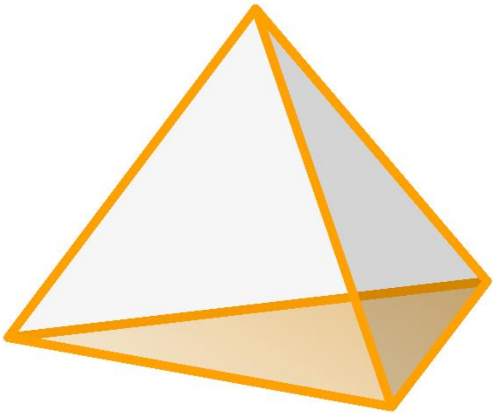
Final report

Distributed Energy Storages for the Integration of Renewable Energy

The Danish Input for the IEA ECES Annex 28



1.1 Project details

Project title	Integration af vedvarende energi ved hjælp af decentrale lagersystemer
Project identification (program abbrev. and file)	IEA ECES Annex 28 EUDP journalnr. 64014-0113 and 64014-0547
Name of the programme which has funded the project	EUDP-14-I and EUDP-14-II
Project managing company/institution (name and address)	PlanEnergi Jyllandsgade 1 DK-9520 Skørping
Project partners	PlanEnergi Aalborg University
CVR (central business register)	74038212
Date for submission	30-11-2018

1.2 Short description of project objective and results

1.2.1 English description

In this work, carried out within subtask 3 of Annex 28 of the IEA ECES programme, the potential for using distributed energy storages (DES) to integrate large amounts of fluctuating renewable energy sources (RES) in the future energy system is investigated. The aim of the project is to identify which DES technologies could be technically and economically beneficial for the integration of RES in different types of energy systems. 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. The results show that sector coupling together with an intelligent choice of DES technologies can enable the integration of large shares of fluctuating RES in an energy efficient and cost-effective way. A full report of the work and its results can be found at www.planenergi.eu/desire.

1.2.2 Danish description

Dette projekt er udført som en del af subtask 3 i Annex 28 af IEAs ECES program. Her undersøges potentialet for brug af distribuerede energilagre (DEL) for integration af store mængder fluktuerende vedvarende energi (VE) i fremtidens energisystem. Projektets formål er at identificere hvilke DEL-teknologier kunne være teknisk og økonomisk attraktive for integration af VE i forskellige typer af energisystemer. For at opnå dette formål modelleres DEL-teknologier som dele af et komplet energisystem på national skala. Energikonverteringsteknologier samt andre metoder for balancering af produktion og efterspørgsel er også inkluderet i modellen til sammenligning med DEL. Resultaterne viser at sammenkobling mellem energisystemets sektorer og et intelligent valg af DEL kan muliggøre integrationen af store mængder fluktuerende VE på en energi-effektiv og -økonomisk måde. Den fulde rapport af arbejdet og dets resultater findes her: www.planenergi.eu/desire.

1.3 Executive summary

1.3.1 Introduction

In 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.

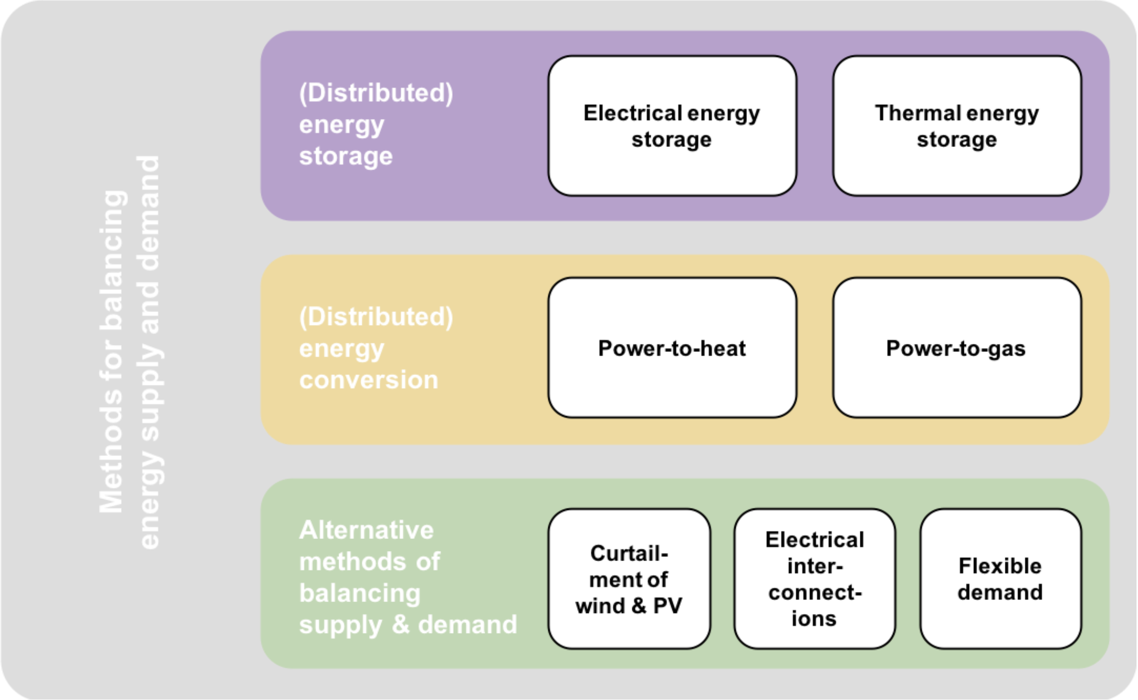
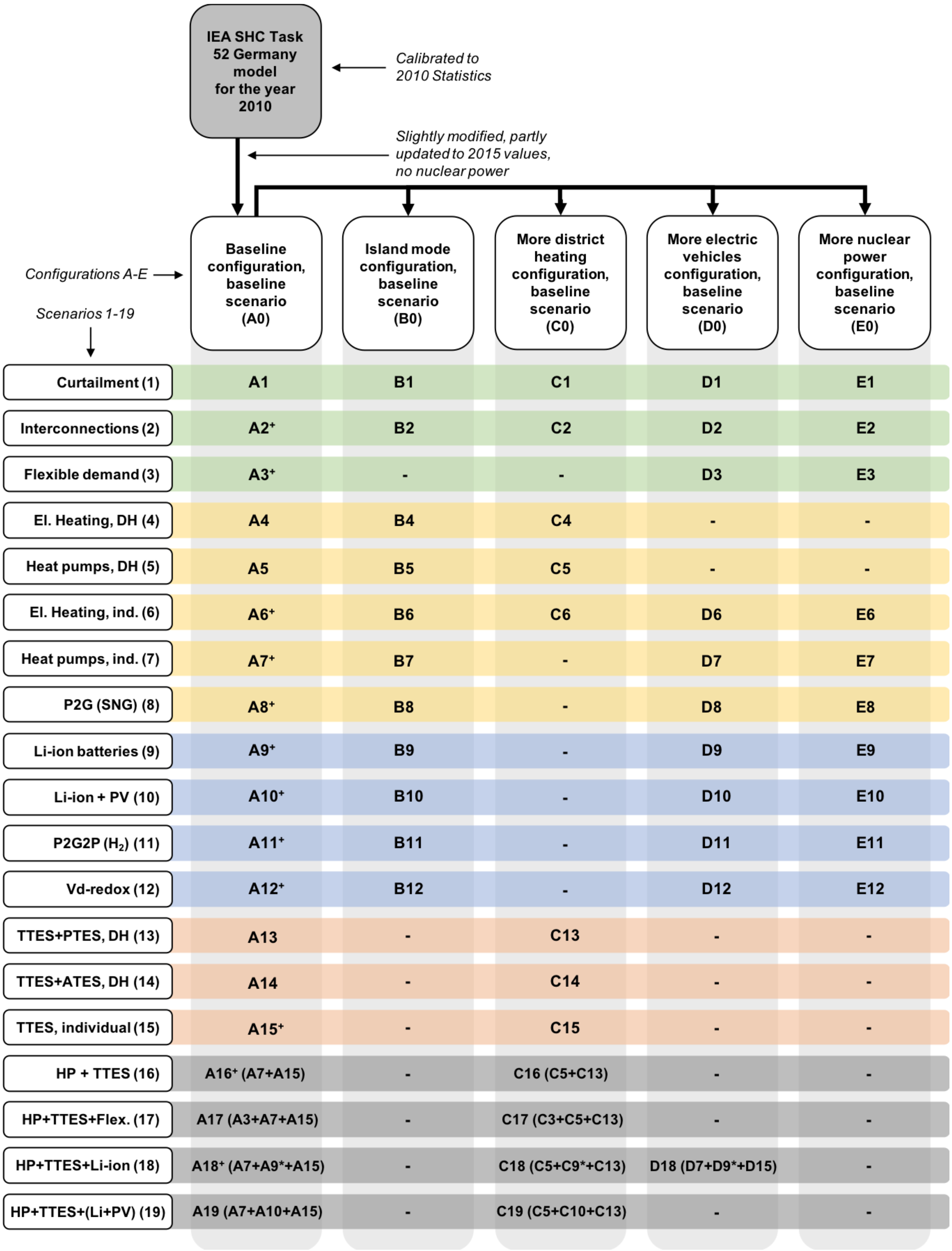


