Unlocking the future: Exploring the untapped potential of renewables and flexibility options in reducing CO_2 emissions - What will it cost?

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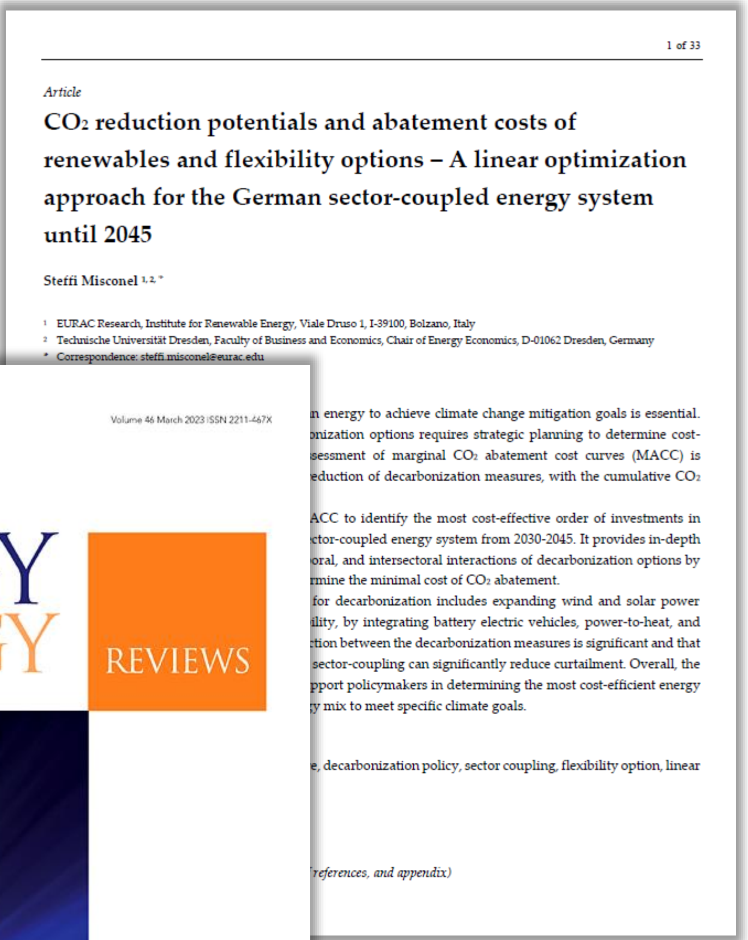
Highlights

- High-resolution **marginal CO_2 abatement cost curve** (MACC) approach for German sector-coupled energy system in **2030/45**.
- Findings suggest **early-phase vRES installation, later sector coupling**, and **storage**.
- Ground-mounted **PV**, **onshore wind**, and **PtH** are the **most cost-effective** measures.
- Policy suggestions include **incentives for vRES**, **BEV**, investments in **sector coupling**.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Article

CO_2 reduction potentials and abatement costs of renewables and flexibility options – A linear optimization approach for the German sector-coupled energy system until 2045

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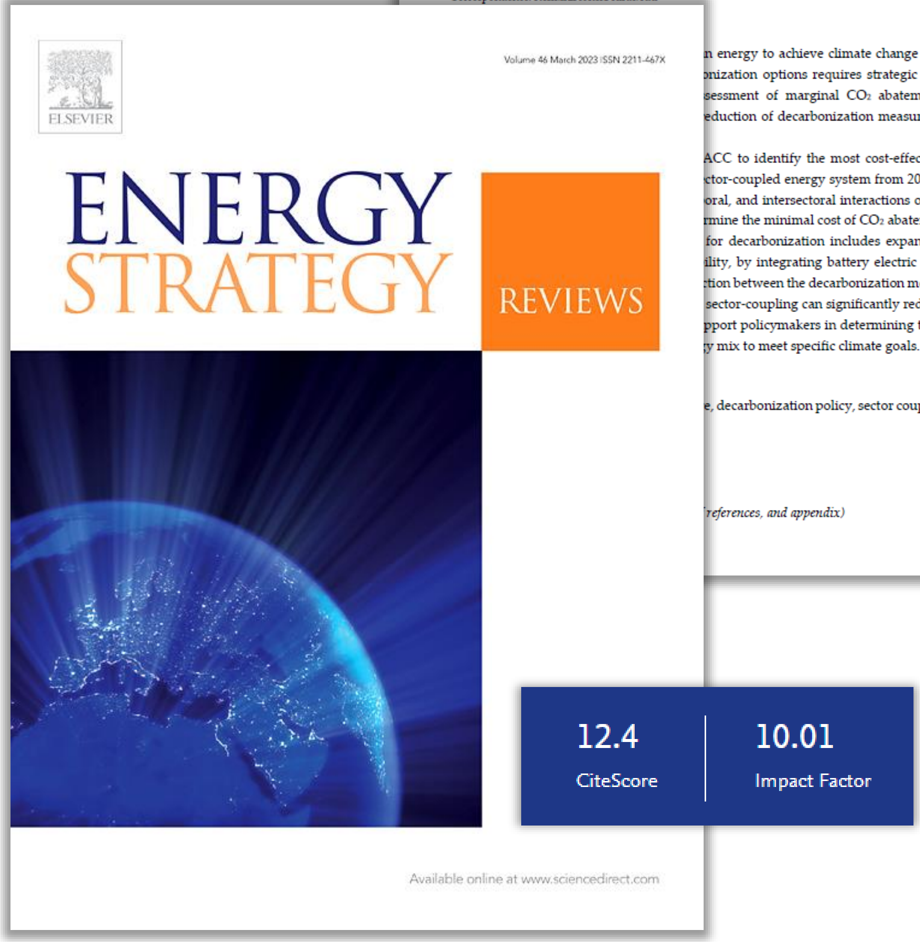
n energy to achieve climate change mitigation goals is essential. onization options requires strategic planning to determine cost- sessment of marginal CO_2 abatement cost curves (MACC) is eduction of decarbonization measures, with the cumulative CO_2

ACC to identify the most cost-effective order of investments in ctor-coupled energy system from 2030-2045. It provides in-depth oral, and intersectoral interactions of decarbonization options by mine the minimal cost of CO_2 abatement. for decarbonization includes expanding wind and solar power ility, by integrating battery electric vehicles, power-to-heat, and tion between the decarbonization measures is significant and that sector-coupling can significantly reduce curtailment. Overall, the pport policymakers in determining the most cost-efficient energy y mix to meet specific climate goals.

