Technical and Economic Potential of Distributed Energy Storages for the Integration of Renewable Energy

Executive Summary

Prepared as a part of IEA ECES Annex 28: Distributed Energy Storage for the Integration of Renewable Energy (DESIRE)

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1 Introduction

In this work, which is carried out as a part of subtask 3 of IEA ECES Annex 28, the aim is to identify which distributed energy storage (DES) technologies could be technically and economically beneficial for the integration of fluctuating renewable energy sources (RES) in different types of energy systems. In the subtask, the technical and economic potential for DES solutions is quantified, and it is identified which DES technologies have the largest total (technical and economic) potential. For this, different DES technologies are modelled in the context of a whole energy system on a national scale. For comparison and combination with the DES technologies, energy conversion technologies and other methods for balancing supply and demand in the system are also included in the modelling work. A categorization of the energy supply and demand balancing methods included in this work is shown in Figure 1.

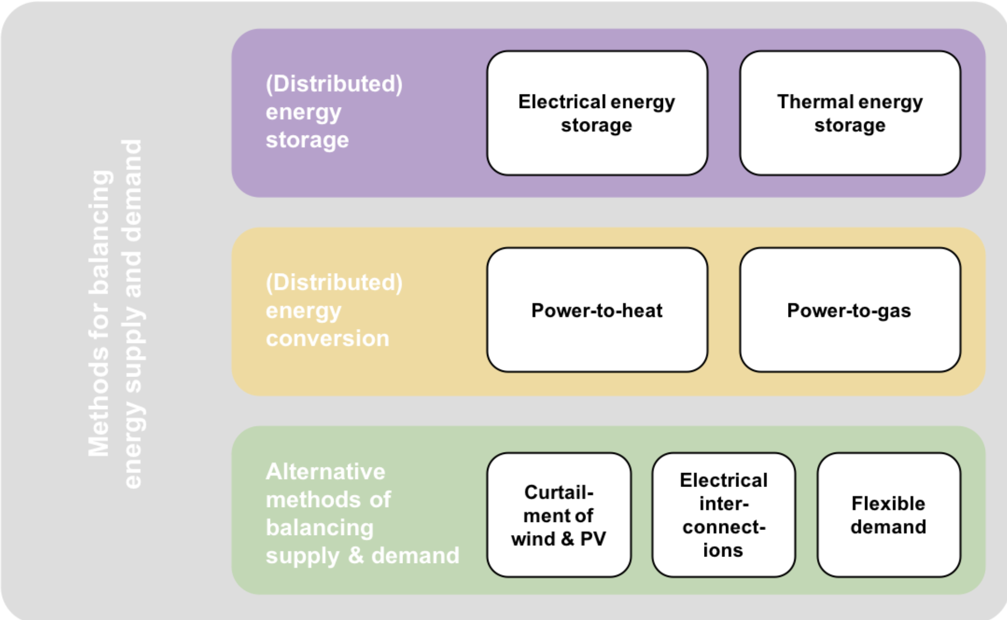


Figure 1 A categorization of the technologies for balancing energy supply and demand that are included in the modelling work in subtask 3.