Figure 1 *A categorization of the technologies for balancing energy supply and demand that are included in the modelling work in subtask 3.*

1.3.2 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.



	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.*

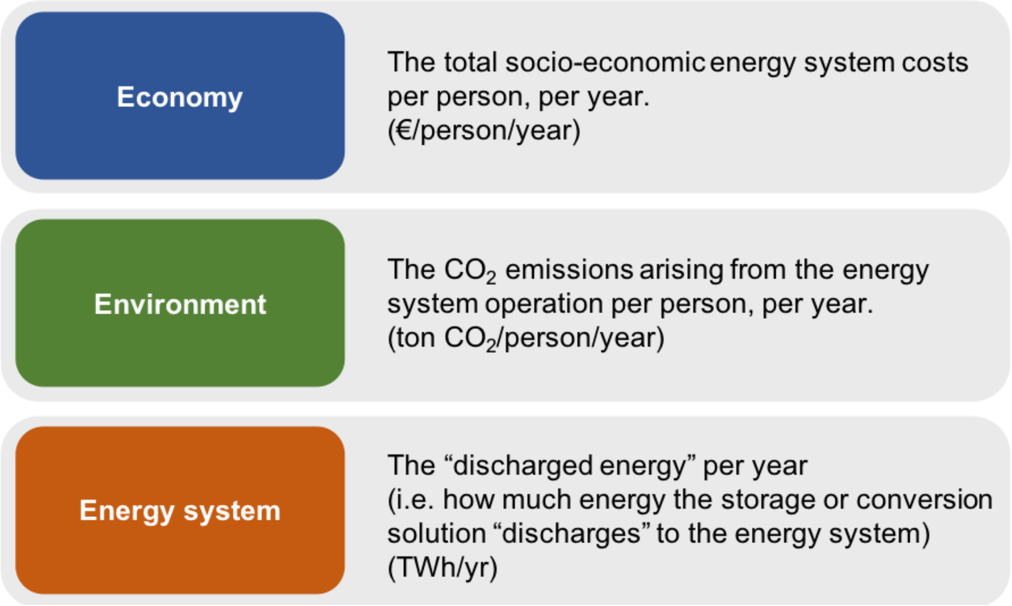
The results of the scenarios have been assessed using the three indicators shown in Figure 3. These indicators are used for quantifying the technical and economic impact of and potential for introduction of each technology in the energy system. The indicators are:

- 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 for one year.

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.



Economy	The total socio-economic energy system costs per person, per year. (€/person/year)
Environment	The CO_2 emissions arising from the energy system operation per person, per year. (ton CO_2/person/year)
Energy system	The “discharged energy” per year (i.e. how much energy the storage or conversion solution “discharges” to the energy system) (TWh/yr)

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

1.3.3 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.

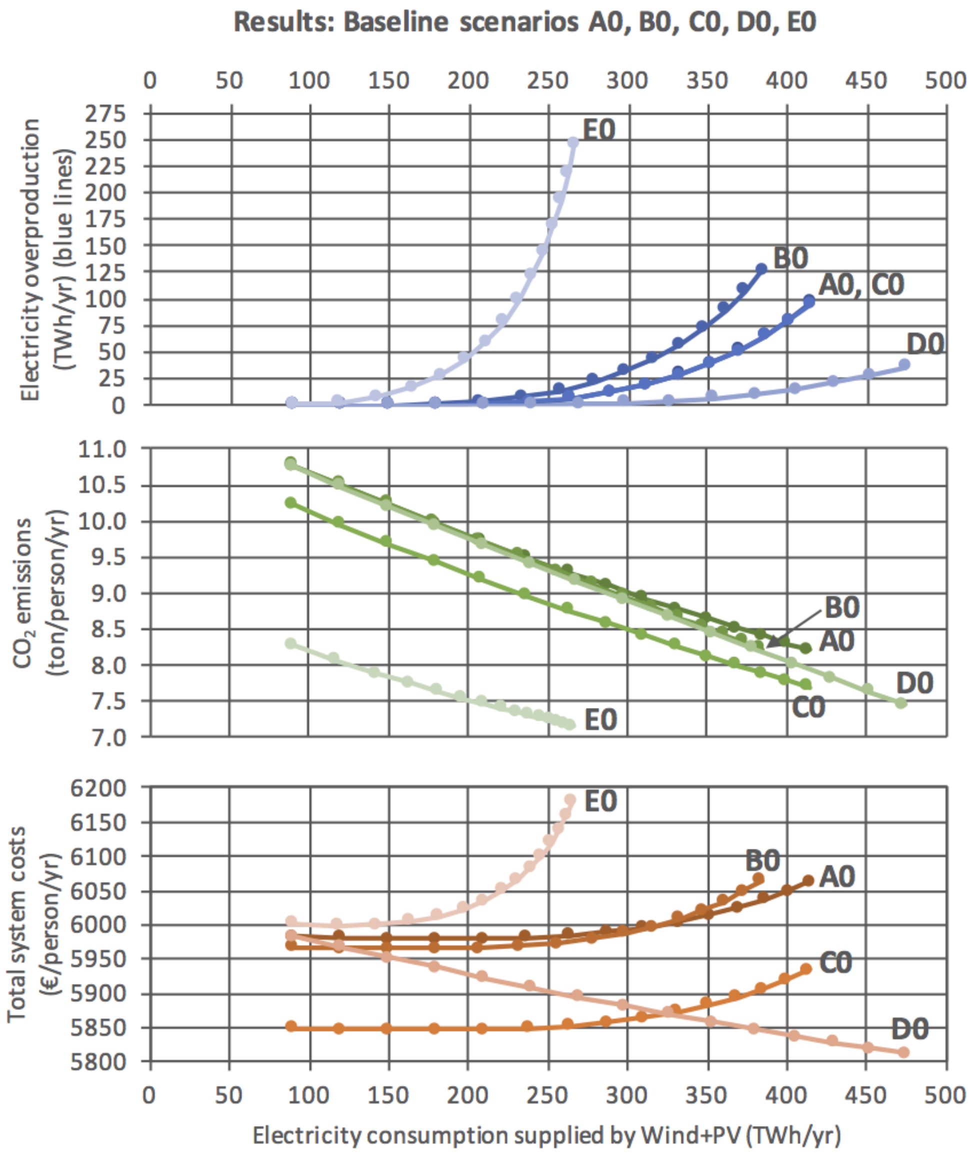


Figure 4 *The results of the simulations for the baseline scenario for each of the energy system configurations (A0-E0). Note that the secondary axes do not all start at zero.*

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.

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.