e, decarbonization policy, sector coupling, flexibility option, linear

references, and appendix)



Content

1. **Introduction** to the importance of identifying CO_2 reduction potentials and costs
2. **Method** and **scenario** framework for the assessment of step-wise marginal CO_2 abatement cost curve
3. **Results** on CO_2 reduction costs and potentials of vRES and flexibility options
4. **Conclusions** and **policy implications**

Introduction to the importance of identifying CO_2 reduction potentials and costs

Meeting Paris Agreement and European Green Deal targets require analyzing methods to switch to renewable energy and alternative decarbonization options

Problem

- Strategic planning needs **evaluation** of **cost-effective decarbonization alternatives**
- Marginal CO_2 abatement cost curves (**MACCs**) are useful but **most approaches neglect interactions** between technologies and lack **high temporal, cross-sectoral,** and **techno-economic resolution**

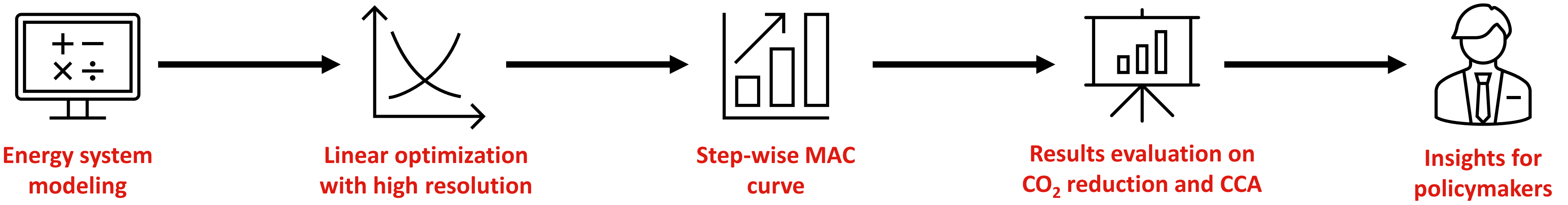
Solution

- Integration of a **step-wise MAC curve** into a **high-resolution model-based approach** (linear optimization) based on a case study for the German sector-coupled energy system for 2030 and 2045
- Approach evaluates **CO_2 abatement costs** and **emission reduction potentials** of vRES and flexibility options, as well as intertemporal and intersectoral interactions

The analysis supplements existing research and can assist policymakers in identifying appropriate measures to attain emission reduction targets!

Objectives

- **Create a modeling methodology** that utilizes a **robust optimization** process to identify **MAC curves**.
- **Integrate high temporal, sectoral,** and **techno-economic resolution** into a MAC curve approach, which will be incorporated into the **linear optimization model ELTRAMOD**.
- Determine the **optimal order of investments** in renewables and flexibility options that minimizes cost, in order to establish **least-cost decarbonization pathways**.
- Assess the **CO_2 reduction potentials** and **CO_2 abatement costs (CCA)** associated with renewables and flexibility options for the German energy transition in 2030 and 2045.
- **Creating insights** regarding the most **cost-effective decarbonization strategies** to support **policymakers**, the research community, and other decision-makers



Method and scenario framework for the assessment of step-wise marginal CO_2 abatement cost curve

Assessing marginal CO_2 abatement cost curves with the electricity system model ELTRAMOD

MODEL INPUT

TECHNO-ECONOMIC DATA

- **Technology-specific** power plant **characteristics** (e.g., capacities, fuel types, emission factors, etc.)
- **Economic parameter** (e.g., load-change costs, etc.)
- European transmission capacity (**NTC**)

SUPPLY SIDE

- **RES** capacities and hourly generation profiles
- Fuel and CO_2 certificate **prices**
- 17 conv. gen. technologies
- Storage systems, DSM processes, heat pumps, electrolyzers, battery electric vehicles (incl. techno-economic parameters)

DEMAND SIDE

- Hourly **electricity demand**
- Hourly **process load** and **charging availability** profile for **BEV**
- Hourly **heat demand** profile
- **Hydrogen demand** for power and industry sector

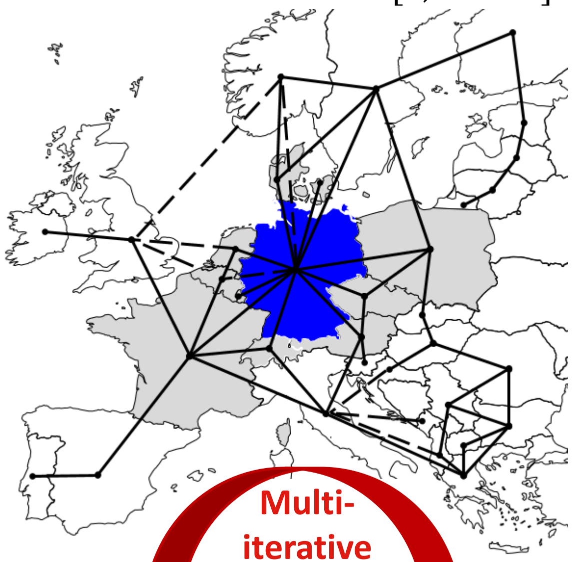
LINEAR OPTIMIZATION

Target function:

Cost-optimal dispatch

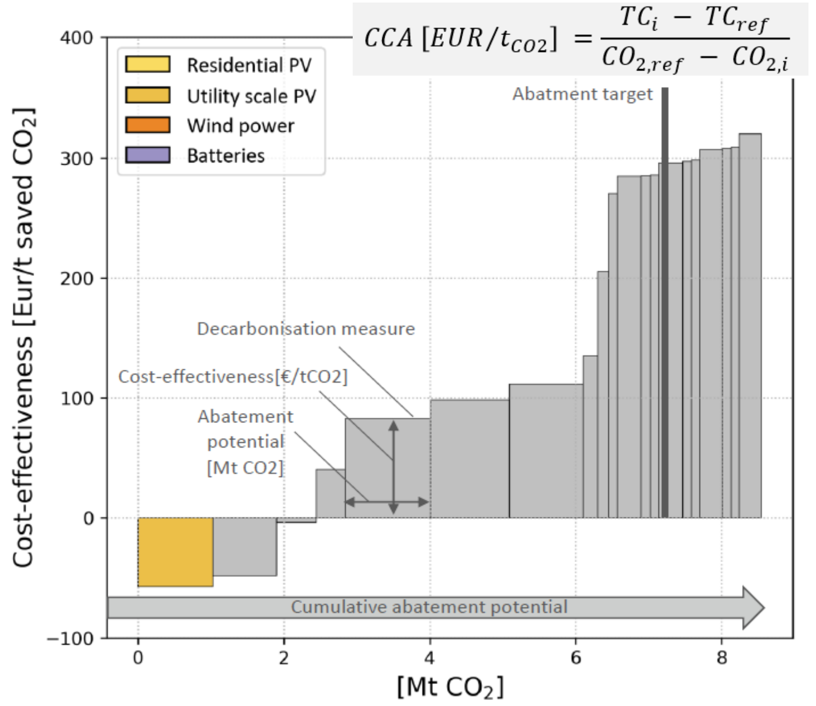
$$Min \sum_{t} TOTAL\ SYSTEM\ COSTS$$

$$t \in T\ [0, 8760\ h]$$



Multi-iterative capacity expansion algorithm

MARGINAL CO_2 ABATEMENT COST CURVE



Source: Prina et al. (2020)

MODEL OUTPUT

- Cost-minimal (optimal) dispatch of power plants and flexibility options
- **Total system costs** / dispatch costs
- **CO_2 emissions / CO_2 reduction**
- **Costs of carbon abatement** (CCA)

Scenario framework and implementation of decarbonization measures and sector coupling

Decarbonization measure	Unit	2030 dv_m^{REF}	2030 dv_m^{MAX}	2030 I_m	2030 IT_m	2045 dv_m^{REF}	2045 dv_m^{MAX}	2045 I_m	2045 IT_m
PV ground-mounted	[GW]	35.2	**140**	1.5	~67	140	**280**	1.5	~91
PV rooftop	[GW]	14.8	**60**	1.5	~29	60	**120**	1.5	~39
Wind onshore	[GW]	52.5	**94**	0.6	~71	94	**160**	0.6	~114
Wind offshore	[GW]	7.6	**30**	0.4	~53	30	**70**	0.4	~96
Power-to-H_2-to-power (electrolyzer, H_2 tanks, fuel cells)	[GW] [GWh]	0	**10**	0.9	~10	10	**50**	0.9	~43
Battery lithium-ion	[GWh]	0	**20**	1.0	20	20	**97.7**	1.0	~77
Battery redox-flow	[GWh]	0	**20**	1.0	20	20	**43.3**	1.0	~23
Power-to-heat (heat pump, heat storage)	[GW] [GWh]	0	**20**	0.3	~62	20	**51.7**	0.3	~98
Battery electric vehicles (private/fleet passenger cars)	[Mio.]	0	**15**	0.067	~224	15	**32**	0.067	~137
Max. number of MAC curve steps / dispatch model runs					~556				~718
Net el. demand*	[TWh]	630				1025			
Gross el. demand**	[TWh]	**669**				**1106**			
Total RES generation	[TWh]	568				1,031			
RES share (net)	[-]	**~90%**				**~100%**			
RES share (gross)	[-]	~85%				~93%			

