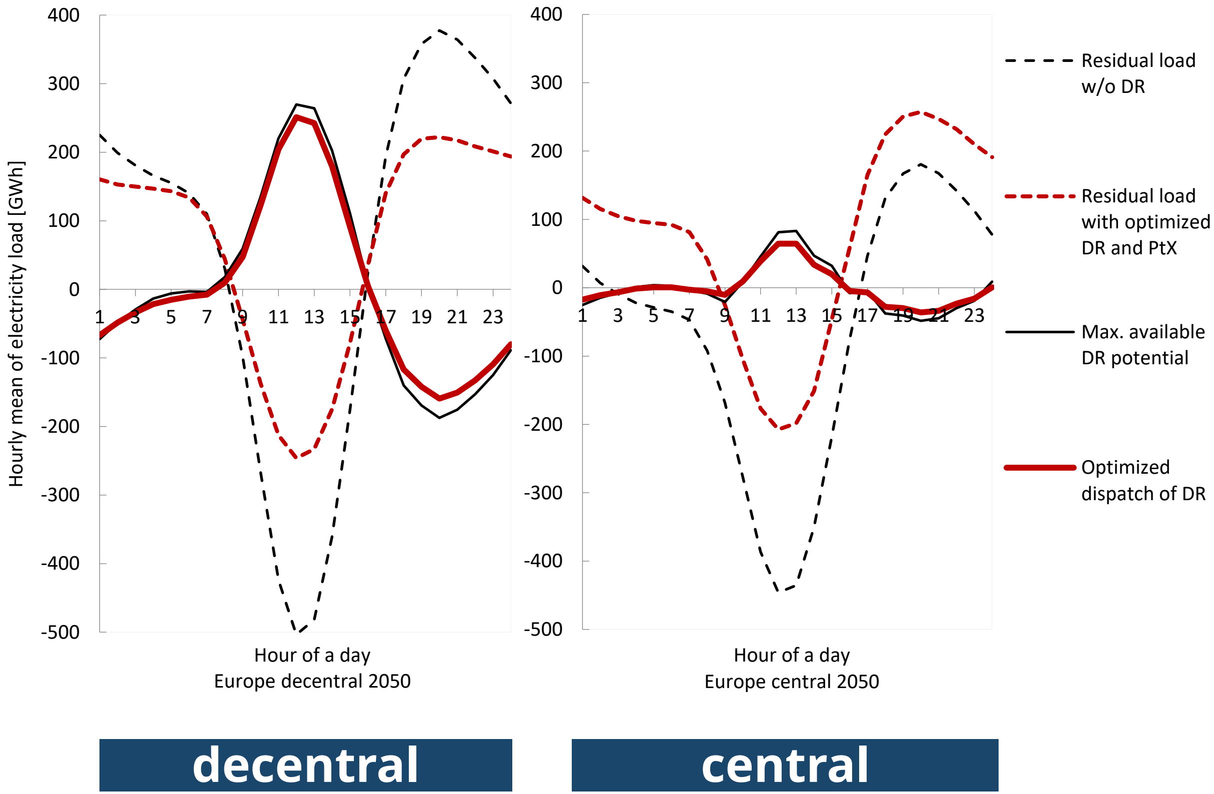
Similar residual load after smoothing effect of demand response and PtX for the decentralized and centralized scenario

Impact of demand response on the residual load

- Model-exogenous input parameter are **different** between the DEC/CEN scenario
- **Centralized scenario –> low** smoothing effect by DR and **high** load increase potentials of PtG
- DR potentials are **not always activated** to its **full extent** in the hourly mean
- In the **midday** and **evening hours** some **DR** potential remains **unused**, in the night and in transition the activated DR potential is often fully exploited



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The smoothening effect of the residual load by demand response directly affects the power plant capacity and generation mix