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 fluctuating 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	🟩	🟩	🟩

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	🟥	🟩	🟩

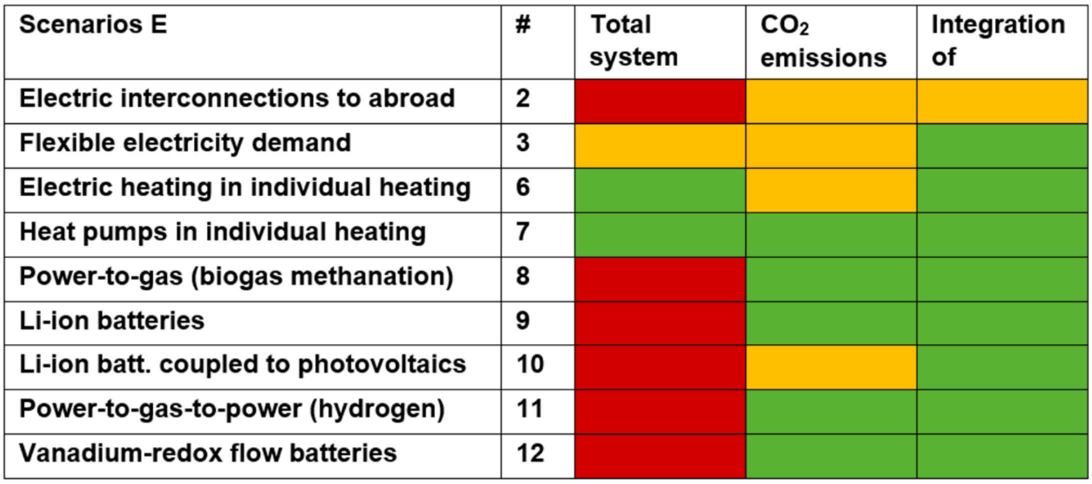
Table 3 *The result trends for all scenarios in energy system configuration C. Scenarios 16-19 are hybrid scenarios with the following combinations: C16=C5+C13; C17=C3+A5+C15; C18=C5+A9+C13; C19=C5+A10+C13.*

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	🟥	🟩	🟩

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.

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.

1.3.4 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 at least 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 over 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.

1.3.5 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.

1.4 Project objectives

1.4.1 IEA ECES Annex 28 Subtask 3 Definition

In the ongoing global transition away from an energy supply based mostly on fossil fuels towards an energy supply based mostly on sustainable energy sources with less greenhouse gas emissions, the share of renewable energy sources is rapidly increasing. This development is expected to continue, with many regions of the world foreseen to reach very high shares of renewable energy in their energy generation mix in the coming years and decades. Some of the most widely used renewable energy sources, wind energy and solar energy, are fluctuating resources that generate energy when the wind blows and the sun shines. The energy generation from these sources cannot be regulated in time to match the demand for energy services, as it has been the case with more conventional energy generation based on easily storable fossil fuels.

The integration of very large amounts of energy from fluctuating renewable sources, while still maintaining a balance between supply and demand in the energy system, will pose new challenges and new energy storage and/or balancing capacities will be needed to handle this. In this IEA ECES annex, the spotlight is turned towards distributed energy storages (DES) and which role they can play in integrating fluctuating renewable energy sources (RES).

Here, fluctuating RES are mainly understood as onshore and offshore wind turbines, and photovoltaics – both large-scale and small-scale installations. These are the two RES technologies with the fastest growing installed capacity, and they both have a large potential for worldwide implementation. The investment costs and energy generation costs from these technologies has fallen rapidly in recent years, with the levelised cost of generation for onshore wind power and photovoltaic power reaching similar levels to that of power generation from fossil fuelled (oil, gas, coal) power plants in many regions of the world [IRENA 2018]. This trend is expected to continue in coming years, making wind power and photovoltaics even more attractive investment options for new electricity generation capacity. For this reason, wind turbines and photovoltaics are considered the most relevant fluctuating RES technologies to investigate in this subtask.

The goal of subtask 3 of the project is to identify the future technical and economic potential for utilizing DES for the integration of renewable energy. This is achieved by a scenario analysis, where scenarios with different DES technologies are simulated in the context of a whole energy system on a country-scale. The performance of the DES technologies is evaluated within different types of energy systems and with varying shares of fluctuating renewable energy supply. The performance of each DES technology in each scenario is evaluated based on three indicators; a technical indicator, an economic indicator and an indicator for how well the DES technology facilitates the integration of fluctuating renewable energy in the energy system.

1.4.2 Distributed Energy Storage

In this annex, distributed energy storages are defined by the location of the storage with the energy system. Energy storage solutions are considered distributed if they are located

- at the consumer site (from household size up to small industry size), or
- decentralized in the distribution grid (e.g. neighbourhood scale), or
- at decentralized power generation sites (e.g. small biogas plant or a single wind turbine).

Energy storage solutions located higher up in the energy system, such as in the transmission grid or at centralized power generation sites are not considered DES in the context of this Annex. As an example, lithium-ion battery storages located in households, buildings or a neighbourhood are considered DES, while lithium-ion battery storages located at a wind turbine park or elsewhere in the transmission system are not considered DES.

1.4.3 Objectives of the Subtask

The objectives of subtask 3 are:

- *To estimate the technical potential for the usage of DES technologies for the integration of renewable energy* (i.e. to quantify how technically useful each DES technology can be for integrating renewable energy sources and thereby lowering the greenhouse gas emissions of the system).

- *To estimate the economic potential for the usage of DES solutions* (i.e. to quantify how the implementation of each DES solution affects the overall costs of the energy system).

- *To estimate the total (technical and economic) potential of different DES solutions within different types of energy systems* (i.e. to identify which DES solutions are most promising technically and economically and in which types of energy system they could be most beneficial).

These objectives are to be fulfilled by means of energy system modelling of DES technologies.

1.4.4 Scope and Limits of the Subtask

In this subtask, DES technologies are simulated in the context of a whole, nation-sized energy system using the energy system modelling tool *EnergyPLAN* [EnergyPLAN 2018], [Lund *et al*. 2015]. The modelling and evaluation of the DES technologies is not confined to the electricity system but includes all sectors of the energy system. The modelled DES technologies include electrical energy storages, thermal energy storages and combinations of these (electrical + thermal). Alternative methods of balancing of supply and demand in the system, such as demand side management, electrical interconnections between countries and cross-sectoral energy conversion (e.g. power-to-heat, power-to-gas) are also included in the simulations for comparison with the DES technologies.

This subtask includes simulations of energy systems on a national (or large state) scale with the goal of identifying large-scale trends and potentials associated with the possible implementation of different DES technologies in the system. Any detailed modelling of the electricity system, such as frequency regulation and primary/secondary reserve power (and any possible revenue from providing such services), as well as the modelling of any transmission or distribution system bottlenecks, is not within the scope of this subtask. The same goes for other energy networks, such as district heating networks and gas networks. These more detailed aspects would certainly be interesting to investigate in future work on the topic of DES.

This subtask is confined to technologies with a technology readiness level (TRL) of 3-9. The subtask is confined to energy system modelling and does not include any experimental or demonstration work. Development of the different DES technologies and R&D work related to this is not within the scope of the subtask (or annex).

The analysis in this subtask is intended for investigating the future potential for DES in energy systems with very high shares of fluctuating renewable energy. For this reason, technology costs and performance projections for the year 2030 are used. This annex is focused on studying the integration of DES on an energy system level, and no experimental technology development or demonstration work on DES is included in the annex. No technology-specific research work and technology roadmaps for how the projected future costs and performance could be reached for each DES technology are therefore included in this annex.

1.4.5 Implementation of the project

The project only involves computational energy system modelling and analysis, and does not involve any physical experiments or implementation work. The modelling and analysis work in IEA ECES Annex 28 subtask 3 developed as expected, with all annex partners agreeing on the methods and execution of the modelling work after discussing this at project meetings. The main focus areas of the modelling (i.e. which DES technologies and in which types of energy systems they should be modelled) and how to disseminate the results was also agreed upon by the project partners after discussions at the project meetings.

A risk involved with such a broadly formulated energy system modelling task (to analyse all DES technologies in as many energy system contexts as possible) is that the work becomes too extensive and thus not feasible to finish within the resources available in the project. Another risk is that the modelling can become too generic, with very course assumptions, in order to make the work more manageable, thus risking that the final results will be of limited use. The modelling tool (EnergyPLAN), the main focus areas of the modelling, the energy system types to analyse as well as the methods for dissemination of the results were all chosen with mitigation of these risks in mind.

