Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Electronic Supplementary Information:

Power-to-What? – Environmental assessment of energy storage systems

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S1 Surplus electricity supply and demand

Table S1: Expected surplus electricity in different countries. Values taken from case studies.

Country	Ireland[1]	Australia[2]	Australia[2]	Germany[3]	Germany[3]	Germany[3]
Intermittent power penetration	37 %	88 %	88 %	84 %	84 %	84 %
Wind power penetration	37 %	46 %	59 %	65 %	65 %	65 %
Solar power penetration	-	42 %	29 %	19 %	19 %	19 %
Considered PHS	0.3 GW	2.2 GW	2.2 GW	-	-	8.6 GW
DSM considered	No	No	No	No	Yes	Yes
Surplus electricity	[a]	9 TWh	25 TWh	154 TWh	83 TWh	79 TWh
share in intermittent power generation	6.6 - 15.3 %	8.5 %	17.2 %	30.2 %	18.7 %	18.4 %
share in total power generation	2.6 - 6.7 %	4.1 %	10.9 %	22.0 %	13.0 %	12.8 %

[a] value not mentioned in reference

Table S2: Surplus electricity demand for global demand of platform chemicals

Platform chemicals	Global demand	Required surplus electricity
Hydrogen [a]	65 Mt/a (Ref[4])	3250 - 5417 TWh/a
Methanol [b]	59 Mt/a (Ref[5])	578 - 964 TWh/a
Syngas [b,c]	2.1 Mt/a	25 - 41 TWh/a

[a] for conversion factor see Table S4 (PEM electrolysis);

[b] for conversion factor see Table S4 (PEM electrolysis) and Table S5 ($m_{H_2,in}$);

[c] syngas demand for polyurethane production (5 Mt/a MDI and 1.9 Mt/a TDI)[6]

Table S3: Surplus electricity demand for space heating, natural gas and mobility in the US.

	US demand	Required surplus electricity
Space heating [a]	1200 TWh/a (Ref [7])	245 - 571 TWh/a
Natural gas [b]	1400 TWh/a (Ref [7])	2500 - 4167 TWh/a
Mobility [c]	2.3E+12 km/a (Ref [7])	316 - 451 TWh/a

[a] for conversion factor see Table S4 (Heat pump);

[b] for conversion factor see Table S4 (PEM electrolysis) and Table S5 ($m_{H_2,in}$);

[c] for conversion factor see Table S4 (Battery electric vehicle)

S2 Data for considered energy storage systems and conventional processes

Table S4: Electricity and natural gas demand of surplus power using devices

PHS	$W_{el,out}/W_{el,in}$	0.65 - 0.85 kWh/kWh	Ref [8–11]
VRB	$W_{el,out}/W_{el,in}$	0.65 - 0.85 kWh/kWh	Ref [8,9,11]
CAES	$W_{el,in}/W_{el,out}$	0.7 - 0.8 kWh/kWh	Ref [12]
	$Q_{natural\ gas,in}/W_{el,out}$	1.2 - 1.3 kWh/kWh	
Heat pump	$Q_{heat,out}/W_{el,in}$	2.1 - 4.9 kWh/kWh	Ref [13]
PEM electrolysis[a]	$W_{el,in}/m_{H_2,out}$	45 - 55 kWh/kg	Ref [14]

[a] Case: Future Central Hydrogen Production from PEM Electrolysis version 3.0

Table S5: Inputs and outputs of hydrogen conversion processes per kg product

Product	Input				Output		
	$m_{H_2,in}$	$m_{CO_2,in}$	$W_{el,in}$ [a]	$Q_{heat,in}$	$m_{CO_2,out}$ [b]	$m_{H_2,out}$ [c]	
	kg	kg	kWh	kWh	kg	kg	
Syngas	0.236	1.303	1.34	0.61	-	-	Ref [15]
Methane	0.506	2.939	0.33	-	0.194	0.009	Ref [16]
Methanol	0.196	1.437	1.33	-	0.046	-	Ref [17]

[a] grid power; [b] emission; [c] mixed with main product

Table S6: Fuel demand of vehicles and fuel cell

Battery electric vehicle	$W_{\mathrm{el,in}}/l_{\mathrm{out}}$	0.14 - 0.20 kWh/km	Ref[18,19]
H_2 fuel cell vehicle	$Q_{\mathrm{H_2,in}}/l_{\mathrm{out}}$	0.34 - 0.36 kWh/km	Ref[20,21]
Gasoline engine[a]	$Q_{\mathrm{gasoline,in}}/l_{\mathrm{out}}$	0.52 kWh/km	Ref[22]
Diesel engine[a]	$Q_{\mathrm{diesel,in}}/l_{\mathrm{out}}$	0.38 kWh/km	Ref[22]
Methanol engine[b]	$Q_{\mathrm{CH_3OH,in}}/l_{\mathrm{out}}$	0.52 kWh/km	
Methane engine[c]	$Q_{\mathrm{CH_4,in}}/l_{\mathrm{out}}$	0.44 kWh/km	
Fuel cell	$W_{\mathrm{el,out}}/Q_{\mathrm{in}}$	0.45 - 0.60 kWh/kWh	Ref[23]

[a] Euro 5, engine displacement $< 1.4\ l$; [b] gasoline engine efficiency[24]; [c] 86.5 % of diesel engine efficiency[25]

Table S7: Considered LCA data sets for energy storage systems and conventional processes[22]

Product	Name of data set	Year
Grid power	electricity mix	2010
CO_2 [a]	thermal energy from coal	2010
Power from gas turbine	based on heat from natural gas (efficiency of 40 %)	-
Mobility (diesel)	diesel mix, at refinery [c]	2010
Mobility (gasoline)	gasoline mix (RON 95), at refinery [c]	2010
Heat	thermal energy from natural gas (efficiency of 91 %)	2010
Hydrogen [b]	hydrogen (steam reforming - natural gas)	2012
Natural gas	natural gas mix	2010
Methanol [b]	methanol from natural gas (integrated technologies)	2012
Syngas [b]	syngas (H_2:CO = 3:1) from natural gas	2012

[a] own calculation based on Ref[26]; [b] country specific values derived from natural gas data set;
[c] Euro 5, engine displacement $< 1.4\ l$

Table S8: Global warming impact (*GW*) and fossil depletion impact (*FD*) for construction of energy storage systems. All values are per MWh surplus electricity.