2 Methodology

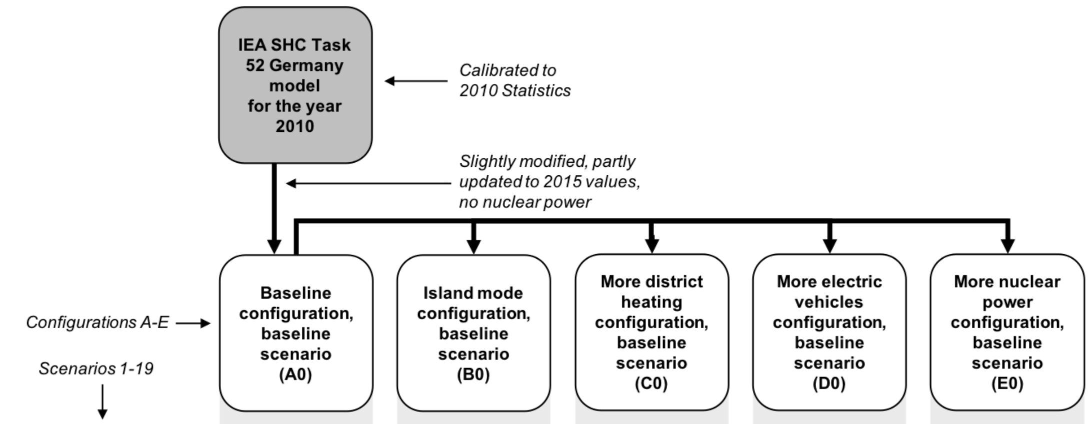
The modelling of the different technologies for energy supply and demand balancing is performed using a scenario-based approach. The scenario structure is illustrated in Figure 2. The technologies are modelled one at a time in scenarios 1-15 and as combinations in scenarios 16-19. The technologies are modelled within the settings of five different energy system typologies (configurations A-E). Each energy system configuration has a baseline scenario (A0-E0), to which the results of the other scenarios within the same configuration are compared. For each of the scenarios fifteen variations are introduced, where the electricity generation from fluctuating renewable energy sources (RES) (wind turbines and photovoltaics) is gradually increased with each variation to investigate the performance of the technologies in integrating fluctuating RES. This approach results in 63 scenarios, which each exist in fifteen variations, making a total of 945 model simulations. In addition to this, variations in the energy storage or conversion capacity have been carried out for some scenarios, and a sensitivity analysis has been carried out on some of the model input parameters. The modelling has been performed using the energy system simulation tool *EnergyPLAN*, developed by Aalborg University.

The results of the scenarios have been assessed using the three indicators shown in Figure 3. These indicators are used for quantifying the technical and economic impact of and potential for introduction of each technology in the energy system. The indicators are:

- The annually discharged energy. This is a measure of how well the technology facilitates the integration of fluctuating RES by consuming overproduction and “discharging” it (i.e. sending energy back) to the system again in another form or at another time.

- The reduction in the total annual CO_2 emissions arising from the operation of the energy system.

- The total annual socio-economic costs of the energy system. This is a measure of how much the operation of the energy system costs society as a whole during one year.



Scenarios 1-19	Baseline configuration, baseline scenario (A0)	Island mode configuration, baseline scenario (B0)	More district heating configuration, baseline scenario (C0)	More electric vehicles configuration, baseline scenario (D0)	More nuclear power configuration, baseline scenario (E0)
Curtailment (1)	A1	B1	C1	D1	E1
Interconnections (2)	A2^{+}	B2	C2	D2	E2
Flexible demand (3)	A3^{+}	-	-	D3	E3
El. Heating, DH (4)	A4	B4	C4	-	-
Heat pumps, DH (5)	A5	B5	C5	-	-
El. Heating, ind. (6)	A6^{+}	B6	C6	D6	E6
Heat pumps, ind. (7)	A7^{+}	B7	-	D7	E7
P2G (SNG) (8)	A8^{+}	B8	-	D8	E8
Li-ion batteries (9)	A9^{+}	B9	-	D9	E9
Li-ion + PV (10)	A10^{+}	B10	-	D10	E10
P2G2P (H_2) (11)	A11^{+}	B11	-	D11	E11
Vd-redox (12)	A12^{+}	B12	-	D12	E12
TTES+PTES, DH (13)	A13	-	C13	-	-
TTES+ATES, DH (14)	A14	-	C14	-	-
TTES, individual (15)	A15^{+}	-	C15	-	-
HP + TTES (16)	A16^{+} (A7+A15)	-	C16 (C5+C13)	-	-
HP+TTES+Flex. (17)	A17 (A3+A7+A15)	-	C17 (C3+C5+C13)	-	-
HP+TTES+Li-ion (18)	A18^{+} (A7+A9*+A15)	-	C18 (C5+C9*+C13)	D18 (D7+D9*+D15)	-
HP+TTES+(Li+PV) (19)	A19 (A7+A10+A15)	-	C19 (C5+C10+C13)	-	-

Figure 2 A listing of all modelled distributed energy storage or conversion technology scenarios (#1-19), and in which energy system configurations (A-E) they were modelled.