The project started in 2014 and was originally intended to finish at the end of 2016, as this was the original end date of IEA ECES Annex 28. The project has since been extended until the end of November 2018, due to delays with the whole annex. The working phase of IEA ECES Annex 28 was extended by one year, until the end of 2017, due to delays in the early phases of the annex. The reporting phase of Annex 28 has also been extended and has been concluded in November 2018 with the annex final report presented to the ECES executive committee. The delays in IEA ECES Annex 28 has caused corresponding delays in the milestones of this project, compared to the original Gantt-chart of the project. The extension of the project period has given PlanEnergi and AAU the opportunity of disseminating the results of the project at two conferences and through the preparation of a journal paper during the year 2018 (submitted end of 2018/beginning of 2019).

1.5 Project results and dissemination of results

1.5.1 Baseline Scenario Results

Scenario	Configurations				
0 Baseline	**A0** Germany	**B0** Island mode	**C0** More DH	**D0** More EVs	**E0** More nuclear

Figure 5 shows the results for the baseline scenario of each energy system configuration (A0-E0). In scenario A0, the total socio-economic energy system costs remain approximately constant up to a wind and PV generation level of 300 TWh/yr (corresponding to 49% of the annual electricity demand in this scenario). Hereafter the total system costs increase non-linearly with increased annual wind and PV generation. The electricity overproduction in this scenario also takes off shortly before reaching 300 TWh/yr wind and PV generation. This shows that for a wind and PV production greater than 300 TWh/yr, the introduction of some energy supply and demand balancing methods or technology could be beneficial. The total system costs increase because for the variations after 300 TWh/yr, the additional investment in RES capacity yields less and less fuel savings and the value of the additional fluctuating electricity generation decreases as it becomes more difficult to integrate it in the system.

The total CO_2 emissions are reduced by 24% in variation 15 compared to variation 1. In variation 15, the electricity overproduction is 95 TWh/yr, spread over 2778 hours of the year and with an overproduction peak of 182 GW. These values indicate the magnitude of the energy supply and demand balancing capacity that is needed for full integration of 510 TWh/yr wind and PV generation in energy system configuration A. Note that the curves for scenario reach a maximum of 415 TWh/yr on the x-axis, in accordance with the fact that out of the total generation from wind and PV of 510 TWh/yr in variation 15, 95 TWh/yr are CEEP.

The results of scenario B0 (island mode) show similar trends to those in scenario A0. The total annual system costs in scenario B0 are slightly lower than in A0 up to a wind and PV generation of 300 TWh/yr, due to the removal of investments in interconnection capacity. The total system cost curves and the electricity overproduction curves in B0 rise non-linearly after a wind and PV generation of approximately 250 TWh/yr. The total system costs and the electricity overproduction are furthermore higher in scenario B0 than in A0 for the variations with the highest wind and PV generation. This shows that integrating fluctuating RES is more difficult in island mode (B0) than in the baseline configuration (A0) and that the need for energy supply and demand balancing measures arises earlier in B0 than in A0. The development of the CO_2 emissions is approximately the same in B0 as in A0.

The trends in the results for scenario C0 (more district heating) are identical to those in scenario A0, and the technical need for energy supply and demand balancing is very similar in both scenarios. Both the total annual system costs and the total annual CO_2 emissions are consistently lower in scenario C0 than in A0. This reflects that in the model, collective heat supply is socio-economically less expensive than individual heat supply, and that the expansion in DH reduces the consumption of fuels for heating.

In scenario D0 (more electric vehicles), the starting point in variation 1 is identical to that of scenario A0, i.e. no electric vehicles. With the gradual introduction of more EVs, alongside with the introduction of more electricity generation from wind and PV, the total annual system costs, the total annual CO_2 emissions and the total annual CEEP all become lower than in scenario A0. Especially the total system costs follow a different trend for scenario D0 than for the other baseline scenarios; the costs in D0 are reduced with increased generation from wind and PV. The need for supply and demand balancing only arises for a wind and PV generation of over 350 GWh/yr in D0. The need for other energy storage and/or conversion technologies is considerably less in configuration D than A. This is because smart charging is assumed for the

EVs, which takes care of a large part of the need for energy supply and demand balancing and makes more integration of fluctuating RES possible.

The results for scenario E0 (more nuclear power) reflect that the introduction of fluctuating RES generation is more difficult in energy systems with a large share of inflexible electricity generation. The need for energy supply and demand balancing arises already at wind and PV generation below 150 TWh/yr. The E0 curves only reach 266 TWh/yr on the x-axis, indicating that close to half of the 510 TWh/yr generation from wind and PV in variation 15 cannot be integrated in the system. This also causes the total system costs in scenario E0 to rapidly increase with more installed capacity of wind turbines and PV, as the electricity generated by this capacity is often unwanted in the system, and thus cannot be sold. The CO_2 emissions in scenario E0 are considerably lower than in the other baseline scenarios. This is because nuclear power generation replaces large amounts of fossil fuel consumption that would otherwise have been required.

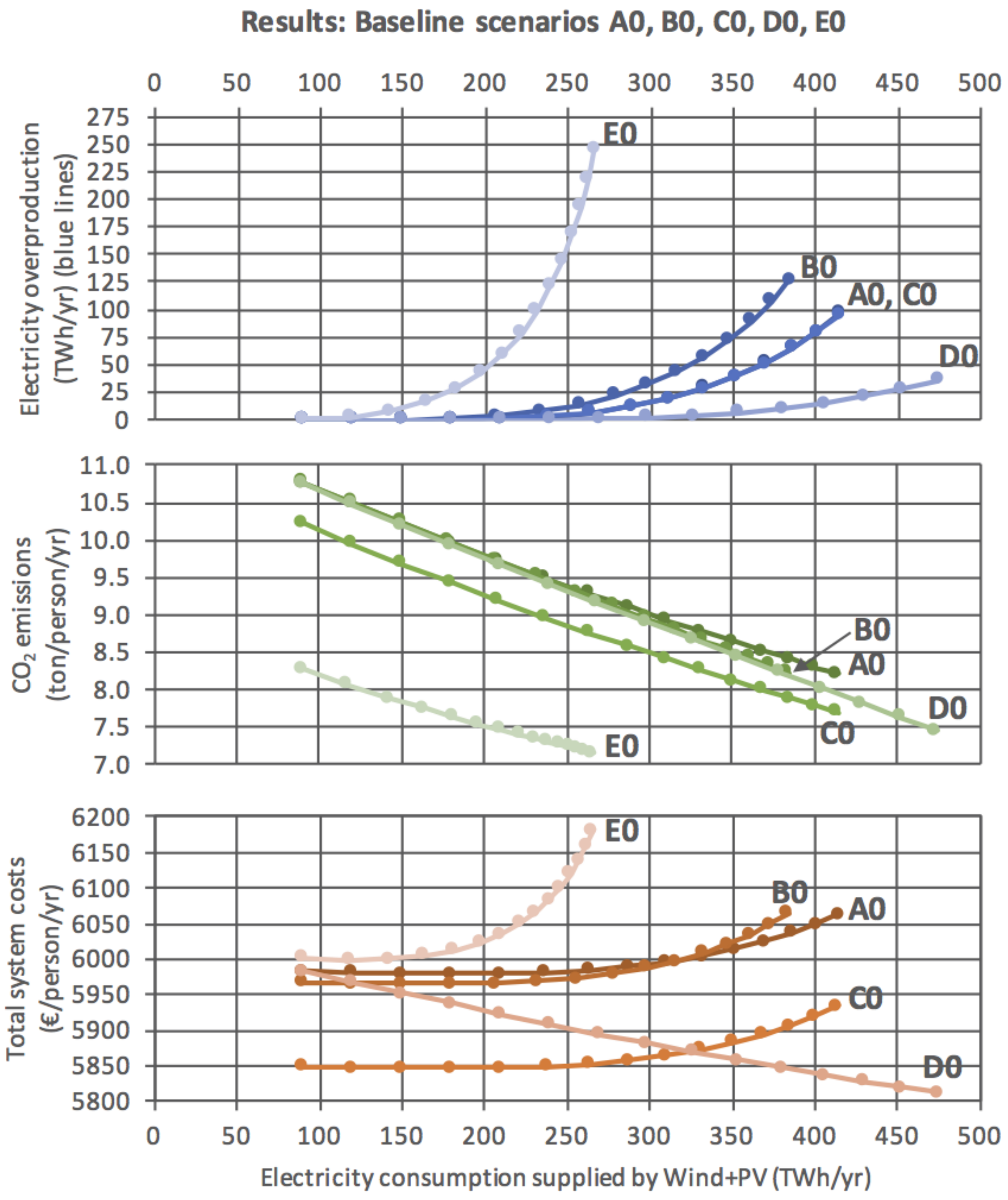


Figure 5 *The results of the simulations for the baseline scenario for each of the energy system configurations (A0-E0). Note that in the topmost chart (blue), the curves for A0 and C0 fully overlap.*

Baseline configuratons (scenario 0): Main conclusions

- In the baseline configuration (A0), energy supply and demand balancing measures are needed for wind and PV generation greater than 300 TWh/yr.
- The introduction of more DH (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 EVs (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.