*with sector coupling **with sector coupling and electricity losses

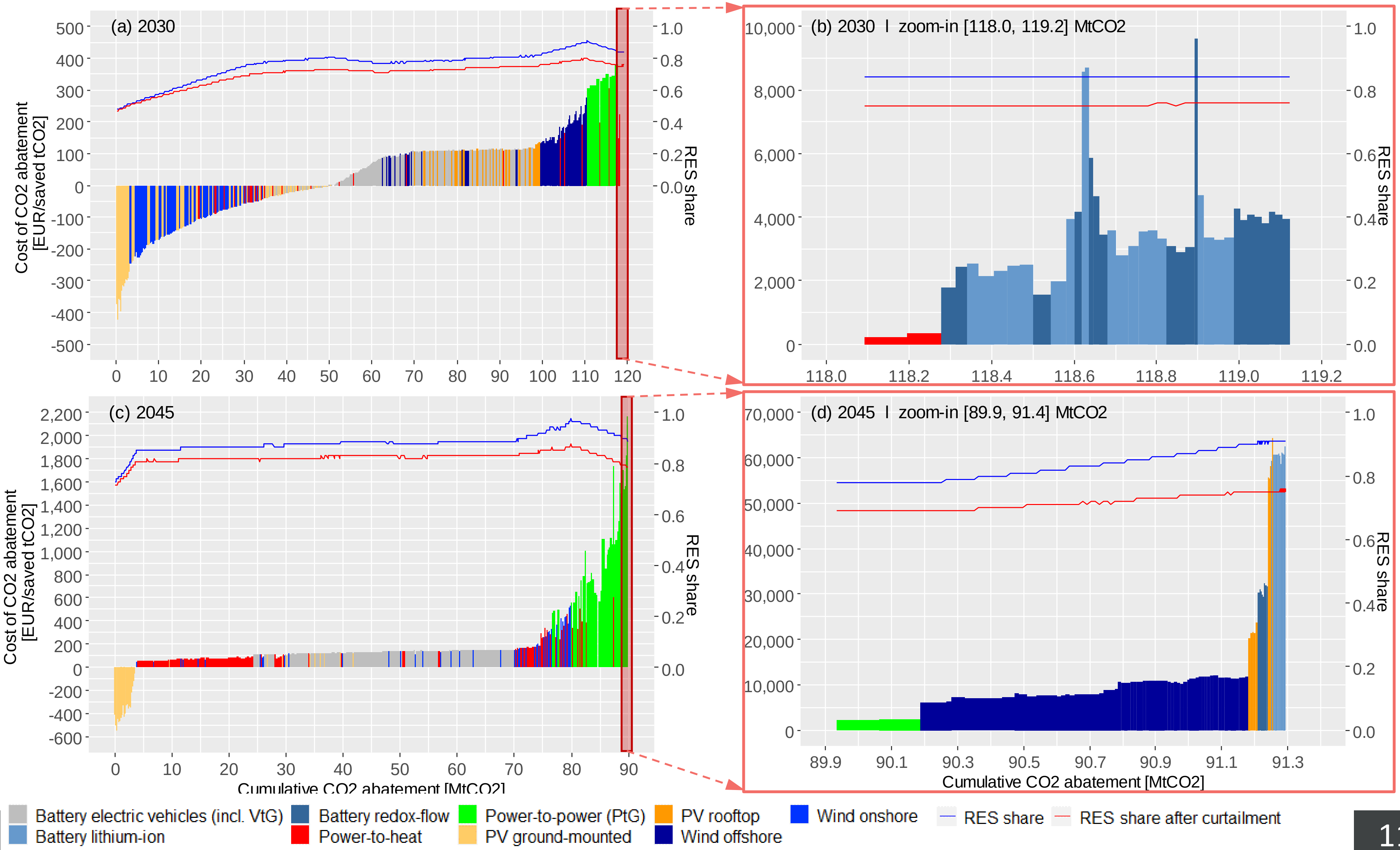
Further assumptions

- Input based on **German Grid Development Plan** (NEP 2023/2037) for 2030/2045
- Germany is considered an "**island**" (no electricity exchange flows between DE and neighboring countries)
- **Model-endogenous investments** in **H_2 power plants** were calculated in the previous model run (40 GW_{2030} / 49 GW_{2045})

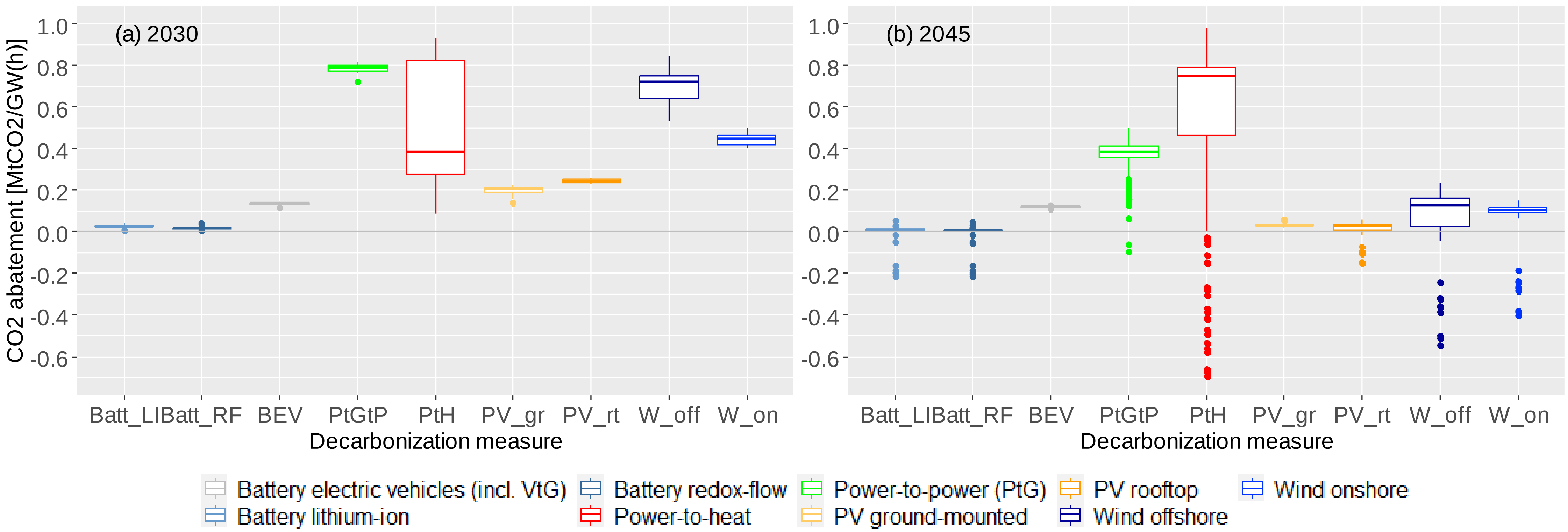
Results on CO_2 reduction potentials and costs of vRES and flexibility options

Comparison of MAC curves, cost-effectiveness, and interplay of decarbonization measures between 2030 and 2045

- **Most cost-effective** decarbonization measures are **ground-mounted PV**, **wind onshore** (2030), and **PtH** with the low and even negative CCA
- **Wind offshore, PtH$_2$tP, batteries** are the **most cost-intensive measures**, which are shifted to a later stage of the MACC (as BEV with storage capacity can be used as a more cost-effective solution in the short term)



Comparison of CO_2 reduction potentials per decarbonization measure for Germany between 2030 and 2045