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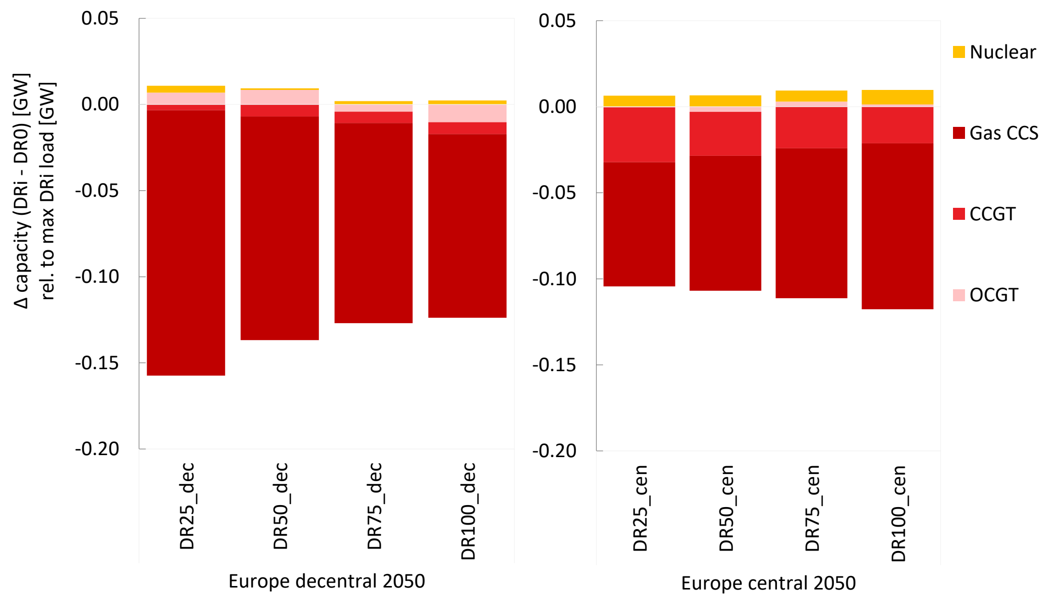
Impact of demand response on the capacity and generation mix

- **Decreasing peak load** and **medium load capacities** due to DR in both scenarios
- **DECENTRALIZED SCENARIO DR$_{25}$-DR$_{100}$**
  - Decline of total capacity by **4-12%** (18-60 GW)
  - Decline of specific capacity per activated DR potential by **0.16-0.13 GW/GW$_{DR25\text{-}100}$**
- **CENTRALIZED SCENARIO DR25-DR100**
  - Decline of total capacity by **1-4%** (3-15 GW)
  - Decline of specific capacity per activated DR potential by **0.10-0.12 GW/GW$_{DR25\text{-}100}$**
- Reduced conventional generation due to DR activation



decentral **central**

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The activation of demand response is more efficient to smooth the residual load than using energy storages

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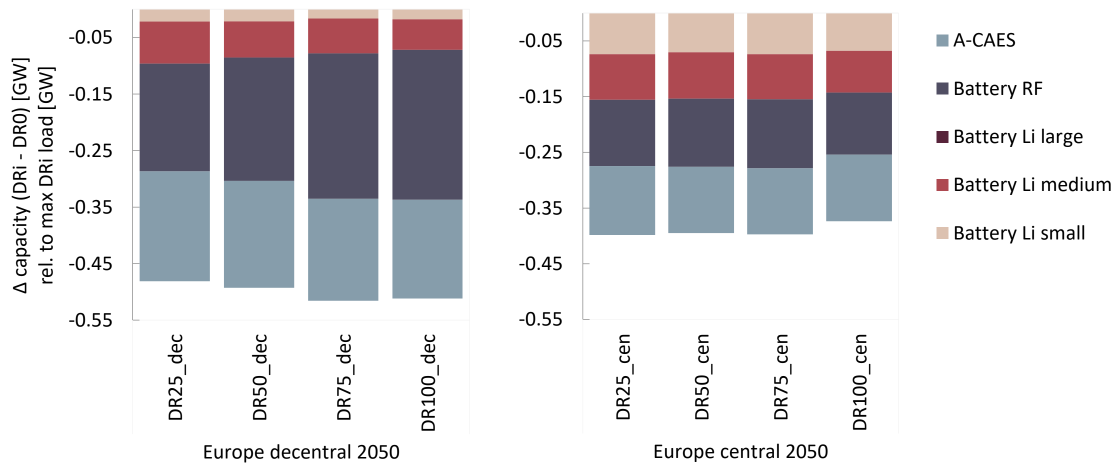
Impact of demand response on storage requirements

- DR **reduces** total storage **capacity** and storage **operation** for both scenarios