Technology	*GW*	*FD*	Life time	
	kg_{CO_2-eq}	kg_{Oil-eq}		
Pumped hydro storage	3.2 - 4.8	1.0 - 1.4	12,000 - 25,000 cycles	Ref [12,27]
Compressed air energy storage	3.8 - 5.4	1.3 - 1.8	8,000 - 25,000 cycles	Ref [12,27]
Vanadium redox flow battery	24.8 - 58.8	8.2 - 19.6	2,900 - 7,500 cycles	Ref [12,27]
Lithium-ion battery for BEV	36.1 - 76.7	7.6 - 16.2	4,000 - 8,500 cycles	Ref [18,27]
Heat pump [f]	76.2 - 89.2	4.7 - 7.0	32,000 - 48,000 h	Ref [28]
PEM electrolysis [a]	1.8 - 2.7	0.7 - 1.1		
Hydrogen storage [b]	2.2 - 3.3	0.9 - 1.3		Ref [29]
Heat storage (hot water tank)[c]	5.1 - 7.6	1.7 - 2.5	20 - 30 a	Ref [28]
Methanol storage[c]	2.4E-02 - 3.7E-02	7.8E-03 - 1.2E-02	40 - 60 a	Ref [28]
Methane plant[d]	1.8E-02 - 1.8E-02	4.9E-03 - 7.3E-03		
Methanol plant	6.9E-02 - 1.0E-01	2.0E-02 - 3.0E-02	24 - 36 a	Ref [28]
Syngas plant	6.4E-02 - 9.6E-02	1.8E-02 - 2.6E-02	40 - 60 a	Ref [28]
PEM fuel cell[e]	1.8 - 2.7	0.7 - 1.1	32,000 - 48,000 h	Ref [30]

[a] value of fuel cell assumed[31]; [b] life time not mentioned in reference; [c] utilization: 200 cycles/a; [d] own calculation based on syngas plant; [e] 90 % platinum group metal recycling assumed; [f] values include leakage of refrigerant

Table S9: Considered countries for heat from natural gas and natural gas mix

Continent	Number of considered countries	ISO-Code of considered countries
America	2	BR US
Asia	2	IN JP
Australia	2	AU NZ
Europe	23	AT BE CH DE DK ES FR GB GR HU IE IT LT LU LV NL NO PL PT RO SE SI SK

Table S10: Considered countries for electricity mix

Continent	Number of considered countries	ISO-Code of considered countries
America	2	BR US
Asia	2	IN JP
Australia	2	AU NZ
Europe	30	AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU
		IE IS IT LT LU LV MT NL NO PL PT RO SE SI SK

Table S11: Considered countries for coal mix

Continent	Number of considered countries	ISO-Code of considered countries
America	2	BR US
Asia	2	IN JP
Australia	2	AU NZ
Europe	10	AT BE DE DK FR
		GB IT NL NO SE

Table S12: Considered countries for gasoline and diesel

Continent	Number of considered countries	ISO-Code of considered countries
America	2	BR US
Asia	2	IN[a] JP
Australia	1	AU
Europe	2	DE GB

[a] For IN only diesel considered

Table S13: Costs for Power-to-Power, Power-to-Mobility, Power-to-Heat, Power-to-H_2 storage systems and conventional systems. All cost are for 2020 ($2010).

Technology	Power capacity capital costs $/ kW	Energy capacity capital costs $/ kWh	variable O&M costs[a] $/ kWh	fixed O&M costs[a] $/ (kW·a)	life time a
Pumped hydro storage (Ref[32])	908 - 1236	12.3 - 17.4	-	3.0	40
Compressed air energy storage (Ref[32])	412 - 501	1.2 - 62.8	-	3.0 - 7.1	40
Vanadium redox flow battery (Ref[32])	537 - 1840	215 - 307	-	56.0	40
Natural gas turbine (Ref[33])	660	-	0.03	5.3	40
Electric drive train for BEV (Ref[20])	1200 - 2030 $	-	-	-	13.2
Battery for BEV (Ref[34])	-	273 - 386	-	-	13.2
Conventional drive train (Ref[20])	2400 - 2530 $	-	-	-	13.2
Heat pump (Ref[35]) [a]	974 - 1491	-	-	6.5	20
Electric boiler (Ref[35]) [a]	182 - 286	-	-	-	20
Heat storage (Ref[36]) [a]	-	116 - 223	-	-	40
Natural gas boiler (Ref[35]) [a]	943	-	-	5.7	20
PEM elctrolysis (Ref[14])	465 - 698	-	-	35.4	40
Hydrogen storage (Ref[14])	-	390 - 584 $/ kg H_2	-	-	30

[a] O&M - operation and maintenance; [a] assumed exchange rate: 1 Euro = 1.3 US Dollar

Table S14: Costs for feedstocks and conventional produced hydrogen for 2020 in the US ($2010)

Feedstock	Costs	
Residential natural gas	49.6 $/ MWh	Ref[14]
Industrial natural gas	29.5 $/ MWh	Ref[14]
Industrial electricity	67.1 $/ MWh	Ref[14]
Gasoline	102.6 $/ MWh	Ref[20]
CO_2	70 $/ t	Ref[37]
Hydrogen	1.6 $/ kg	Ref[14]

Table S15: Inputs per kg product for conventional production of methanol and syngas

Product	natural gas	electricity	
Methanol	9.03 kWh	0.074 kWh	Ref[28]
Syngas	10.44 kWh	0.713 kWh	Ref[15]