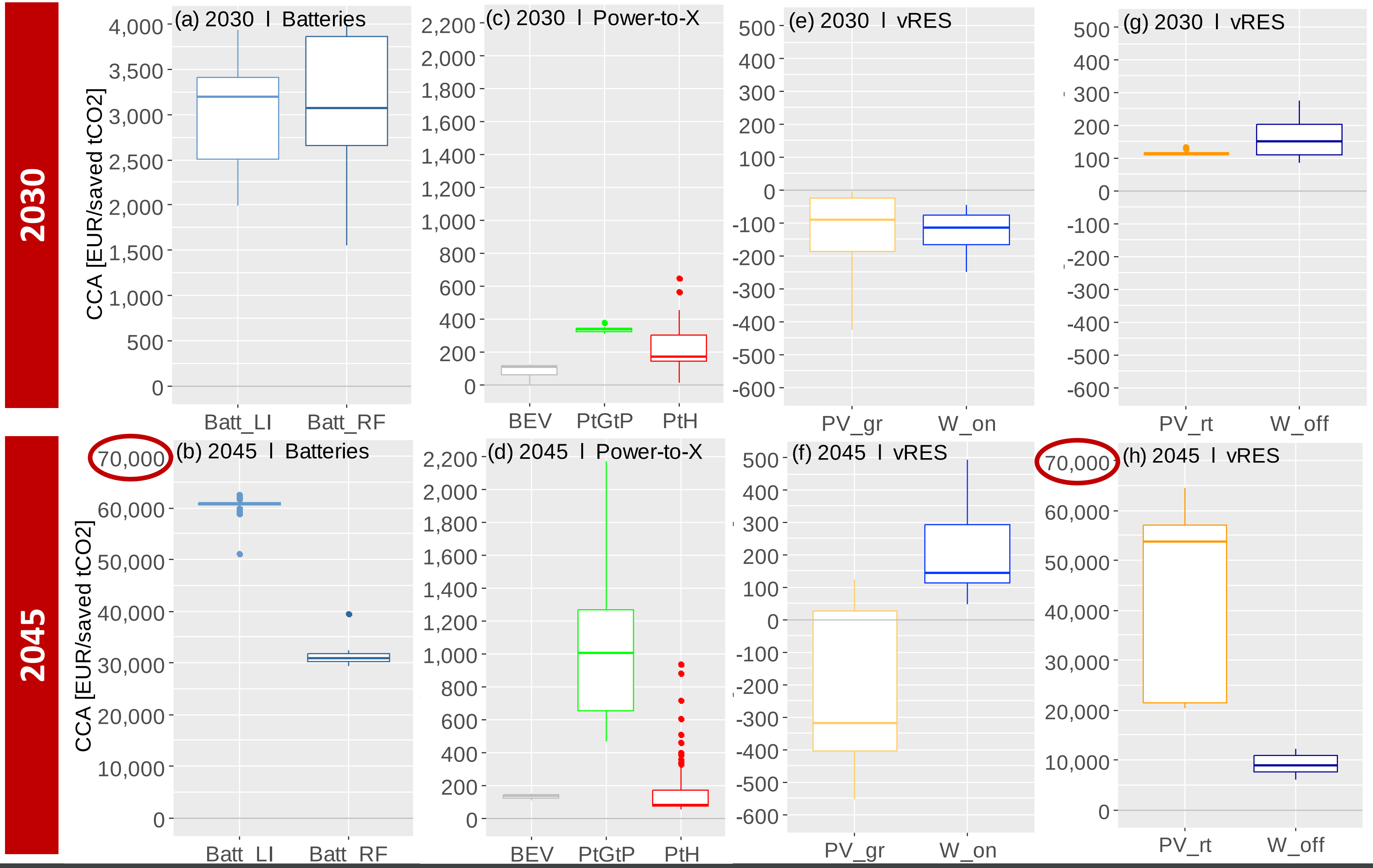


- **Decreasing CO_2 reduction potential** for almost all considered measures from 2030 to 2045, **despite** for **BEV** and **PtH**
- **PtH$_2$tP**, wind **offshore**/wind **onshore** have the **highest CO_2 reduction potential** (median)
- With a higher RES share in **2045**, **PtH increase CO_2 reduction** potential (median)

*including all solutions, not only the least-cost solution of the MACC

Comparison of CO_2 abatement costs for different decarbonization measures between 2030 and 2045

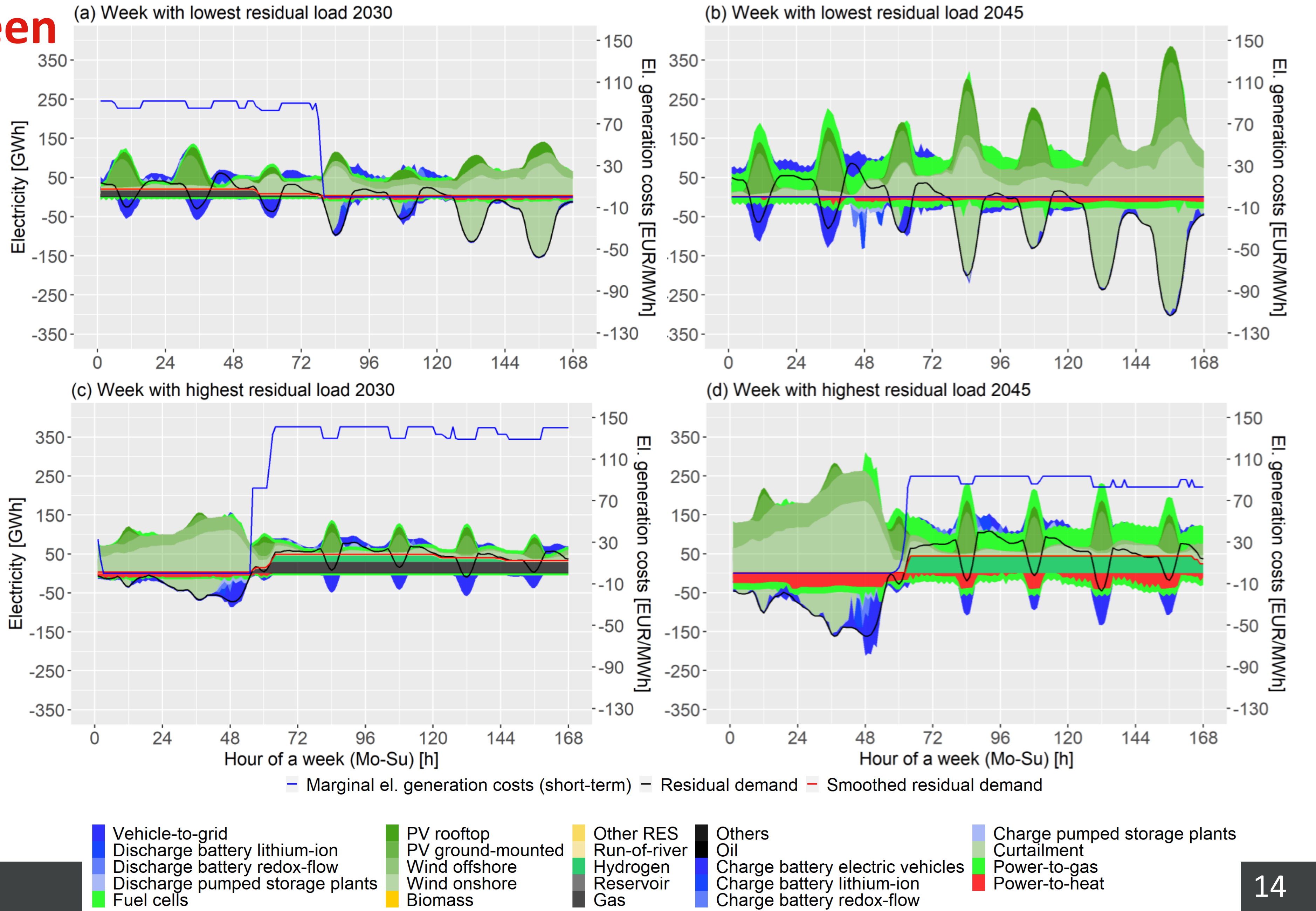
- **Most** decarbonization measures will **increase CCA** by 2045, **except** for **PtH** and **ground-mounted PV** with median CCA
- **Battery** storage, **rooftop PV**, and **offshore wind** become significantly **less cost-effective** with reduced CO_2 reduction potential, resulting in high CCA values