- **DECENTRALIZED SCENARIO DR_{25}-DR_{100}**
  - Decline of **13-54%** (from **464 GW**)
  - A-CAES and redox-flow batteries reduced by 0.44 GW/GW_{DR100} (EPR 10 MWh/MW)
  - Small / medium-sized lithium-ion batteries 0.07 GW/GW_{DR100} (EPR 1-4 MWh/MW)
- **CENTRALIZED SCENARIO DR_{25}-DR_{100}**
  - Decline of **4-16%** (from **318 GW**)
  - A-CAES and redox-flow batteries 0.23 GW/GW_{DR100}
  - Small / medium-sized lithium-ion batteries 0.14 GW/GW_{DR100}



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Higher vRES integration due to demand response, but slightly declining market value factors due to lower electricity prices

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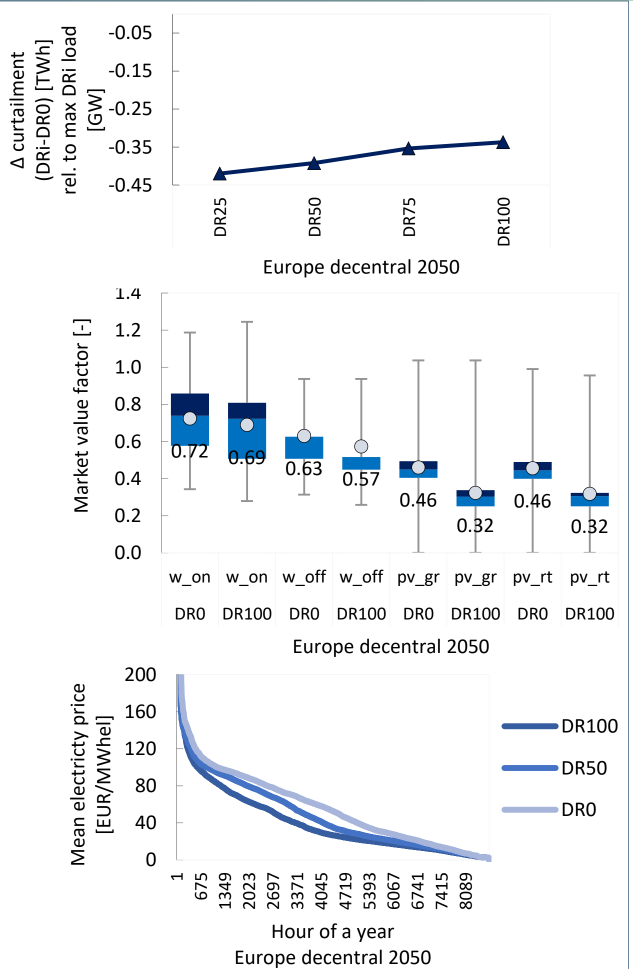
Impact of demand response on integration and market value factors of vRES

- Curtailment can be decreased due to DR in both scenarios
- **Market values** of vRES correspond to the specific market revenues earned (without subsidies)
- **Market value factor** avoids the effect that countries with on average higher electricity prices achieve higher market values for vRES

CENTRALIZED SCENARIO DR_{25}-DR_{100}

- **More stable** and **higher electricity prices** lead to lower declining effect of DR on market value factors of vRES



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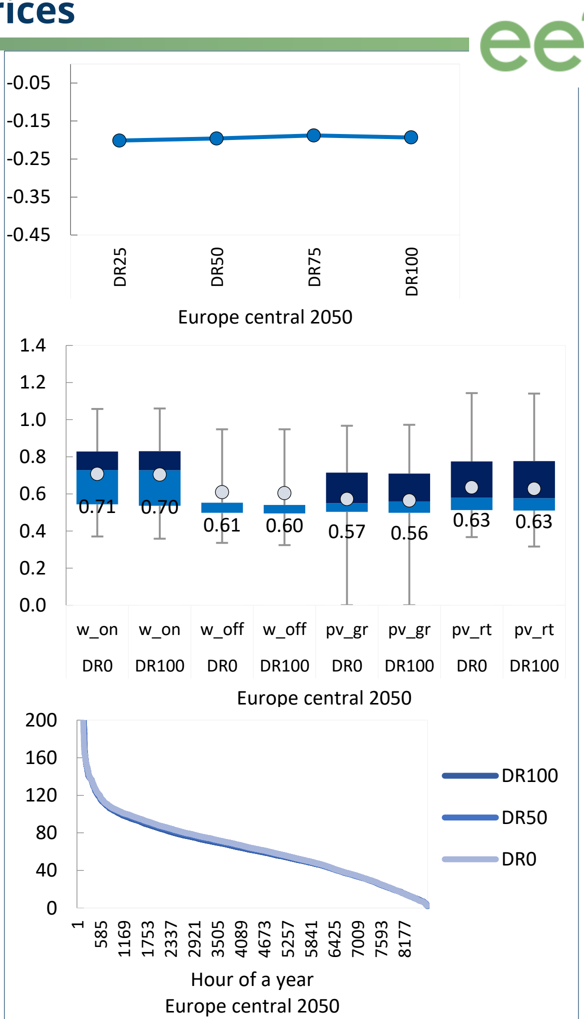