1.5.2 Technology and Scenario Specific Result Summary

The overall trends in the results of scenarios 2-19, are summarized for each energy system configuration A-E in Table 6 through
Table ***10***. 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 baseline scenario):
    - Green: $x < -25$
    - Yellow: $-25 \leq x \leq 25$
    - Red: $x > 25$
- Total annual CO_2 emissions from the operation of the energy system
  (change in ton/person/year, relative to 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 in variation 15 (510 TWh/yr wind and PV generation) are used as a basis for the categorisation. As can be seen by these definitions, increases in total CO_2 emissions and negative values for the discharged energy (i.e. worse integration of RES) is not tolerated and leads to red labels in the tables. This is because the aim of this project is to identify DES technologies or solutions that can facilitate the integration of more RES, with the ultimate goal of reducing negative effects from the energy system operation on the environment and climate. Technologies that do not reduce CO_2 emissions and do not facilitate the integration of more RES in the energy system are therefore not considered useful for fulfilling the aim of the current project. Relatively small increases in the socio-economic total system costs are, however tolerated, as this may not necessarily be prohibitive for the implementation of the technologies. In the following subsections, the main conclusions for each energy system configuration A-E will be summarised along with the corresponding table for the performance of the indicators in each scenario of the current configuration.

1.5.2.1 Result Summary, Configuration A (Germany's Energy System)

Five scenarios in configuration A are feasible according to all three indicators (only green labels in Table 6):

- A7: *Heat pumps in individual heating*
- A16: *A combination of heat pumps and tank TES in individual heating.*
- A17: *A combination of heat pumps and tank TES in individual heating and flexible electricity demand (A3+A7+A15).*
- A18: *A combination of heat pumps and tank TES in individual heating and lithium-ion batteries (A7+A9+A15).*
- A19: *A combination of heat pumps and tank TES in individual heating and lithium-ion batteries that are coupled directly to PV (A7+A10+A15).*

Heat pumps in individual heating (A7) provide the system with a highly efficient pathway for utilizing excess electricity generation in the heating sector, thereby allowing for more integration of fluctuating RES in a cost-effective way. The hybrid scenarios (A16-A19) all combine the heat pumps with further methods of increasing the flexibility of the heating sector (via TES) and/or of the electricity sector. The combination with TES and flexible demand (scenarios A16 and A17) makes the system even more feasible on all indicators than in the heat pump scenario A7. This flexibility and the power-to-heat sector coupling offered by the heat pumps results in a cost-effective method for integrating more fluctuating RES and lowering the CO_2 emissions from the operation of the system.

The scenarios where Li-ion batteries are combined with heat pumps and TES (scenarios A18 and A19) are beneficial on all indicators for high levels of wind and PV generation, compared to the baseline scenario A0, but the total system cost in these scenarios is higher than when the batteries are not included (i.e. compared to scenarios A7 and A16). Scenarios A18 and A19 are not beneficial compared to the baseline scenario A0 *because* they have Li-ion batteries; they are beneficial *because* they have heat pumps and *even though* they have Li-ion batteries. The implementation of batteries is more feasible in connection with heat pumps and TTES than as a stand-alone solution, as the Li-ion scenarios A9 and A10 are not economically feasible compared to the baseline A0.

Five scenarios in configuration A are potentially feasible (or indifferent) for the energy system (some yellow labels but no red labels in Table 6):

- A3: *Flexible electricity demand*
- A4: *Electric boilers in district heating*
- A13: *Pit and tank thermal energy storages in district heating*
- A14: *Aquifer and tank thermal energy storages in district heating*
- A15: *Tank thermal energy storages in individual heating*

Flexible electricity demand (A3) has a positive effect on all indicators. Electric boilers in DH have a positive effect on all indicators except for the total CO_2 emissions, for which they have almost no effect. The impacts of these two technologies on the total system costs and the CO_2 emissions are rather small, resulting in yellow labels. Combining flexible electricity demand with other technologies increases the impact. The effect of the thermal energy storage technologies on the system are also rather limited, especially in the case of TES in DH (A14 and A15). This results in yellow labels for all indicators in the TES scenarios. The effect of TES on the integration of more fluctuating RES can be increased by a combination with power-to-heat technologies. The limited effect of DH technologies in other configurations than C is furthermore a consequence of the low share of district heating in the total heating demand.

The remaining eight scenarios in configuration A are not feasible for at least one of the indicators (a red label in Table 6):

- A2: *Electrical interconnections to abroad*
- A5: *Heat pumps in district heating*
- A6: *Electric heating in individual heating*
- A8: *Power-to-gas (methanation)*
- A9: *Lithium-ion batteries*
- A10: *Lithium-ion batteries directly coupled to photovoltaics*
- A11: *Power-to-gas-to-power (hydrogen)*
- A12: *Vd-redox flow batteries*

Table 6 *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. Model-external uncertainty factors related to some of the scenarios are listed in a separate column; they are discussed further in Subsection 1.5.4.*

Scenarios A	**#**	**Total system cost**	**CO$_2$ emissions**	**Integration of fluctuating 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**	🟩	🟩	🟩

The scenarios with electrical interconnectors (A2), heat pumps in DH (A5), power-to-gas (A8) and EES technologies (A9-A12) are not economically beneficial. In all these cases, the reason is that the annualised capital costs associated with the introduction of these technologies weigh heavier than the economic benefits that the technologies can deliver. It is thus socio-economically more beneficial not to introduce these technologies in the system (or possibly to introduce them in much lower capacities to those chosen in the current analysis). These technologies are, however, beneficial for reducing the total system CO$_2$ emissions and for integrating more fluctuating RES. In case very ambitious policies or goals regarding CO$_2$ emission reduction or RES integration are being followed, the increase in total system costs may not be completely prohibitive for the introduction of some of these technologies. The introduction of individual electric heating (A6) causes increased CO_2 emissions, and is therefore not environmentally feasible in this configuration.

1.5.2.2 Result Summary, Configuration B (Island Mode)

The results in energy system configuration B show identical trends to the results in configuration A. This is reflected in Table 7, where it can be seen that the labels of each scenario are identical to the labels in Table 6. The summary of the configuration A results therefore also applies to configuration B.

The main difference between configuration A and B is that there is more need for balancing energy supply and demand in B, due to the absence of electrical interconnections. This usually leads to slightly more feasible results on the discharged energy indicator in configuration B than in A, and similar or slightly more favourable results for the economic and environmental indicator in configuration B than in A.

Table 7 *The result trends for all scenarios in energy system configuration B, divided into the categories "beneficial" (green), "neutral" (yellow) and "not beneficial" (red) for each of the three indicators. Grey cells indicate that the scenario was excluded in the modelling of this configuration. Model-external uncertainty factors related to some of the scenarios are listed in a separate column; they are discussed further in Subsection 1.5.4.*

Scenarios B	**#**	**Total system cost**	**CO_2 emissions**	**Integration of fluctuating 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**	🟥	🟩	🟩

1.5.2.3 Result Summary, Configuration C (More District Heating)

One scenario in configuration C is feasible according to all three indicators (only green labels in Table 7):

- C17: *A combination of heat pumps and tank TES in district heating and flexible electricity demand (A3+A5+A13).*

This scenario is feasible in configuration C for the same reasons as scenario A17 is feasible. The combination of heat pumps, TES and flexible electricity demand makes the demand in the heating sector and the electricity sector flexible, as well as providing a link between the two sectors. This allows for improved utilisation of resources and an increased integration of fluctuating RES, in comparison with the baseline scenario C0.