*with different primary y-axis scaling, and including all solutions, not only the least-cost solution of the MACC

Comparison of hourly utilization of decarbonization measures between 2030 and 2045

- High **vRES** share (≥80%), **storage** solutions such as **BEV** with bidirectional charging and **PtH$_2$tP substitute conv.** electricity **generation**
- Integration of **vRES**, **BEV** with bidirectional charging and **PtH$_2$tP lower** short-term **electricity generation costs** (a proxy for wholesale el. prices)
- However, even in **2045 H$_2$ power plants** are **needed** as **backup** capacities in times of high residual load



Conclusions

Conclusions on modeling results

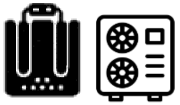
MAC curves provide not only the **'best' energy mix** for **decarbonization strategies** but also information on the **least-cost sequential order** for decarbonization measures

- Prioritizing **vRES** in the **initial stage** of decarbonization is more cost-effective
- **Sector-coupling** measures **improve vRES integration** in a later stage
- By **2030**, ground-mounted **PV**, **onshore wind**, and **PtH** are the most cost-effective decarbonization measures
- By **2045**, ground-mounted **PV**, **BEV** with controlled bi-directional charging, and **PtH** are cost-effective decarbonization measures
- **PtH_2tP** has the **highest potential for CO_2 reduction** but is also one of the **most cost-intensive** measures
- **Curtailment increases** with rising vRES, despite sector-coupling and storage technologies, leading to the **need** for carbon-neutral **backup capacities** (H_2 power plants) in 2045 (in periods with high residual load)

Policy implications for decarbonization strategies

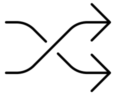
1) **Incentivize** installation and integration of **rooftop PV** and **offshore wind**, and invest in **grid infrastructure** for vRES integration.

2) **Support BEV adoption** and **flexible utilization** through controlled bidirectional charging.



3) **Invest** in **sector-coupling technologies**, such as PtH$_2$tP and PtH, to reduce CO_2 emissions and enable flexibility provision.

4) **Encourage innovation** through research and development in clean energy technologies, including **green hydrogen-fired power plants** for **backup** capacity.



5) **Be aware of negative interaction effects** between different CO_2 abatement options and address these effects through effective policy formulations.

Overall, policymakers should use **step-wise model-derived MAC curves** to guide discussions on **climate change mitigation** and **achieve greater CO_2 emission reductions**.

Thank you for your attention!

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MACC algorithm integrated in the linear optimization model ELTRAMOD

Approach

- Analysis is based on the **linear optimization model ELTRAMOD** (dispatch version / MIN TC) with an **integrated multi-iterative capacity expansion algorithm** that determines the **minimal CCA** of an additional unit of a decarbonization measure (ELTRAMOD-MACC)

5-steps MACC algorithm

0) Input for the **reference system** is defined.
1) Reference system is **modified by adding an incremental value** (I_m) of a decarbonization measure.
2) Model determines the **cost-minimal dispatch** and the **CO_2 reduction**.
3) If CO_2 is reduced by adding a decarbonization, the **CCA is calculated**.
4) Algorithm checks whether **CCA** of the modified system is **lower than the CCA of the previous 'best' energy**. If true, the modified system with its results is saved as the **new 'best' system**.
5) In the outer loop, the model validates if the decarbonization measures' **expansion potential** (dv_{Max}) **will be exceeded** in the next step.

$\boldsymbol{loop}$ $(\boldsymbol{it},$ $\quad it \in \{1,\dots,228\};\ m \in \{1,\dots,9\}$

$\boldsymbol{loop}$ $(\boldsymbol{m},$

$\boldsymbol{if}$ $(limit(m) = false),$

1. $dv_{new} = dv + I_m;$ Eq. (1)

2. *Solve ELTRAMOD using LP, minimizing TC;*

Calculation of dispatch results, e.g.:

$CO_2;\ TC;$

$CO_2red = CO_2 - CO_2^{Ref};$ Eq. (2)

3. $\boldsymbol{if}$ $(CO_2red < 0),$

$$CCA = \frac{\Delta TC}{\Delta CO_2} = \frac{TC - TC^{Ref}}{CO_2^{Ref} - CO_2},$$ Eq. (3)

$else\ CCA\ not\ defined;$

4. $\boldsymbol{if}$ $(CO_2red < 0$ $\boldsymbol{and}$ $CCA < CCA^{Best}),$ Eq. (4)

$dv^{Best} = dv_{new};$

$CCA^{Best} = CCA;$

$CO_2^{Best} = CO_2;$

$TC^{Best} = TC;$

inner loop

);

5. $\boldsymbol{if}$ $((dv^{Best} + I_m \geq dv^{Max}),$ Eq. (5)