S3 Results

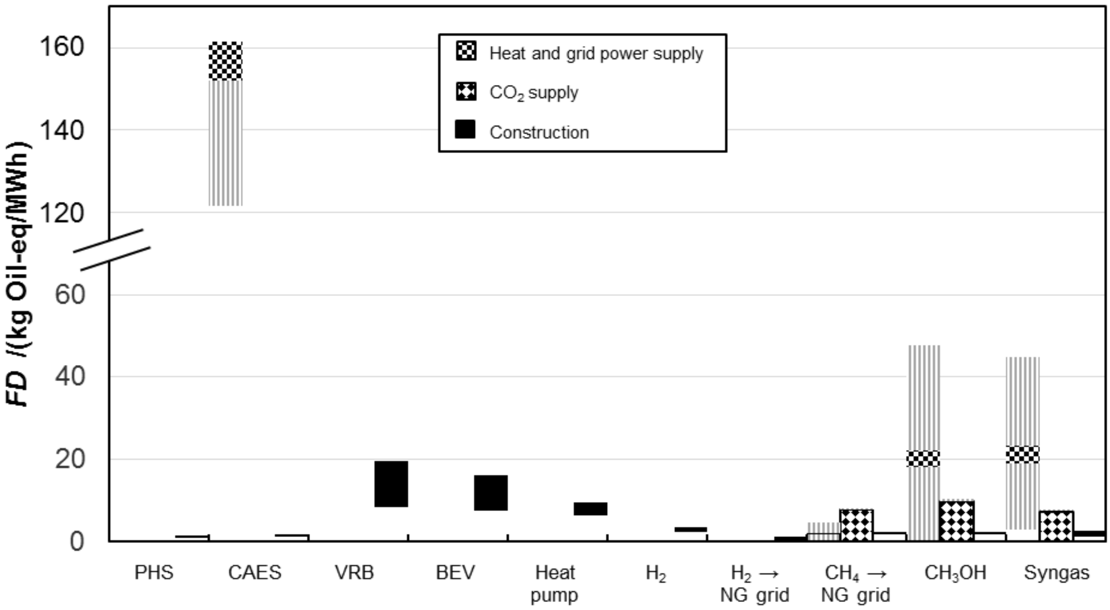

Fig. S1: Breakdown of fossil depletion (*FD*) impact of energy storage systems into considered processes. All values are per MWh surplus electricity. The narrow ranges (patterned) represent country-specific LCA data sets for the US considering the technology uncertainties. The broad ranges (gray striped) further include the full range of LCA data sets for all countries. If only one range is shown, fossil depletion impacts are independent from country-specific LCA data sets. For CO_2 supply, only the fossil depletion impact for the scenario *CO_2 emissions avoided* is shown. For the scenario *CO_2 storage avoided*, the corresponding fossil depletion impact would be zero. PHS - pumped hydro storage; CAES - compressed air energy storage; VRB - vanadium redox flow battery; BEV - battery electric vehicle; NG - natural gas

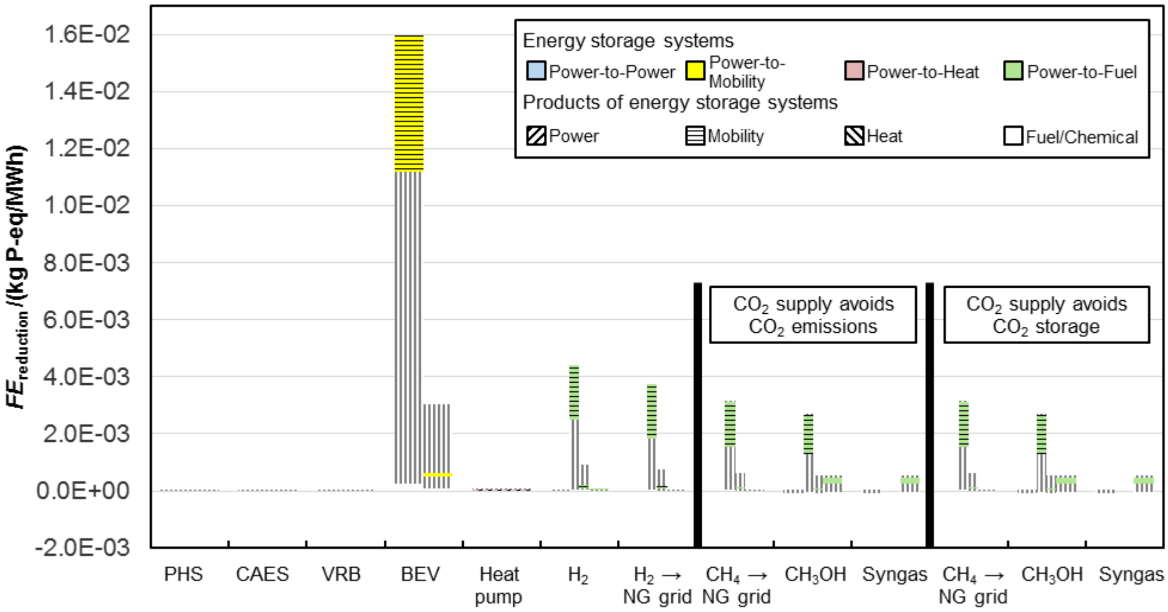

Fig. S2: Freshwater eutrophication (FE) impact reduction for the considered energy storage systems. The narrow ranges (colored) represent country-specific LCA data sets for the US considering the technology uncertainties. The broad ranges (gray striped) further include the full range of LCA data sets for all countries. For Power-to-Fuel systems, impact reductions are shown for the different utilization routes of the products. For CO_2-using Power-to-Fuel systems, the freshwater eutrophication impact reductions are shown for both CO_2 supply scenarios (*CO_2 emissions avoided* and *CO_2 storage avoided*). PHS - pumped hydro storage; CAES - compressed air energy storage; VRB - vanadium redox flow battery; BEV - battery electric vehicle; NG - natural gas

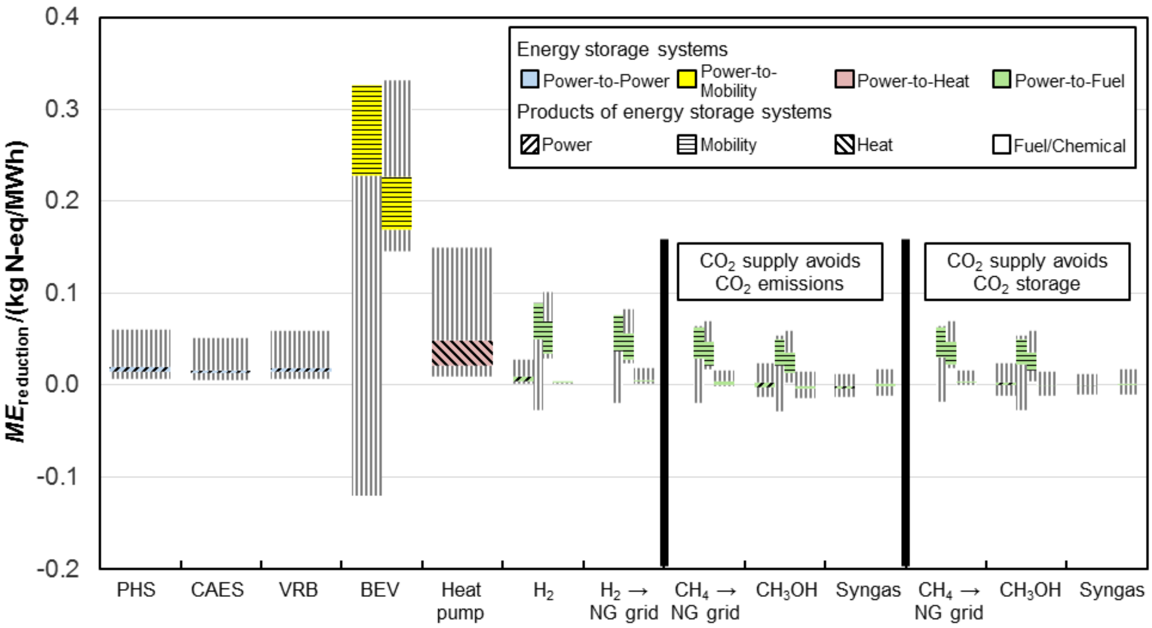

Fig. S3: Marine eutrophication (ME) impact reduction for the considered energy storage systems. For further information, see caption Fig. S2.