The scenarios are considered feasible if the introduction of the technology simultaneously lowers the CO_2 emissions and total system cost and increases the discharged energy, compared to the baseline scenario of the same energy system configuration. The potential of each technology is assessed based on the combined performance of each technology in the three indicators.

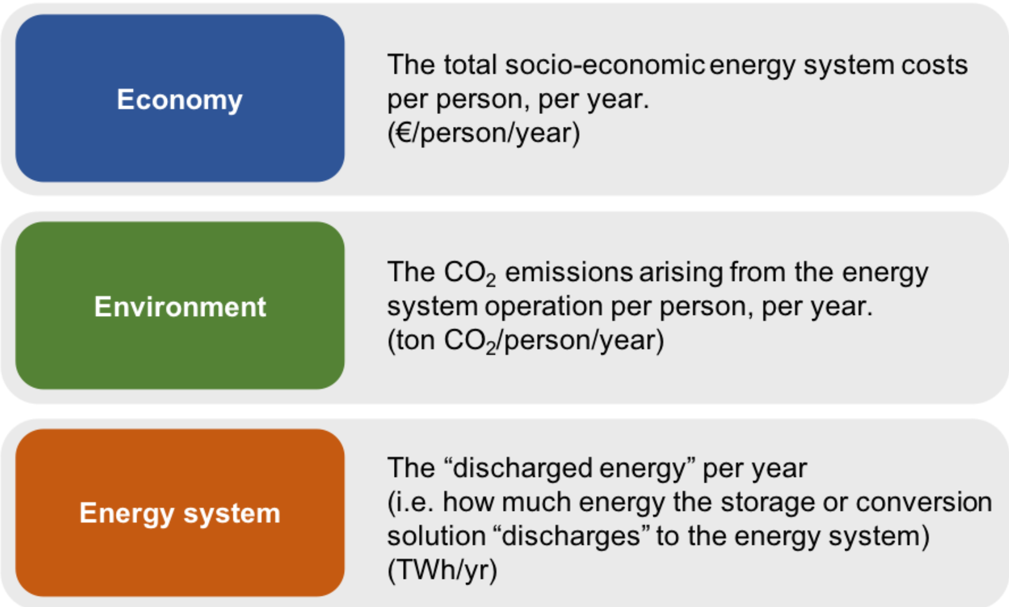


Figure 3 A description of the three indicators used for quantifying and comparing the results of the model scenarios.

3 Main Results

The results of the baseline scenarios of all configurations A0-E0 are shown in Figure 4. The results are shown in terms of the economic indicator (total annual socio-economic energy system costs per person), the environmental indicator (total annual CO_2 emissions per person) and in terms of the electricity overproduction in the system on an annual basis (i.e. the amount of electrical energy that cannot be integrated in the energy system). The energy system indicator of “discharged energy” is not applicable for the baseline scenarios, as they contain no DES or other technologies for balancing energy supply and demand in the system.

In the baseline configuration (A0), which resembles Germany’s energy system, energy supply and demand balancing measures are needed for wind and PV generation greater than 300 around TWh/yr. The island mode configuration (B0) has total system costs and CO_2 emissions similar to A0, but a greater need for energy supply and demand balancing. The introduction of more district heating (C0) lowers both the total system costs and the CO_2 emissions without introducing more need for energy supply and demand balancing, compared with the baseline configuration (A0). The introduction of electric vehicles (D0) together with more wind and PV generation can yield the largest cost savings and CO_2 reduction, and has the least need for energy system balancing measures out of all the baseline configurations. The nuclear power configuration (E0) has lower CO_2 emissions than the other baseline configurations but is the most expensive baseline scenario and has the greatest need for supply and demand balancing.