$limit(m) = true);$

$dv = dv^{Best};$

$CO_2^{Ref} = CO_2^{Best};$

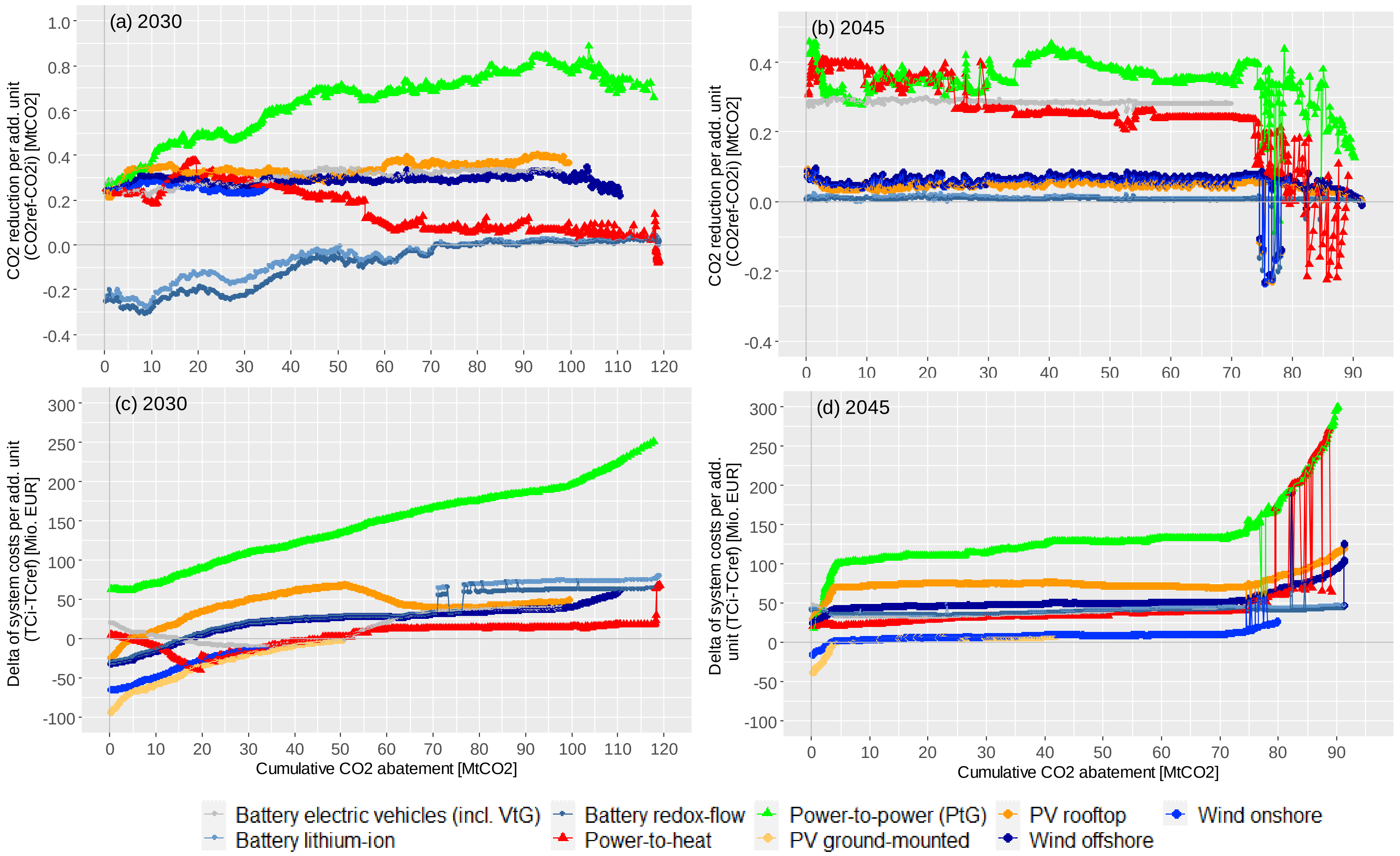
$TC^{Ref} = TC^{Best};$

outer loop

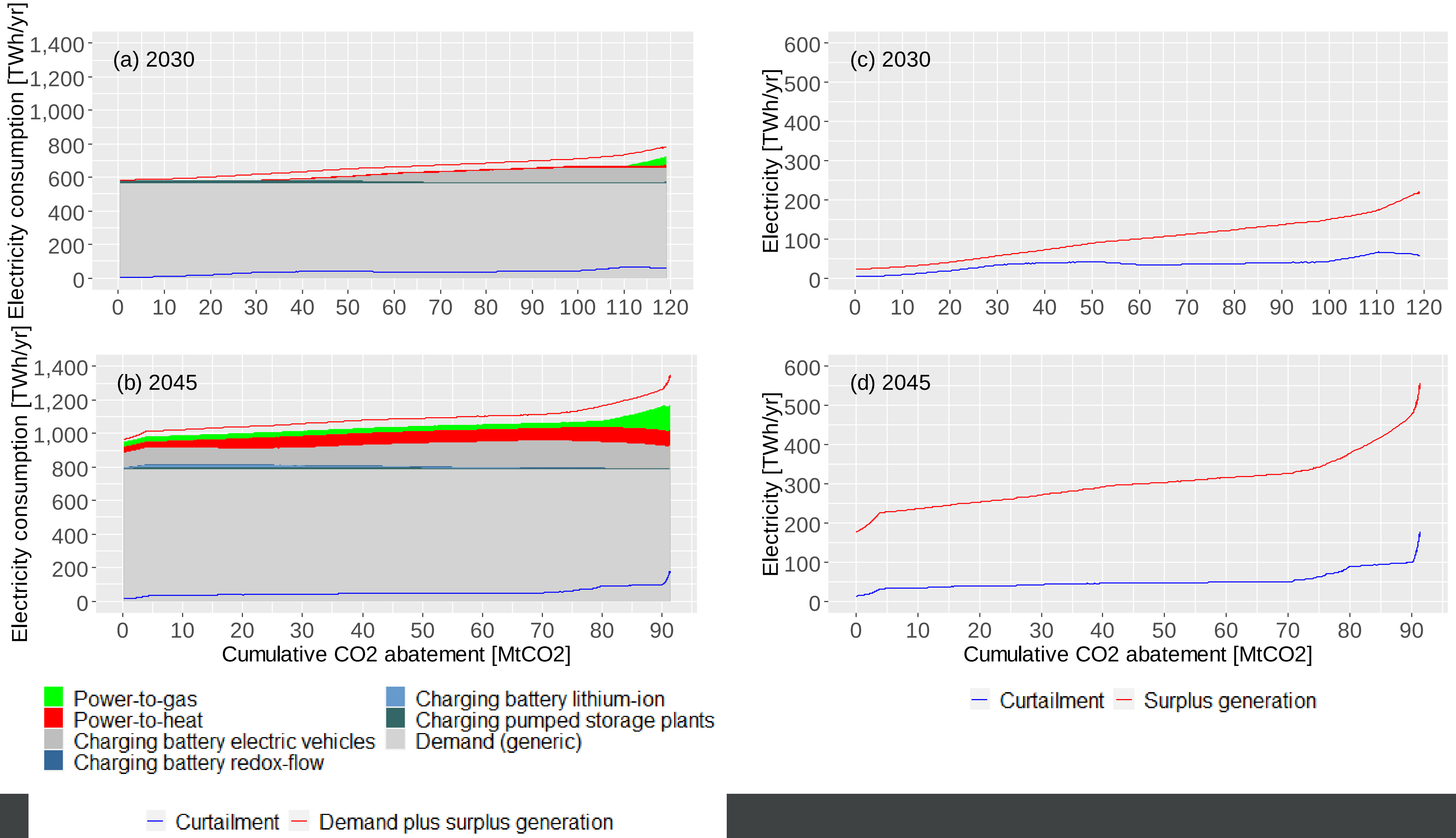
);