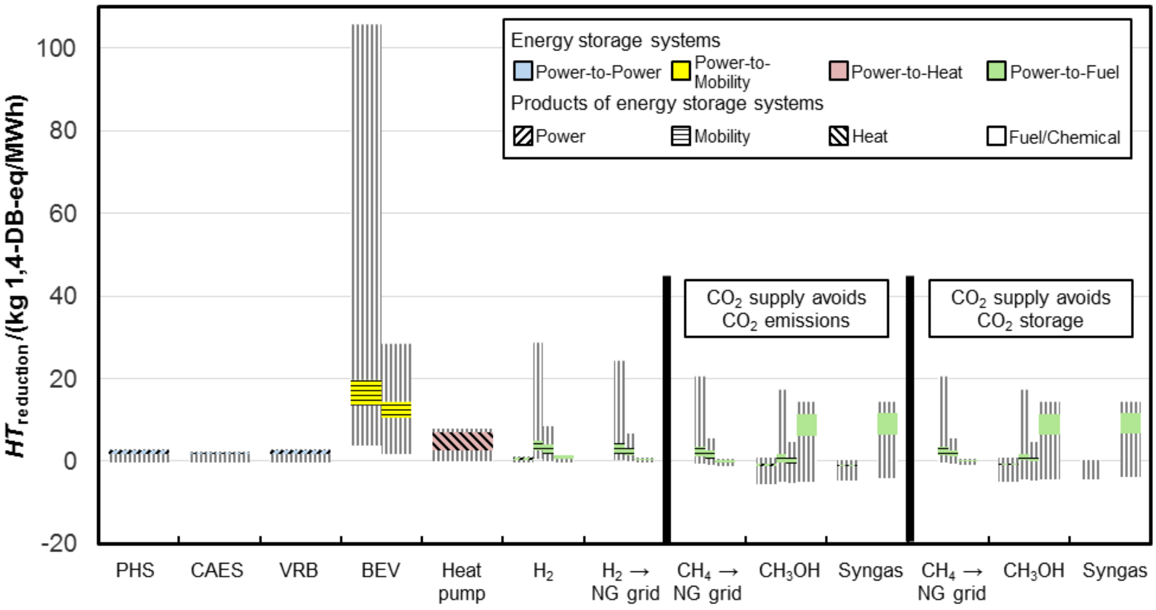

Fig. S4: Human toxicity (HT) impact reduction for the considered energy storage systems. For further information, see caption Fig. S2.

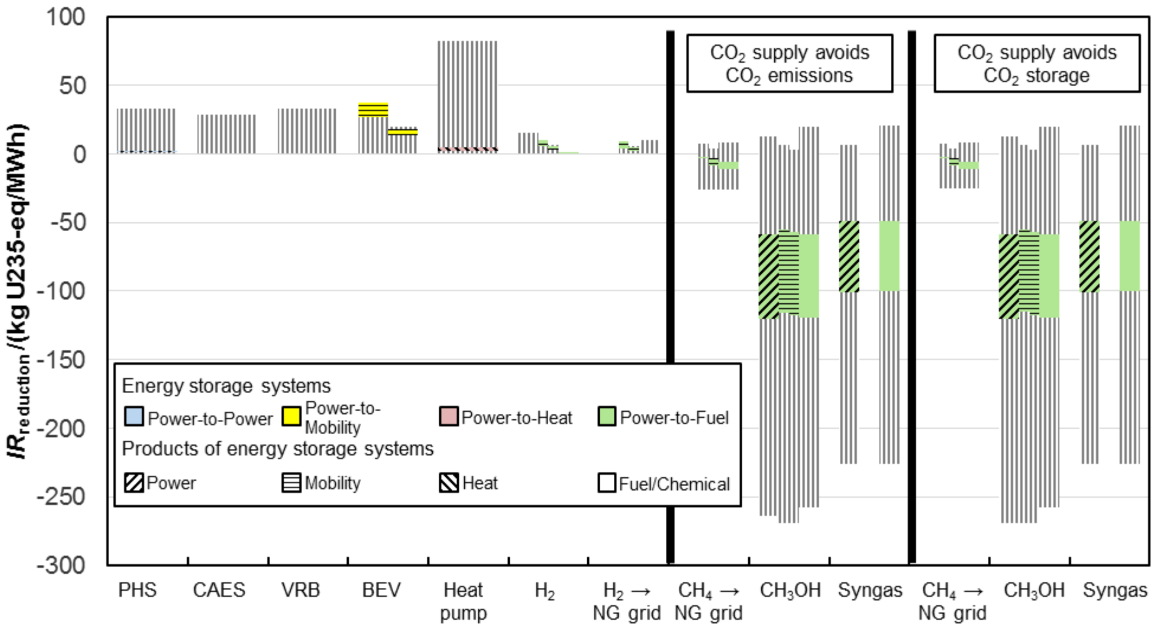

Fig. S5: Ionizing radiation (*IR*) impact reduction for the considered energy storage systems. For further information, see caption Fig. S2.