System redesign measures can be a very effective way of cost-effectively integrating large amounts of fluctuating RES and reducing CO_2 emissions. The results show that a transition away from energy system configurations A (based on Germany's energy system), B (island mode) or E (more nuclear power) towards a combination of C (more district heating, DH) and D (more electric vehicles, EVs) is beneficial on the indicators. The introduction of more DH increases the potential for inexpensive large distributed thermal energy storage and the transition to more EVs leads to the introduction of a large distributed electrical energy storage capacity in the system. This capacity can be utilised as flexibility for the system by ensuring that the electric vehicles are smart charged (i.e. charged in times of excess electricity generation). Together with such redesign measures, flexibility in the electricity and/or heating sectors should be introduced along with a power-to-heat coupling of these sectors. An example of this is the combination of heat pumps and thermal energy storages in individual heating solutions and flexible electricity demand.

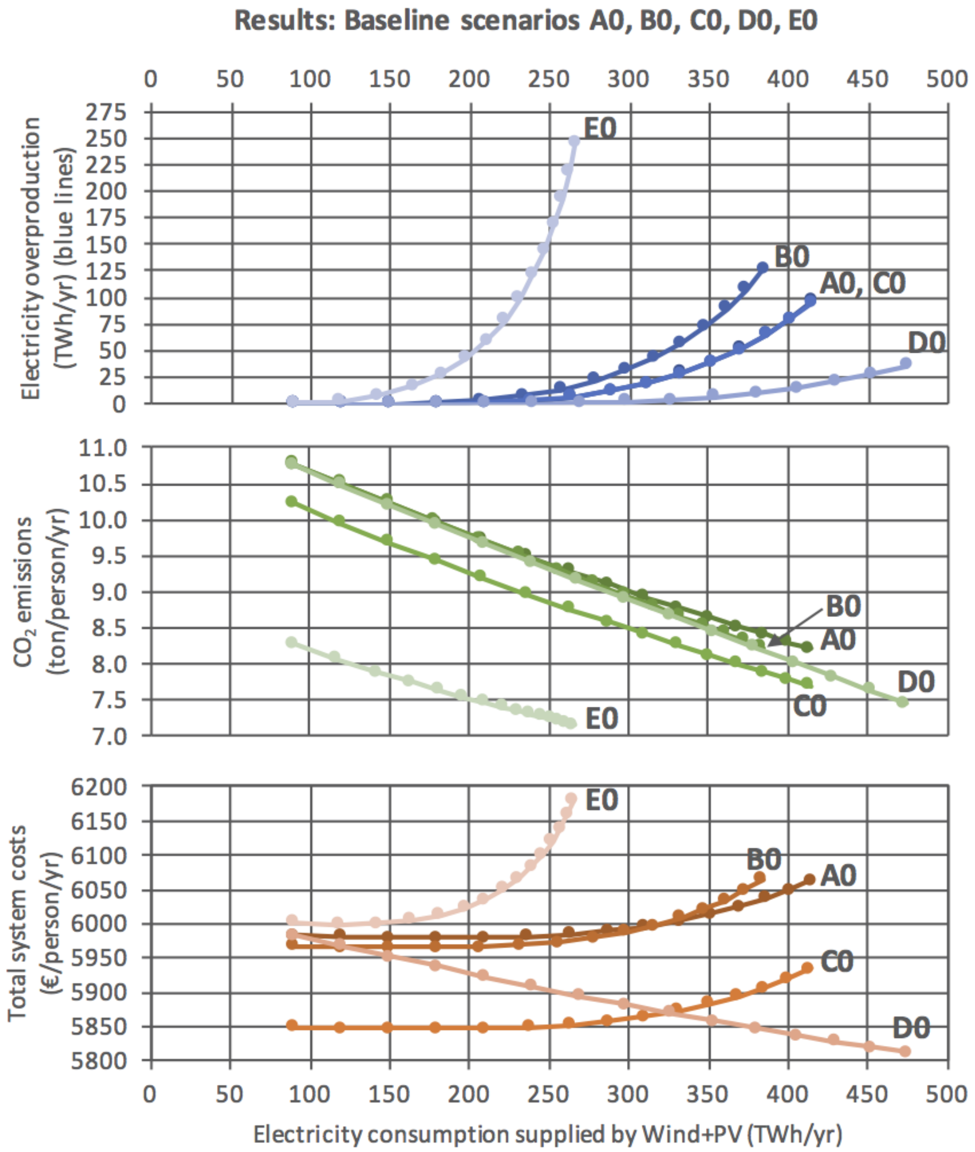


Figure 4 The results of the simulations for the baseline scenario for each of the energy system configurations (A0-E0). Note that the secondary axes do not all start at zero.

The overall trends in the results of scenarios 2-19, are summarized for each energy system configuration A-E in Table 1 through Table 5. In the tables, the effect of each energy supply and demand balancing technology (or combination of technologies) on the system is categorized for the indicators into "beneficial" (green), "neutral" (yellow) or "not beneficial" (red). The division in these three categories is defined as follows for the three indicators:

- *Total annual socio-economic energy system costs (change in €/person/year, relative to the corresponding baseline scenario):*
  Green: $x < -25$; yellow: $-25 \leq x \leq 25$; red: $x > 25$

- *Total annual CO_2 emissions from energy system operation (change in ton/person/year, relative to the corresponding baseline scenario):*
  Green: $x < -0.2$; yellow: $-0.2 \leq x \leq 0$; red: $x > 0$

- *The annual discharged energy (TWh/yr):*
  Green: $x > 10$; yellow: $0 \leq x \leq 10$; red: $x < 0$