Source: based on an approach of EPLANoptMAC from Prina et al. (2021)

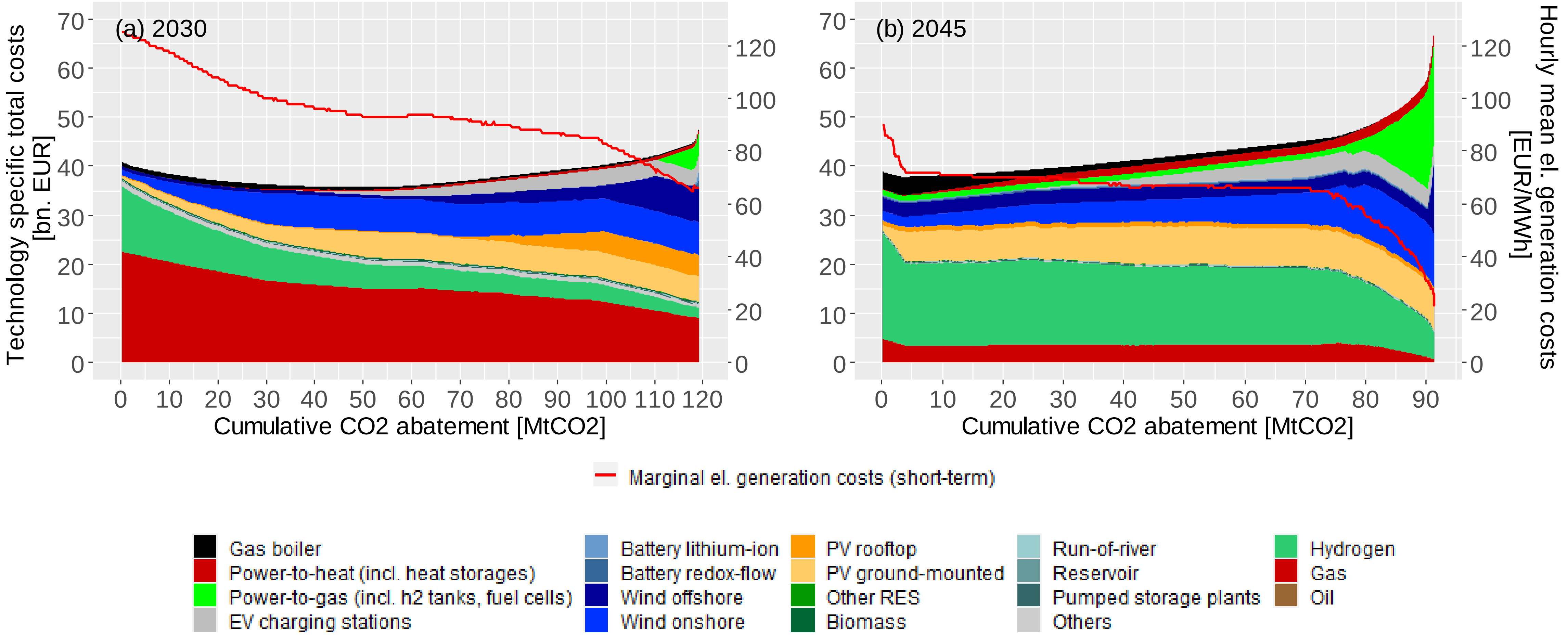
Comparison of CO_2 reduction potential and total cost development



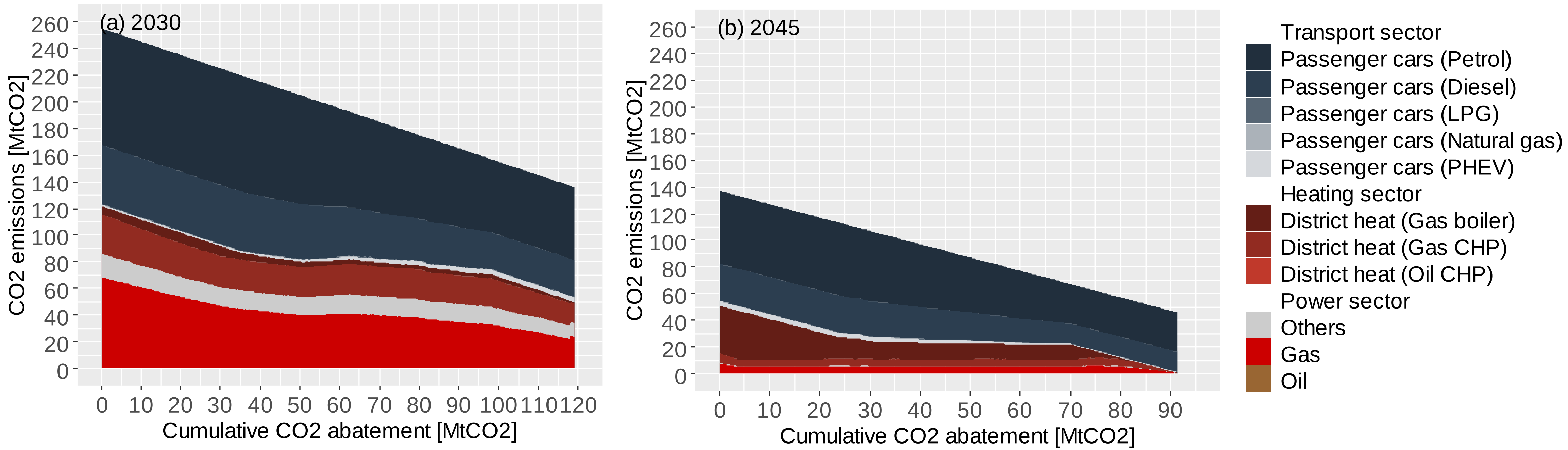
Comparison of electricity consumption, curtailments, and surplus generation



Comparison of technology-specific total cost development and short-term electricity generation costs



Comparison of sector-specific CO_2 emission reduction



	2030		2045	
	Remaining CO_2	CO_2 reduction	Remaining CO_2	CO_2 reduction
Sector	*[Mtco2]*	*[Mtco2]*	*[Mtco2]*	*[Mtco2]*
Power	34.6	51.6	0.1	5.6
Heating	15.1	20.4	0.5	28.5
Transport	86.3	47.0	45.3	16.7
Total	**135.9**	**119.1**	**45.8**	**50.9**