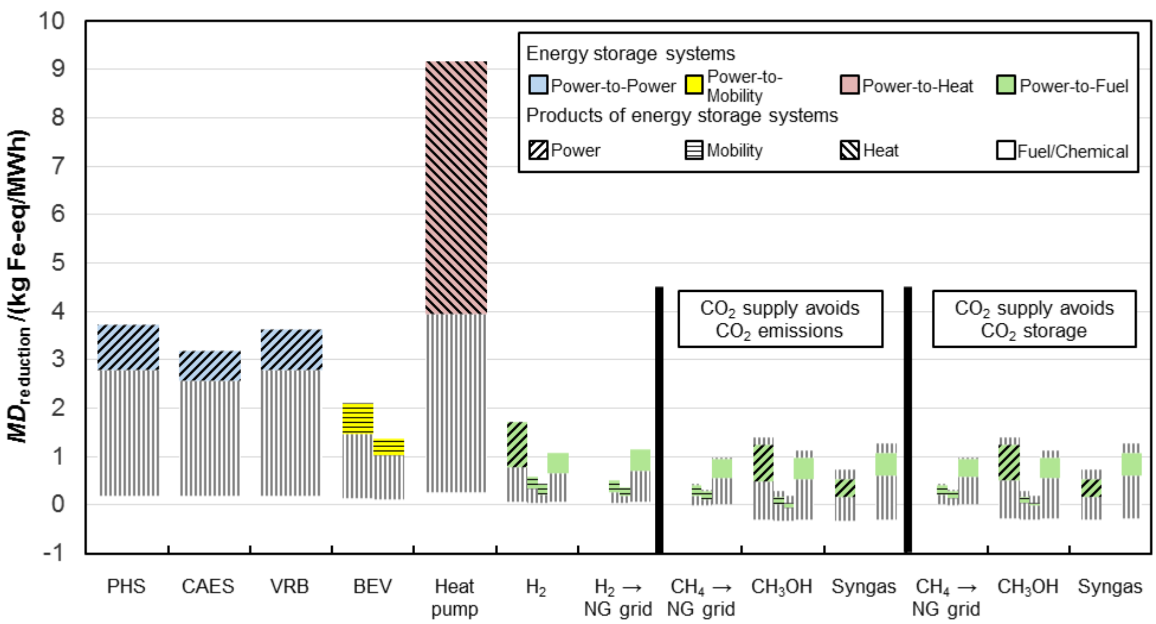

Fig. S6: Mineral resource depletion (*MD*) impact reduction for the considered energy storage systems. For further information, see caption Fig. S2.

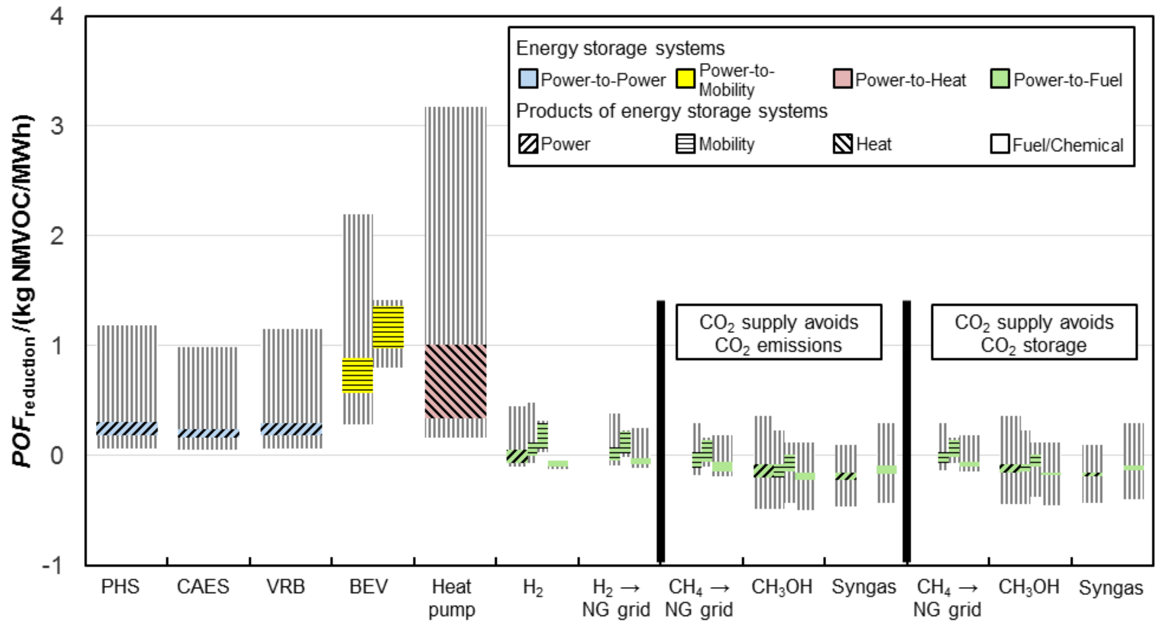

Fig. S7: Photochemical oxidant formation (*POF*) impact reduction for the considered energy storage systems. For further information, see caption Fig. S2.

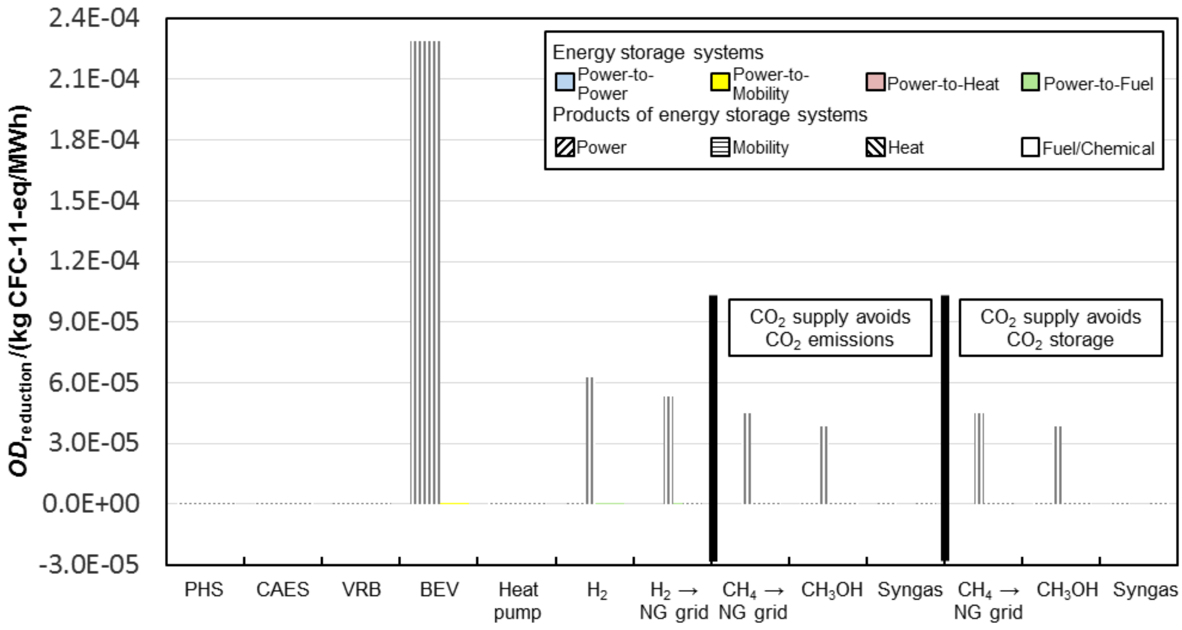

Fig. S8: Ozone depletion (*OD*) impact reduction for the considered energy storage systems. For further information, see caption Fig. S2.