Table 8 *The result trends for all scenarios in energy system configuration B, divided into the categories "beneficial" (green), "neutral" (yellow) and "not beneficial" (red) for each of the three indicators. Grey cells indicate that the scenario was excluded in the modelling of this configuration. Model-external uncertainty factors related to some of the scenarios are listed in a separate column; they are discussed further in Subsection 1.5.4.*

Scenarios C	**#**	**Total system cost**	**CO_2 emissions**	**Integration of fluctuating 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**	🟨	🟩	🟩

Seven scenarios in configuration C are potentially feasible (or indifferent) for the energy system (some yellow labels but no red labels in Table 7):

- C3: *Flexible electricity demand*
- C5: *Heat pumps in district heating*
- C13: *Pit and tank thermal energy storages in district heating*
- C14: *Aquifer and tank thermal energy storages in district heating*
- C15: *Tank thermal energy storages in individual heating*
- C16: *A combination of heat pumps and tank TES in district heating.*
- C19: *A combination of heat pumps and tank TES in district heating and lithium-ion batteries that are coupled directly to PV (A7+A10+A15).*

The results for flexible electricity demand (C3) are virtually identical to the results in configuration A (A3), as this does not affect the district heating sector much when little or no power-to-heat capacity is present. Heat pumps in DH are more feasible in this configuration than in A and B, but still have very small impacts on the total system costs and CO_2 emissions. Similar to configuration A and B, the TES technologies (C13-C15) have no or very small impacts on the system, although the impacts of the DH TES are somewhat larger in scenario C than in A and B due to the increased share of DH in the total heating demand. The combined impact of heat pumps and TES in DH (C16) on the system is also very small.

Two scenarios in configuration C are not feasible for at least one of the indicators (a red label in Table 7):

- C4: *Electric boilers in district heating*
- C18: *A combination of heat pumps and tank TES district heating and lithium-ion batteries (A7+A9+A15).*

Similar to electric heating in individual heating in configurations A and B, the introduction of large amounts of electric heating in DH (C4) causes increased CO_2 emissions. The combination of Li-ion batteries (C18) with heat pumps and TES does not yield the same economic benefits as it does in configurations A and B, and the introduction of Li-ion batteries in configuration C is therefore not feasible, due to high battery investment costs.

1.5.2.4 Result Summary, Configuration D (More Electric Vehicles)

Only one of the ten scenarios modelled in configuration D is potentially feasible according to all three indicators, as shown in Table 9:

- D7: *Heat pumps in individual heating*

All other scenarios in configuration D cause increased socio-economic system costs compared to the baseline scenario D0. This also goes for the scenarios that are found to be economically beneficial in other configurations. Furthermore, the total CO_2 emissions from the operation of the system are either lowered by very a very small amount or increased, compared with D0, in almost all scenarios in configuration D. The exception from this is scenario D16 (heat pumps, TTES and Li-ion batteries), where the CO_2 emissions are considerably lowered.

Table 9 *The result trends for all scenarios in energy system configuration D, divided into the categories "beneficial" (green), "neutral" (yellow) and "not beneficial" (red) for each of the three indicators. Grey cells indicate that the scenario was excluded in the modelling of this configuration. Model-external uncertainty factors related to some of the scenarios are listed in a separate column; they are discussed further in Subsection 1.5.4.*

Scenarios D	#	Total system cost	CO_2 emissions	Integration of fluctuating 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	🟥	🟩	🟩

The explanation for the generally decreased feasibility of introducing the energy supply and demand balancing technologies in configuration D, compared to the other configurations, is that the electric vehicles in D already provide the energy system with considerable flexibility. They are assumed to be charged via smart charging, which introduces a great deal of flexibility to the electricity demand in an economically feasible way. This also allows for a lowering of the CO_2 emissions in the system, without the introduction of specific technologies for balancing supply and demand. It is thus more difficult for these technologies to compete economically and environmentally with the baseline scenario in configuration D.

An additional reason for the low feasibility of introducing electricity conversion technologies that consume electricity (electric heating, heat pumps and power-to-gas) in the EV configuration is that these technologies increase the electricity demand in the system even further. When the combined additional electricity demand from these technologies and EVs is introduced in the system, the RES electricity generation is not sufficiently large during all hours of the year. In this case the system must respond by producing electricity with higher marginal costs and more fuel consumption. This leads to a decreased economic and environmental feasibility, compared to the configurations where the conversion technologies are introduced without also having EVs in the system. This is therefore not a problem of the energy conversion technologies but rather a problem of too little RES electricity generation in the system. The feasibility of introducing the energy conversion technologies could likely be improved in configuration D by increasing the RES electricity generation to even larger amounts than are included in this work.

1.5.2.5 Result Summary, Configuration E (More Nuclear Power)

One scenario in configuration E is feasible according to all three indicators (only green labels in Table ***10***):

- E7: *Heat pumps in individual heating*

Individual heat pumps are feasible in configuration E for the same reasons as in A and B. They enable the integration of excess electricity generation in the heating sector via highly efficient power-to-heat conversion. Combining the heat pumps with TES and flexible electricity demand is also anticipated to be feasible in configuration E, based on the results in A. Such hybrid scenarios are, however, not included in the modelling in configuration E.

Two scenarios in configuration E are potentially feasible (or indifferent) for the energy system (some yellow labels but no red labels in Table ***10***):

- E3: *Flexible electricity demand*
- E6: *Electric heating in individual heating*

Table 10 *The result trends for all scenarios in energy system configuration E, divided into the categories "beneficial" (green), "neutral" (yellow) and "not beneficial" (red) for each of the three indicators. Grey cells indicate that the scenario was excluded in the modelling of this configuration. Model-external uncertainty factors related to some of the scenarios are listed in a separate column; they are discussed further in Subsection 1.5.4.*

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**	🟥	🟩	🟩

Flexible electricity demand and individual electric heating both have slightly positive effects on the total system cost and CO_2 emissions in configuration E, and highly positive effects on the integration of fluctuating RES. The economic and environmental impacts are, however, so small that these technologies are labelled yellow in these indicators.

Six scenarios in configuration E are not feasible for at least one of the indicators (a red label in Table ***10***):

- E2: *Electrical interconnections to abroad*
- E8: *Power-to-gas (methanation)*
- A9: *Lithium-ion batteries*
- A10: *Lithium-ion batteries directly coupled to photovoltaics*
- A11: *Power-to-gas-to-power (hydrogen)*
- A12: *Vd-redox flow batteries*

These technologies are all very good for integrating more fluctuating RES in the system and good for lowering the CO_2 emissions in the system in configuration E. The relatively high investment costs for these technologies does, however, result in increased total system costs.

1.5.3 Sensitivity Analysis

1.5.3.1 Fuel Price Variation

The changes in the total socio-economic system costs indicator have been investigated for higher fuel prices and for lower fuel prices than those assumed in the modelled scenarios. This has been performed by increasing (or decreasing) the unit price of all fuels in the model (fossil fuels, biomass and uranium) for all scenarios, (including the corresponding baseline scenarios), and then calculating the total system cost indicator again for all scenarios.

The change in the total system costs between each technology scenario (2-15) and the corresponding baseline scenario (0) is then calculated, based on the new total system cost values obtained both for the technology scenario and the baseline scenario. This is a measure of how economically feasible each technology scenario is in a world where the increased (or decreased) fuel prices are assumed.

The economic feasibility of each scenario, calculated based on the increased (or decreased) fuel prices, is then compared to the economic feasibility of the corresponding scenario that contains the unaltered fuel prices.