central

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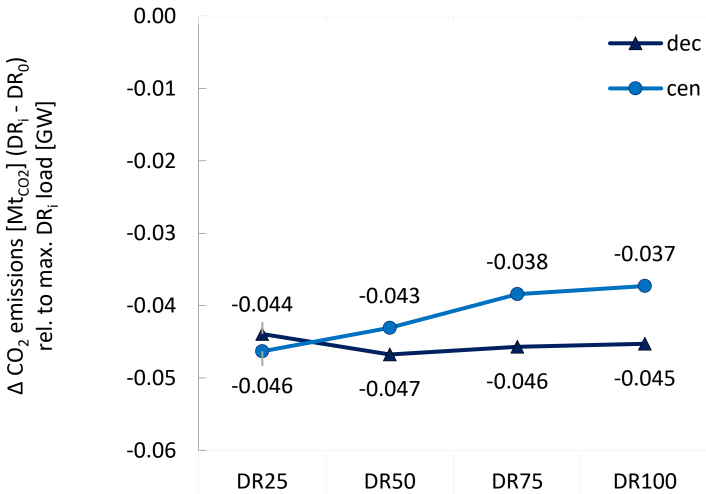
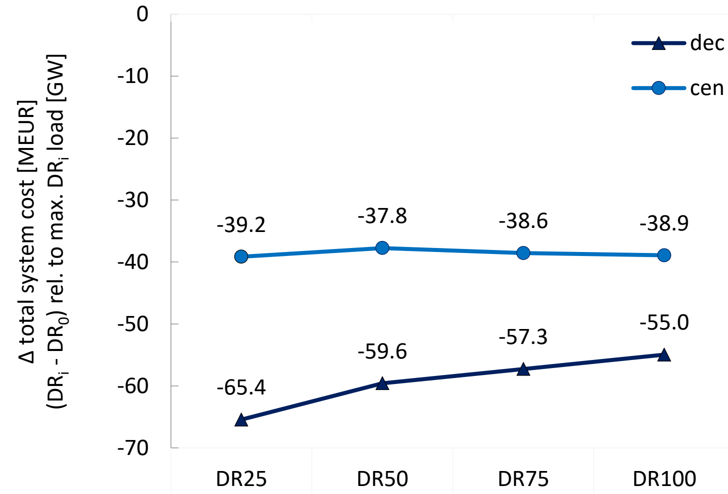
A decentralized system with demand response achieves higher CO_2 reductions at lower system costs compared to the centralized system





Impact of demand response on CO_2 emissions of the electricity sector

- Additional vRES integration and reduced conventional generation due to **DR lead to CO_2 emissions reduction**
- Similar range of CO_2 reduction related to max. DR potential **0.045 Mt_{CO2}/GW_{DR100}** (**dec**) and **0.037 Mt_{CO2}/GW_{DR100}** (**cen**)

Impact of demand response on total system costs

- **Higher decline in total system costs** in **DEC** scenario due to **avoided investments** and lower electricity generation by backup and peak load capacities, **higher fuel savings** and **lower expenditures for CO_2 emission allowances**

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Straightforward method to estimate the value of demand response in a large-scale electricity market model