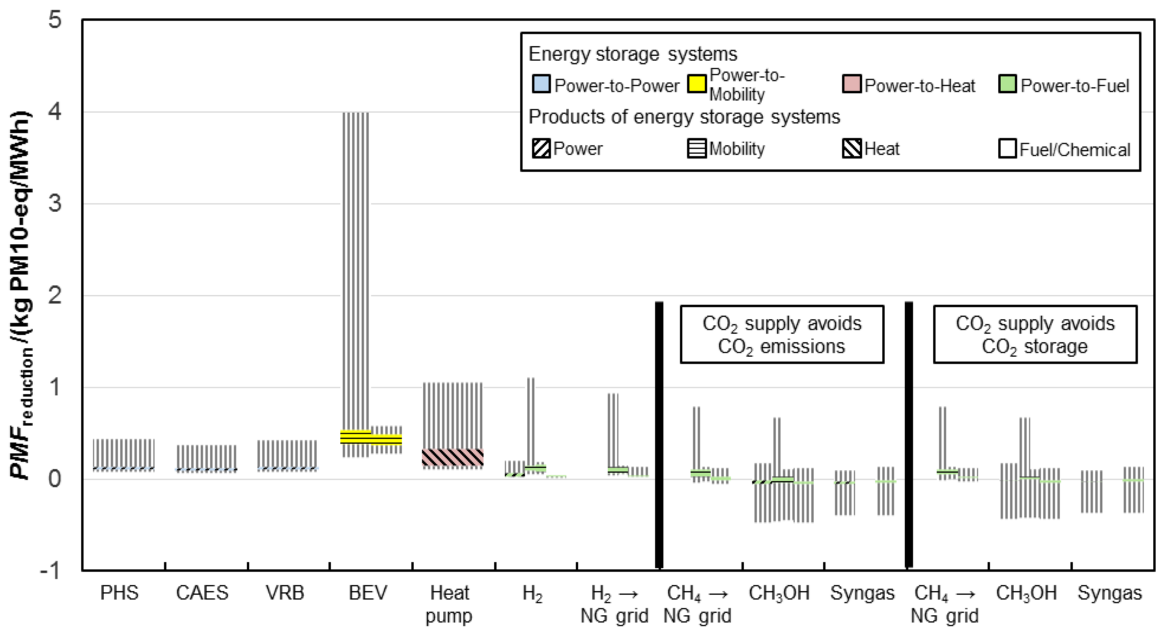

Fig. S9: Particulate matter formation (*PMF*) impact reduction for the considered energy storage systems. For further information, see caption Fig. S2.

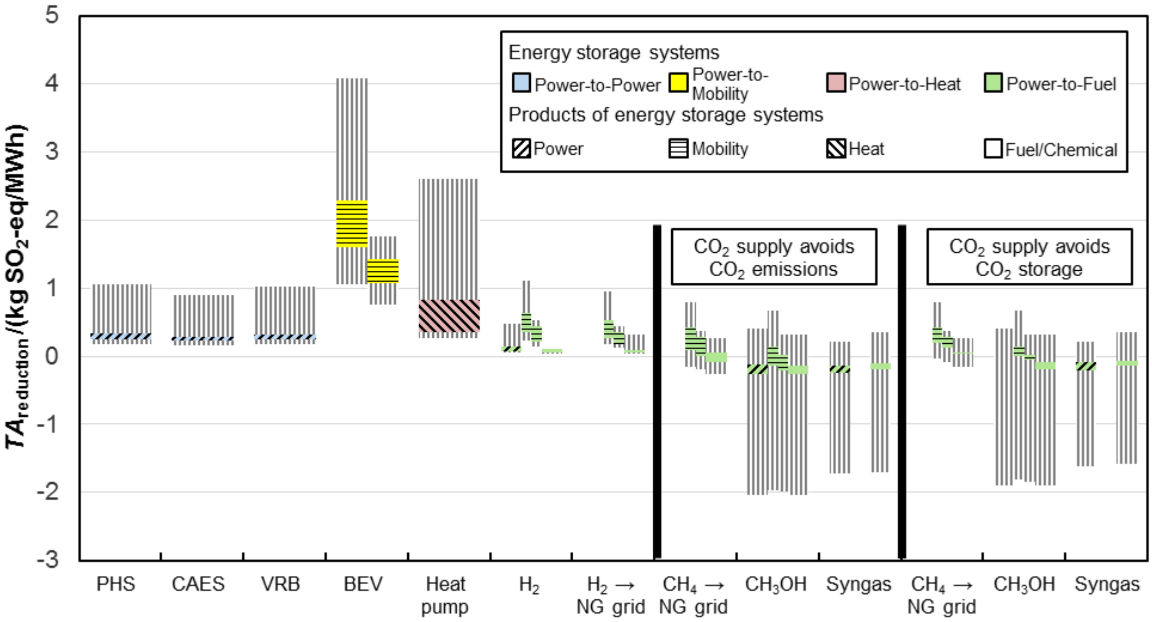

Fig. S10: Terrestrial acidification (*TA*) impact reduction for the considered energy storage systems. For further information, see caption Fig. S2.