The results of this comparison are shown in Table **11** for a 30% decrease in fuel prices and in Table 12 for a 30% increase in fuel prices (compared to the fuel prices used in the rest of the modelling work). The values in the tables denote how much more feasible (negative values, i.e. savings in total system costs) or less feasible (positive values, i.e. increase in total system costs) each scenario becomes with a 30% increase (or decrease) in the fuel prices. All values in the tables correspond to variation 15 (i.e. 510 TWh/yr wind and PV generation). The values in the tables are supplemented with bars that illustrate the sign and the magnitude of the change in feasibility with the increase (or decrease) in total system costs. Green bars denote a reduction in total system costs (i.e. increased feasibility with the new fuel prices compared with the unaltered fuel prices); orange bars denote an increase in total system costs (i.e. decreased feasibility with the new fuel prices compared with the unaltered fuel prices).

The result of the sensitivity analysis on the fuel prices shows that in a large majority of the scenarios, the fuel prices do not alter the economic feasibility of the scenarios substantially, e.g. by less than 25 €/person/year. In the scenarios with individual heat pumps (scenario 7) and in all hybrid scenarios (scenarios 16-19), the economic feasibility of the scenarios is altered by more than 25 €/person/year or more. The largest change in economic feasibility is observed in scenario D18, where it changes by 303 €/person/year.

The conclusions regarding the economic feasibility of the scenarios remain unaltered with the 30% increase or decrease in fuel prices for all scenarios except in the following cases:

- A 30% increase in fuel costs for scenario C5 (heat pumps in DH) makes this scenario slightly economically beneficial (whereas it is not when unaltered fuel costs are assumed).

- A 30% decrease in fuel costs for scenarios A18 and A19 (the hybrid scenarios including Li-ion batteries) pushes them from being economically feasible towards being less economically feasible than the baseline scenario A0.

- A 30% decrease in fuel costs for scenario D18 makes it very economically feasible. This scenario is the most sensitive to changes in fuel prices out of all calculated scenarios. This is because this scenario is more dependent on fuels than the others, as there is not sufficient RES electricity generation to cover the demand due to increased demand from EVs and heat pumps. More fuels must therefore be consumed for generating electricity in this scenario than in most of the other scenarios. Increasing the RES electricity generation in D18 even further would make this scenario less sensitive to changes in fuel prices.

Table 11 *Changes in the total system cost indicator when all fuel costs are lowered by 30%. All values in the table are in units of €/person/year. The values show how much more or less economically beneficial the introduction of each technology would be in each configuration in a world with 30% lower fuel prices. A positive value indicates an increase in total system cost (less feasible), a negative value indicates a decrease in the total system cost (more feasible). The values in the table correspond to variation 15 of each scenario (510 TWh/yr wind and PV generation).*

Scenarios	#	Energy system configuration				
		A	**B**	**C**	**D**	**E**
Interconnections	**2**	-0.03			-4.31	-0.06
Flexible demand	**3**	2.35	2.35	2.26	1.17	1.95
El. heating, DH	**4**	4.88	4.88	-1.21		
Heat pumps, DH	**5**	6.14	6.14	11.19		
El. heating, ind.	**6**	7.58	7.58		6.68	8.37
Heat pumps, ind.	**7**	40.24	40.24		39.34	40.50
P2G	**8**	10.13	10.13		-2.65	22.25
Li-ion	**9**	5.85	5.85		2.51	3.98
Li-ion + PV	**10**	2.03	2.03		0.63	1.51
P2G2P	**11**	3.39	3.39		1.33	3.57
Vd-redox	**12**	4.90	4.90		2.02	3.85
TTES+PTES, DH	**13**	0.86		0.51		
TTES+ATES, DH	**14**	0.86		0.51		
TTES, ind.	**15**	0.95		0.37		
HP+TTES	**16**	45.31		17.98		
HP+TTES+Flex.	**17**	46.94		19.78		
HP+TTES+Li-ion	**18**	47.53		21.88	303.78	
HP+TTES+(Li+PV)	**19**	46.64		25.62		

Table 12 *Changes in the total system cost indicator when all fuel costs are increased by 30%. All values in the table are in units of €/person/year. The values show how much more or less economically beneficial the introduction of each technology would be in each configuration in a world with 30% higher fuel prices. A positive value indicates an increase in total system cost (less feasible), a negative value indicates a decrease in the total system cost (more feasible).The values in the table correspond to variation 15 of each scenario (510 TWh/yr wind and PV generation).*

Scenarios	#	Energy system configuration				
		A	**B**	**C**	**D**	**E**
Interconnections	**2**	0.03			4.31	0.06
Flexible demand	**3**	-2.35	-2.35	-2.26	-1.17	-1.95
El. heating, DH	**4**	-4.88	-4.88	1.21		
Heat pumps, DH	**5**	-6.14	-6.14	-11.19		
El. heating, ind.	**6**	-7.58	-7.58		-6.68	-8.37
Heat pumps, ind.	**7**	-40.24	-40.24		-39.34	-40.50
P2G	**8**	-10.13	-10.13		2.65	-22.25
Li-ion	**9**	-5.85	-5.85		-2.51	-3.98
Li-ion + PV	**10**	-2.03	-2.03		-0.63	-1.51
P2G2P	**11**	-3.39	-3.39		-1.33	-3.57
Vd-redox	**12**	-4.90	-4.90		-2.02	-3.85
TTES+PTES, DH	**13**	-0.86		-0.51		
TTES+ATES, DH	**14**	-0.86		-0.51		
TTES, ind.	**15**	-0.95		-0.37		
HP+TTES	**16**	-45.31		-17.98		
HP+TTES+Flex.	**17**	-46.94		-19.78		
HP+TTES+Li-ion	**18**	-47.53		-21.88	-303.78	
HP+TTES+(Li+PV)	**19**	-46.64		-25.62		

1.5.3.2 CO_2 Emission Price Variation

The same type of sensitivity analysis as for the fuel prices has been performed on the CO_2 emission prices in the model. The changes in the socio-economic feasibility of each scenario have been investigated with a 50% increase and decrease in the CO_2 emission price. This has been performed with the same method as described for the fuel price sensitivity analysis. The results are also presented in the same manner, with Table **13** showing the change in the economic feasibility when the CO_2 emission price is decreased by 50% and Table 14 showing the change in the economic feasibility when the CO_2 price is increased by 50%. All values in the tables correspond to variation 15 of each scenario (510 TWh/yr wind and PV generation).

The results of the sensitivity analysis on the CO_2 emission price show that the emission price does not alter the economic feasibility of the scenarios substantially, or by less than 25 €/person/year in all scenarios. The conclusions regarding the economic feasibility of all scenarios remain unchanged with the 50% increase or decrease in CO_2 emission prices in all cases.

It should be noted that the total CO_2 emissions from the system operation are not changed when the model is run with increased or decreased CO_2 emission prices. This is because *EnergyPLAN* is a simulation model and not an optimization model, and the CO_2 prices does not alter the technical operation of the energy system in the model, but only alters its economic results.

Table 13 *Changes in the total system cost indicator when the CO_2 emission price is set to 50% of the value of the baseline CO_2 price. The values show how much more or less economically beneficial the introduction of each technology would be in each configuration in a world with 50% lower CO_2 emission prices. A positive value indicates an increase in total system cost (less feasible), a negative value indicates a decrease in the total system cost (more feasible). The values in the table correspond to variation 15 of each scenario (510 TWh/yr wind and PV generation).*

Scenarios	#	Energy system configuration				
		A	B	C	D	E
Interconnections	**2**	-0.01			-5.26	-0.03
Flexible demand	**3**	2.92	3.31	2.87	1.48	1.84
El. heating, DH	**4**	0.62	0.99	-10.25		
Heat pumps, DH	**5**	2.04	2.42	0.72		
El. heating, ind.	**6**	-1.83	-1.45		-2.93	1.45
Heat pumps, ind.	**7**	9.61	9.99		8.50	12.43
P2G	**8**	5.81	7.39		-20.12	11.61
Li-ion	**9**	7.16	8.55		3.07	3.77
Li-ion + PV	**10**	2.54	2.92		0.84	1.43
P2G2P	**11**	4.15	5.26		1.63	3.39
Vd-redox	**12**	6.00	7.39		2.47	3.65
TTES+PTES, DH	**13**	0.97		1.71		
TTES+ATES, DH	**14**	0.97		1.71		
TTES, ind.	**15**	1.16		0.45		
HP+TTES	**16**	15.82		3.10		
HP+TTES+Flex.	**17**	17.79		5.31		
HP+TTES+Li-ion	**18**	18.54		7.44	10.91	
HP+TTES+(Li+PV)	**19**	17.46		10.68		