The indicator values for the scenario variations with the highest amount of wind power and photovoltaic generation are used as a basis for the categorisation in the tables. Not all technologies were modelled in energy system configurations B-E; the results of the excluded scenarios in configurations B-E were not anticipated to provide substantial additional information compared to the results of these scenarios in configuration A.

Table 1 The result trends for all scenarios in energy system configuration A, divided into the categories "beneficial" (green), "neutral" (yellow) and "not beneficial" (red) for each of the three indicators. Scenarios 16-19 are hybrid scenarios with the following combinations: A16=A7+A15; A17=A3+A7+A15; A18=A7+A9+A15; A19=A7+A10+A15.

Scenarios A	**#**	**Total system cost**	**CO_2 emissions**	**Integration of fluctu-ating RES**
Electric interconnections to abroad	**2**			
Flexible electricity demand	**3**			
Electric heating in district heating	**4**			
Heat pumps in district heating	**5**			
Electric heating in individual heating	**6**			
Heat pumps in individual heating	**7**			
Power-to-gas (biogas methanation)	**8**			
Li-ion batteries	**9**			
Li-ion batt. coupled to photovoltaics	**10**			
Power-to-gas-to-power (hydrogen)	**11**			
Vanadium-redox flow batteries	**12**			
Pit & tank TES in district heating	**13**			
Aquifer & tank TES in district heating	**14**			
Tank TES in individual heating	**15**			
Heat pumps + Tank TES	**16**			
Heat pumps + Tank TES + Flex. dem.	**17**			
Heat pumps + TTES + Li-ion batteries	**18**			
Heat pumps + TTES + (Li-ion+PV)	**19**			

None of the individual changes can make up for the gains of an energy system redesign. The results show that individual heat pumps are feasible in all energy system configurations. Flexible electricity demand is potentially feasible in all configurations except the EV configuration (D). With even more RES electricity generation than introduced in the scenarios, it would likely also be feasible in configuration D. Tank thermal energy storages (TTES) are potentially feasible in all investigated configurations but have a small effect on the integration of RES when implemented alone. A connection with the electricity sector through power-to-heat should be looked into when implementing TTES, for pursuing the benefits of this storage technology.