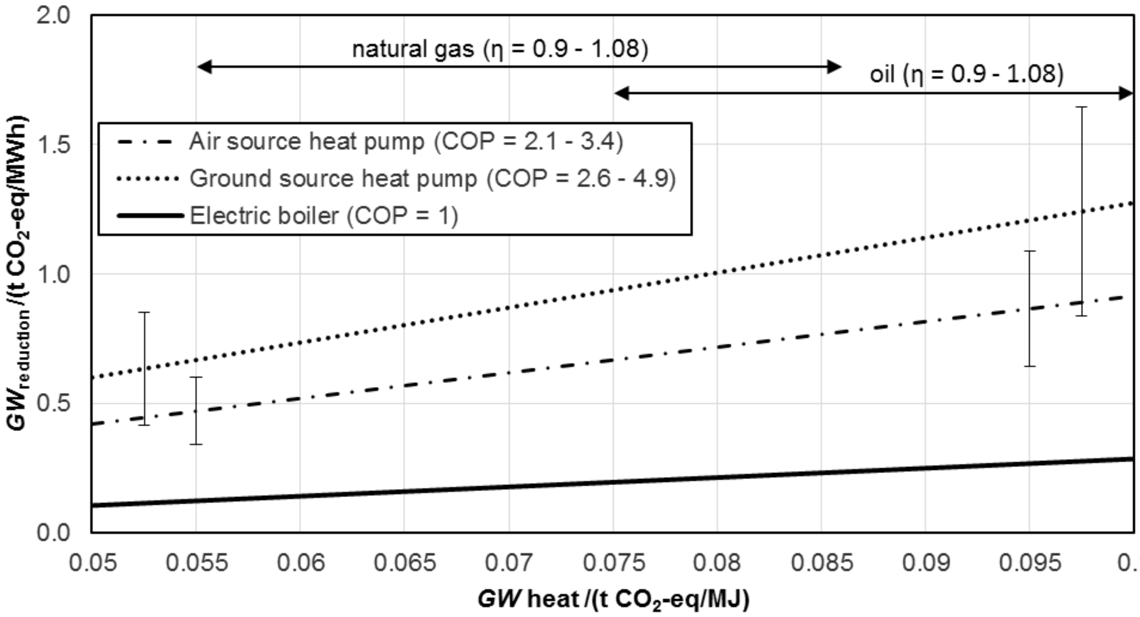

Fig. S11: Global warming impact reductions ($GW_{reduction}$) for Power-to-Heat storage systems depending on the global warming impact of the conventional process (*GW* heat). The error bars indicate the possible range for each energy storage system considering the presented coefficient of performance (COP). On top of the graph, the typical range for the conventional processes heat from oil and heat from natural gas is shown. This range includes the presented range of efficiencies and LCA data sets for different countries.

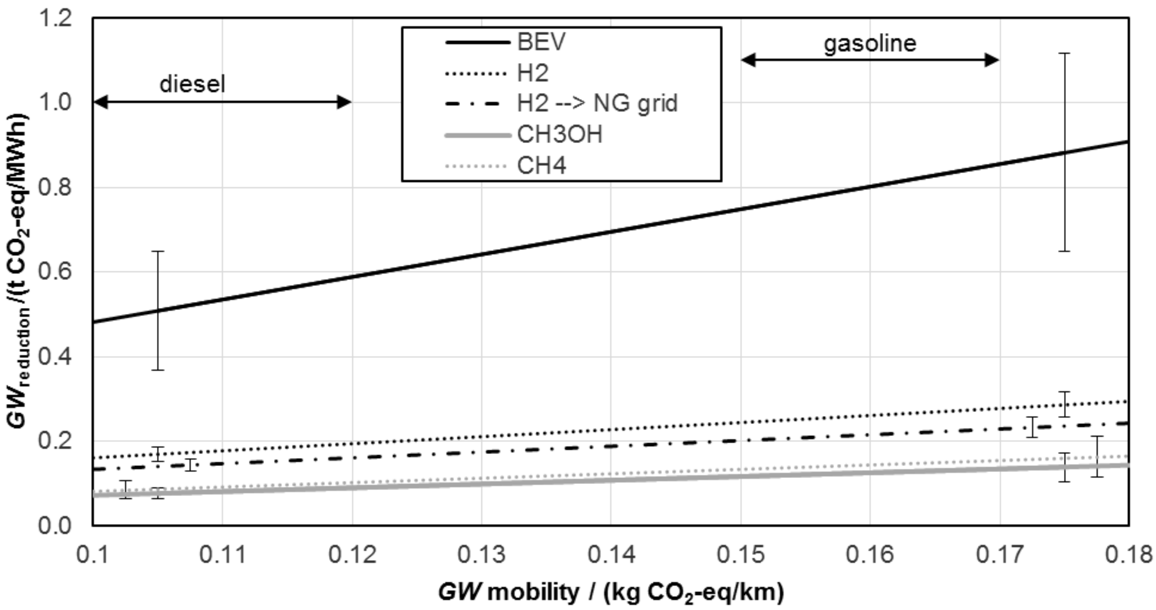

Fig. S12: Global warming impact reductions ($GW_{reduction}$) for Power-to-Mobility storage systems depending on the global warming impact of the conventional process (*GW* mobility). The error bars indicate the possible range for each energy storage system considering the presented efficiencies in Table S4 and S6. On top of the graph, the typical range for the conventional processes mobility from gasoline and mobility from diesel is shown. This range includes LCA data sets for different countries.