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- The results confirm earlier findings, underlining the significant value of demand response measures to **reduce power plant** and **storage capacities**.
- Compared to the results without activation of the demand response potential, **total system costs** and **CO_2 emissions** can be **reduced**.
- However, **differences** occur **between** the **decentralized** and **centralized scenario**, mainly influenced by **diverging assumptions** on **fluctuating renewable energy expansion** and the **availability of demand response application potentials**.
- In the **decentralized system** with **higher share of PV** (with daily and seasonal fluctuation characteristics), demand response can balance daily short-term fluctuations more efficiently, and thus
  - higher marginal reduction values of **55 MEUR/GW_{DR}** concerning the total system costs and of **0.045 Mt_{CO2}/GW_{DR}** regarding CO_2 emissions per activated demand response potential can be achieved
  - compared to the **centralized scenario** with **39 MEUR/GW_{DR}** and **0.037 Mt_{CO2}/GW_{DR}** , which is dominated by high penetration of **wind offshore power plants** (with consistent, short but strong fluctuations, particularly in the evening/night when DR potential is lower)

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DRESDEN concept

Steffi Misconel
Research Associate

University of Technology Dresden
Faculty of Business and Economics
Chair of Energy Economics

Email: steffi.misconel@tu-dresden.de

Website: www.ee2.biz

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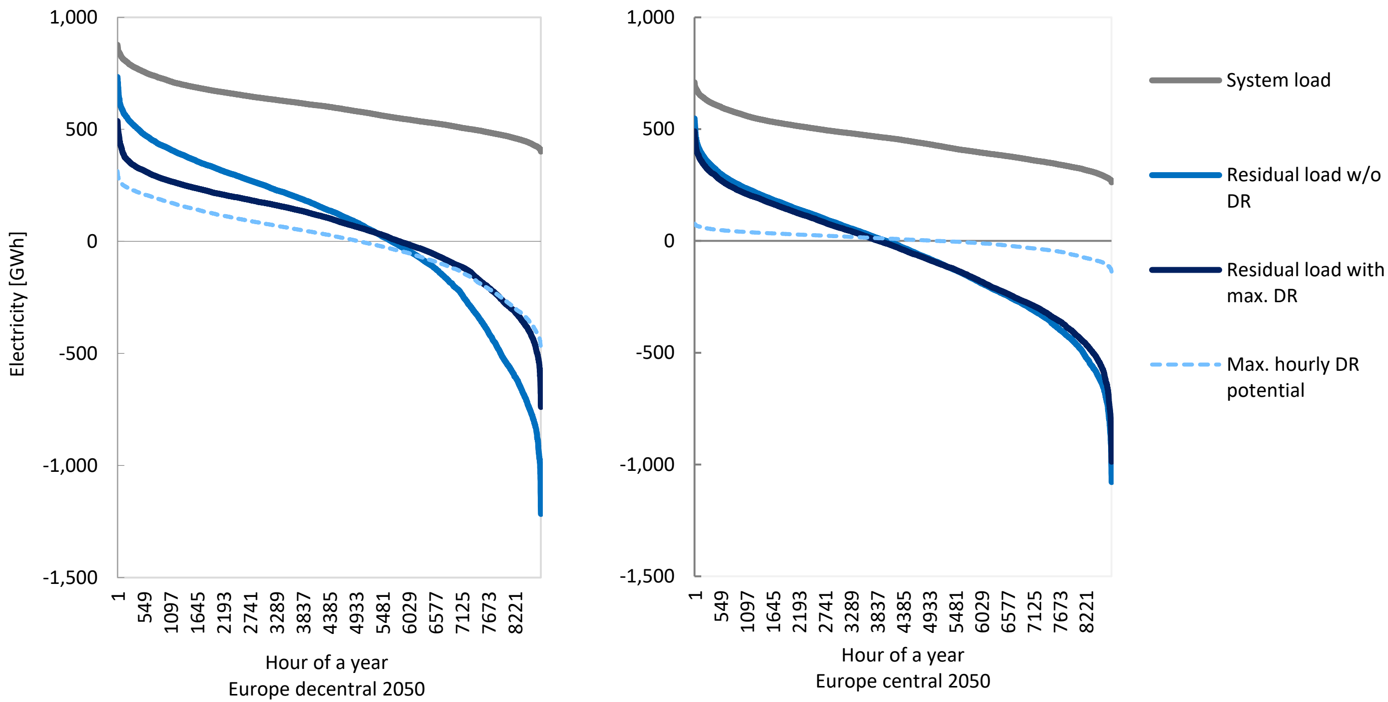
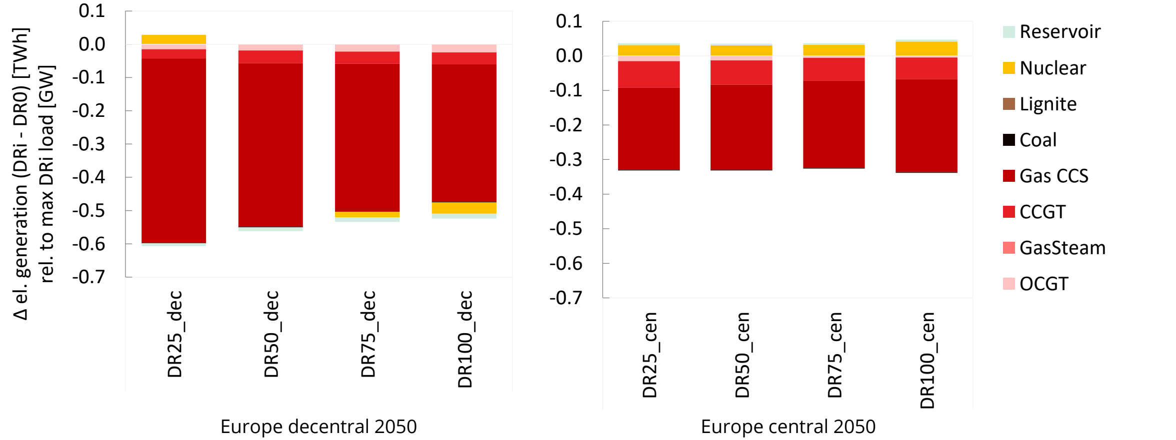
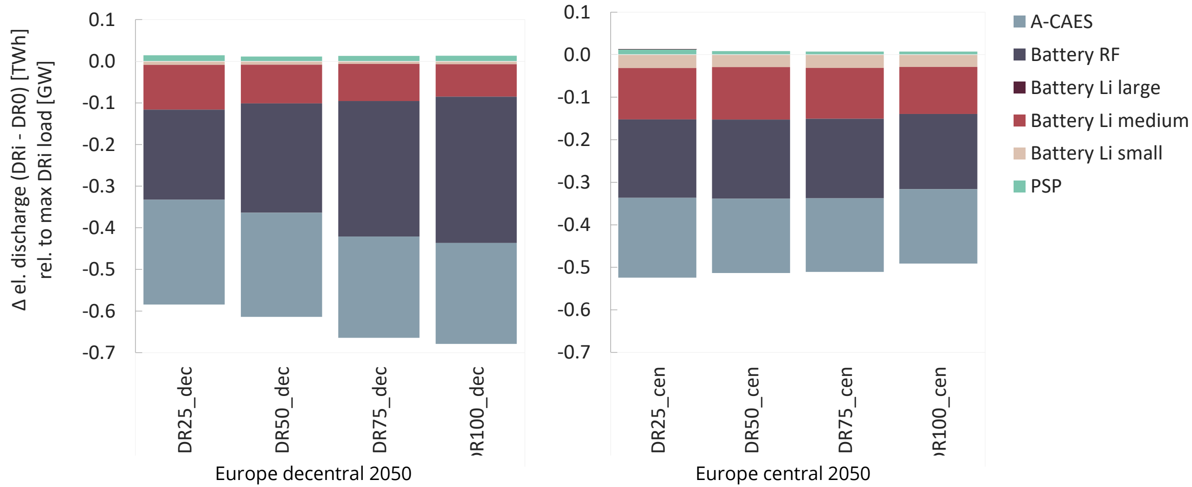
System load, residual load and max. hourly demand response potential as model input parameter



Results conventional electricity generation and storage dispatch





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Calculation of the market value factor for volatile renewable energy sources

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$$MVF_c^{tech} = \frac{\sum_{t=1}^{T} g_{t,c}^{tech} \cdot p_{t,c}}{\sum_{t=1}^{T} \frac{p_{t,c}}{T} \cdot \sum_{t=1}^{T} g_{t,c}^{tech}}$$

$$\overline{MVF}^{tech} = \frac{MVF_c^{tech}}{C}$$

MVF_c^{tech}	Technology-specific market value factor
$\overline{MVF}^{tech}$	Average technology-specific market value factor
$g_{t,c}^{tech}$	Technology-specific electricity generation
$p_{t,c}$	Day-ahead wholesale electricity price
$t \in T$	Hour of a year
$c \epsilon C$	Country of EU-27, United Kingdom, Norway, Switzerland, Balkan countries

Source: based on Eising et al. 2020