The most feasible technology combinations are those that provide flexibility both in the electricity sector and the heating sector and have a link between the two (power-to-heat). An example of such flexible sector coupling is a combination that includes TTES, heat pumps and if possible also flexible electricity demand.

Table 2 The result trends for all scenarios in energy system configuration B.

Scenarios B	#	Total system cost	CO_2 emissions	Integration of fluctu-ating RES
Flexible electricity demand	3			
Electric heating in district heating	4			
Heat pumps in district heating	5			
Electric heating in individual heating	6			
Heat pumps in individual heating	7			
Power-to-gas (biogas methanation)	8			
Li-ion batteries	9			
Li-ion batt. coupled to photovoltaics	10			
Power-to-gas-to-power (hydrogen)	11			
Vanadium-redox flow batteries	12			

Table 3 The result trends for all scenarios in energy system configuration C. Scenarios 16-19 are hybrid scenarios with the following combinations: C16=C5+C13; C17=C3+A5+C15; C18=C5+A9+C13; C19=C5+A10+C13.

Scenarios C	#	Total system cost	CO_2 emissions	Integration of fluctu-ating RES
Flexible electricity demand	3			
Electric heating in district heating	4			
Heat pumps in district heating	5			
Pit & tank TES in district heating	13			
Aquifer & tank TES in district heating	14			
Tank TES in individual heating	15			
Heat pumps + Tank TES	16			
Heat pumps + Tank TES + Flex. dem.	17			
Heat pumps + TTES + Li-ion batteries	18			
Heat pumps + TTES + (Li-ion+PV)	19			

Table 4 The result trends for all scenarios in energy system configuration D. Scenario 18 is a hybrid scenario with the combination D7+D9+A15.

Scenarios D	#	Total system cost	CO_2 emissions	Integration of fluctu-ating RES
Electric interconnections to abroad	2			
Flexible electricity demand	3			
Electric heating in individual heating	6			
Heat pumps in individual heating	7			
Power-to-gas (biogas methanation)	8			
Li-ion batteries	9			
Li-ion batt. coupled to photovoltaics	10			
Power-to-gas-to-power (hydrogen)	11			
Vanadium-redox flow batteries	12			
Heat pumps + TTES + Li-ion batteries	18			

Table 5 The result trends for all scenarios in energy system configuration E.

Scenarios E	#	Total system	CO_2 emissions	Integration of
Electric interconnections to abroad	2			
Flexible electricity demand	3			
Electric heating in individual heating	6			
Heat pumps in individual heating	7			
Power-to-gas (biogas methanation)	8			
Li-ion batteries	9			
Li-ion batt. coupled to photovoltaics	10			
Power-to-gas-to-power (hydrogen)	11			
Vanadium-redox flow batteries	12			

Electrical energy storages are in general technically feasible, but not economically feasible due to high investment costs. It may, however, be possible to implement electrical energy storages in an economically beneficial way in some electricity system configurations by combining them with the above-mentioned flexibility and power-to-heat technologies. The economic feasibility of the energy supply and demand balancing technologies is generally less in the configuration with EVs as the EVs already offer considerable flexibility via smart charging. The feasibility of these technologies in the EV configuration can be expected to increase with even more fluctuating renewable electricity generation. The results of the vast majority of scenarios are very robust against changes in fuel costs and CO_2 emission prices, as shown in a sensitivity analysis.