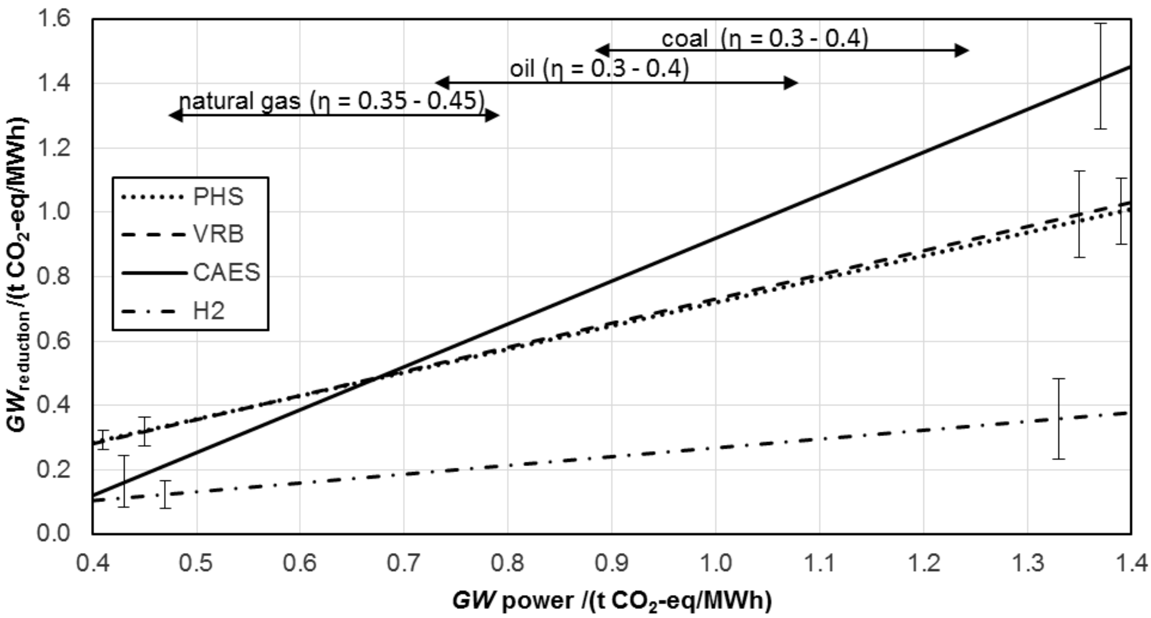

Fig. S13: Global warming impact reductions ($GW_{reduction}$) for Power-to-Power storage systems depending on the global warming impact of the conventional process (*GW* power). The error bars indicate the possible range for each energy storage system considering the presented efficiencies in Table S4 and S6. On top of the graph, the typical range for the conventional processes power from natural gas, oil and coal is shown. This range includes the presented range of efficiencies and LCA data sets for different countries.

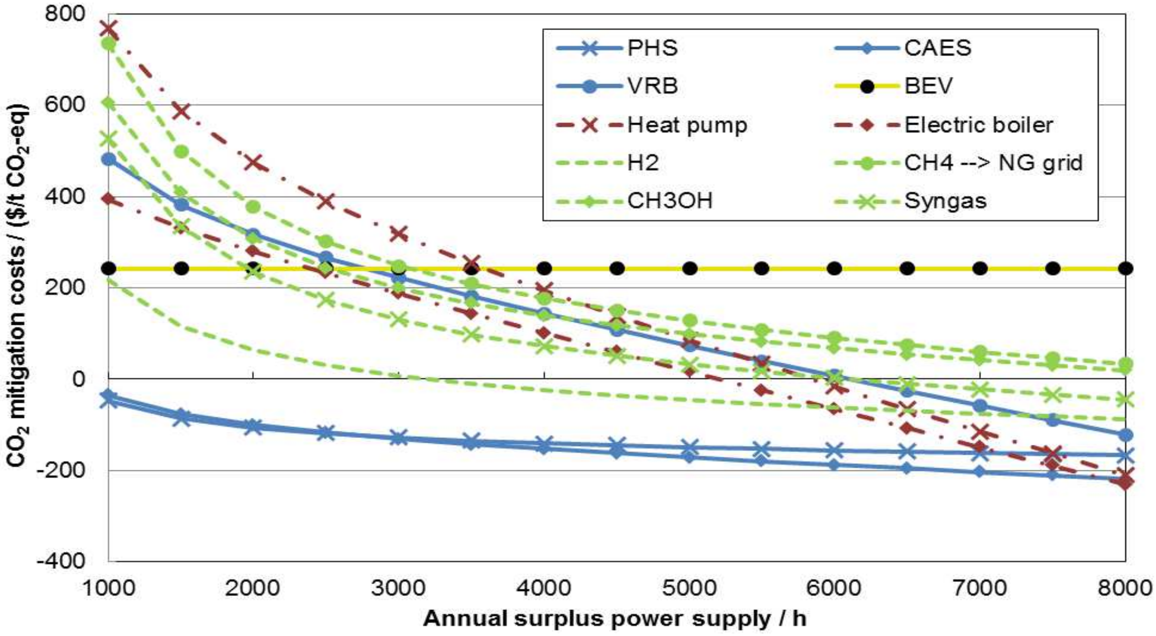

Fig. S14: CO_2 mitigation costs of energy storage systems as a function of available surplus power. In this case, surplus power occurs once a week.

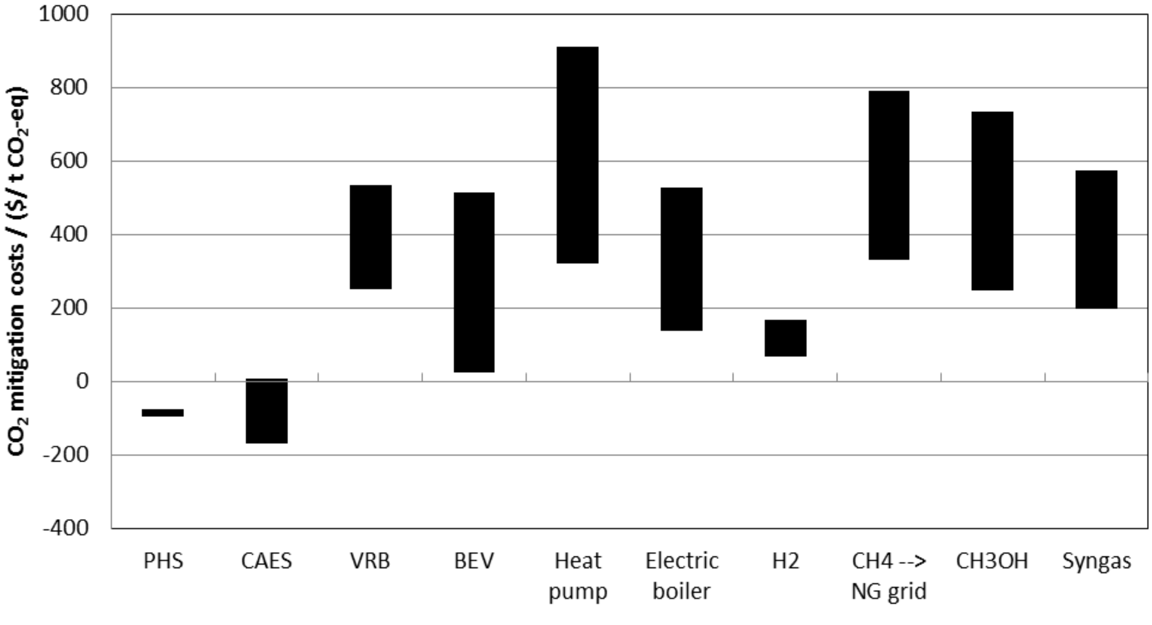

Fig. S15: CO_2 mitigation costs of energy storage systems for 1500 hours with surplus power supply. In this case, surplus power occurs once a week. The ranges represent US-specific LCA data sets considering the technology uncertainty and the economic uncertainty presented in Table S13.

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