4 Policy Recommendations

Based on the results of the modelling in this subtask, the following policy recommendations can be given in order to obtain the best integration and the greatest technical and economic benefits of transitioning towards very large capacities of fluctuating renewable energy generation:

Recommendations for energy system redesign

- **District heating, with low-carbon heat generation:** A system redesign towards more district heating would be feasible. A conversion away from individual heating towards district heating with low-CO_2 emitting heat generation should be prioritised. The redesign towards more district heating increases the potential for introducing *low-cost distributed energy storage in the form of large-scale thermal energy storages*.

- **Electric vehicles with smart charging:** A system redesign towards more electric vehicles would be feasible. A conversion away from internal combustion engine vehicles towards electric vehicles should be prioritised. To maximize the positive effects of introducing electric vehicles, they should be smart charged. The redesign towards more electric vehicles with smart charging introduces a *substantial and cost-effective distributed electrical energy storage capacity in the system in the form of vehicle batteries*.

- **Some level of electrical interconnections to island systems can be beneficial:** Going away from island systems towards interconnected systems would be beneficial on all indicators to some extent. This measure, however, has a limited potential with a high penetration of renewable electricity generation. The feasibility of interconnecting current island energy systems to other energy systems should be investigated carefully where this is geographically and technically possible.

- **Less inflexible nuclear power**: A conversion away from inflexible nuclear power towards other forms of low-CO_2 emitting power generation or towards very flexible nuclear power generation should be prioritised in energy systems with a large nuclear power capacity, that wish to integrate fluctuating RES.

Recommendations for distributed energy storage and conversion technologies

- **Flexible sector coupling:** The most feasible technology combinations are those that provide flexibility both in the electricity sector and the heating sector (district heating), and have a link between the two (power-to-heat). An example of this is a combination of DES and flexible sector coupling; e.g. combinations that include tank thermal energy storage (TTES), heat pumps and flexible electricity demand.

- **Individual heat pumps:** The introduction of heat pumps should be prioritized in order to replace fossil fuelled heat generation in individual heating.

- **Flexible electricity demand:** It should be investigated and tested (e.g. in demonstration projects) to which extent electricity consumers are willing to be flexible and how socio-economically expensive it would be to compensate them for their flexibility.

- **Thermal energy storages:** When thermal energy storages are implemented, connections with the electricity sector through power-to-heat should be looked into for increasing the positive impacts of the TTES. Thermal energy storages in district heating are more economical and can have the potential to provide more flexibility than thermal storages in individual heating.

- **Reduction of electrical energy storage investment costs:** Electrical energy storages, power-to-gas and electrical interconnections are all technically beneficial for the energy system but cause increased total system costs due to high investment costs. Research and development should be prioritized with the goal of reducing the price of these solutions. With the price levels used in this model, the implementation of these technologies should only be prioritized in energy systems where very high integration of fluctuating RES and very large reductions in CO_2 emissions are clearly prioritized higher than the minimisation of the total socio-economic energy system costs. The economic feasibility of these solutions may be improved by implementing them in combination with flexible sector coupling.

Other policy recommendations

- **Ensure a positive investment framework for technologies that generate and integrate renewable energy:** Measures should be taken to ensure that energy technologies that generate or integrate renewable energy in the energy system have a positive investment environment compared to energy generation based on fossil fuels. This can be endorsed e.g. by removing subsidies for fossil fuel consumption and/or by introducing economic incentives for renewable energy generation and balancing technologies. Such policies would advance the transition towards a CO_2 neutral energy supply and make the integration of large amounts of fluctuating renewable energy more economically viable. Higher fuel prices make the introduction of DES and other technologies for balancing energy supply and demand more economically feasible, as shown by the sensitivity analysis of the results.

- **Increase CO_2 emission prices:** Measures should be taken to ensure that for existing polluters, the costs of emitting CO_2 reflect the actual socio-economic costs related to the emissions. This would make the integration of large amounts of fluctuating renewable energy more economically viable and would make the introduction of DES and other technologies for balancing energy supply and demand more economically feasible, as shown by the sensitivity analysis of the result.

Acknowledgements

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