Table 14 *Changes in the total system cost indicator when the CO_2 emission price is set to 150% of the value of the baseline CO_2 price. The values show how much more or less economically beneficial the introduction of each technology would be in each configuration in a world with 50% higher CO_2 emission prices. A positive value indicates an increase in total system cost (less feasible), a negative value indicates a decrease in the total system cost (more feasible). The values in the table correspond to variation 15 of each scenario (510 TWh/yr wind and PV generation).*

		Energy system configuration				
Scenarios	**#**	**A**	**B**	**C**	**D**	**E**
Interconnections	**2**	0.01			5.26	0.03
Flexible demand	**3**	-2.92	-3.31	-2.87	-1.48	-1.84
El. heating, DH	**4**	-0.62	-0.99	10.25		
Heat pumps, DH	**5**	-2.04	-2.42	-0.72		
El. heating, ind.	**6**	1.83	1.45		2.93	-1.45
Heat pumps, ind.	**7**	-9.61	-9.99		-8.50	-12.43
P2G	**8**	-5.81	-7.39		20.12	-11.61
Li-ion	**9**	-7.16	-8.55		-3.07	-3.77
Li-ion + PV	**10**	-2.54	-2.92		-0.84	-1.43
P2G2P	**11**	-4.15	-5.26		-1.63	-3.39
Vd-redox	**12**	-6.00	-7.39		-2.47	-3.65
TTES+PTES, DH	**13**	-0.97		-1.71		
TTES+ATES, DH	**14**	-0.97		-1.71		
TTES, ind.	**15**	-1.16		-0.45		
HP+TTES	**16**	-15.82		-3.10		
HP+TTES+Flex.	**17**	-17.79		-5.31		
HP+TTES+Li-ion	**18**	-18.54		-7.44	-10.91	
HP+TTES+(Li+PV)	**19**	-17.46		-10.68		

1.5.3.3 Lithium-ion Battery Price Variation

The investment costs for lithium-ion batteries have fallen rapidly in recent years. It is anticipated that this trend will continue, but it is not certain how fast or how far the batteries will come down in price in the coming years. To illustrate how different developments in the lithium-ion battery price would affect the model, a sensitivity analysis has been carried out the total system costs of scenario A9. The total system costs of this scenario have been calculated for three different levels of lithium-ion battery investment costs; unchanged costs (180 €/kWh), 50% of the scenario A9 battery costs (90 €/kWh) and 10% of the scenario A9 battery costs (18 €/kWh, i.e. a reduction by 90%). The 50% price reduction is viewed as a plausible price level for Li-ion batteries in the not-so-distant future. The 90% price level is, however, viewed mainly as an academic exercise to investigate how a drastic (and perhaps unrealistic) reduction in battery prices would affect the results.

The results of this sensitivity analysis are shown in Figure 6. The results show that even with a 50% reduction in the Li-ion battery investment costs, scenario A9 would still be substantially more socio-economically costly than the baseline scenario A0. With a 90% reduction in the battery price, the total socio-economic system costs of scenario A9 would be slightly lower than that of the baseline scenario A0 for a high generation from wind and PV. This can be used as a benchmark for how low the investment costs of battery technologies (with an installed capacity and efficiency comparable to that of Li-ion in scenario A9) would have to be for them to be economically feasible in the energy system variation A in this model

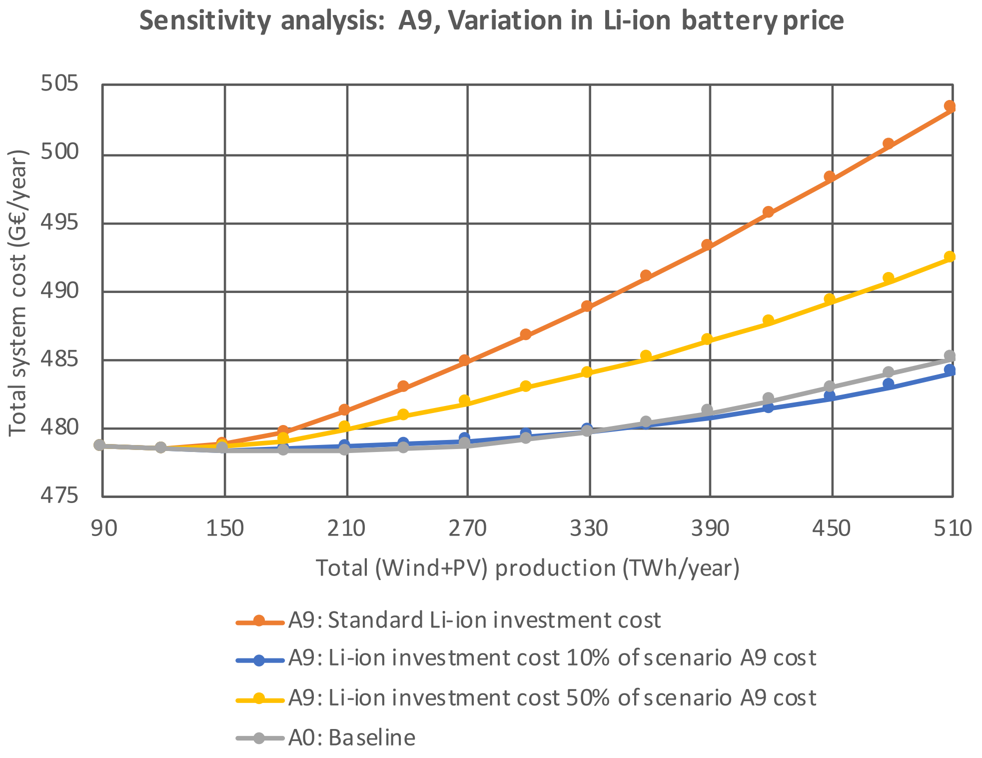


Figure 6 *A sensitivity analysis on the investment costs of lithium-ion batteries in scenario A9. The absolute value of the total system cost indicator is shown as a function of the wind and PV generation for three different levels of Li-ion investment costs. The total system cost indicator for the baseline scenario A0 is shown for comparison.*

It should be mentioned that a sensitivity analysis has not been carried out on the investment costs of wind turbines or photovoltaics. This was not considered necessary, as all scenarios include the same development in wind turbine and PV capacity in variations 1-15 (from 90 TWh/yr up to 510 TWh/yr). Changes in the price levels for wind turbines or PV would affect all scenarios equally, leaving the differences between the total system costs of each scenario and the total system costs of the corresponding baseline scenario unaltered.

1.5.3.4 Variation in the Ratio Between Wind and Photovoltaic Power

The optimal ratio between the installed capacity of wind turbines and PV in the baseline scenario A0 of the model was found to be at approximately 25% PV capacity out of the total wind+PV capacity. It is, however, not clear if or how this optimal ratio between the installed capacity of wind and PV moves as the various technologies for balancing supply and demand are introduced in the model. To investigate this, a variation in the ratio between the installed capacities of wind turbines and PV was carried out for scenario A18. This was calculated for variation 9 (330 TWh/yr wind and PV generation). In this scenario, three technologies have been introduced that were not present in the baseline scenario A0.

The result of this variation in the ratio between the wind and PV capacity is shown in Figure 7. It can be seen that for scenario A18, the optima of the curves are located at approximately 35% PV capacity out of the total installed wind+PV capacity. This variation gives slightly more feasible results on all indicators than the 25% PV capacity used in the standard version of scenario A18 (and in all other scenarios in this work). It is therefore clear that the optimal mix between the installed capacity of wind turbines and photovoltaics changes somewhat between scenarios. This effect is not expected to change the conclusions of this modelling work, but is worth having in mind in further work and when investigating specific cases for the implementation of DES.

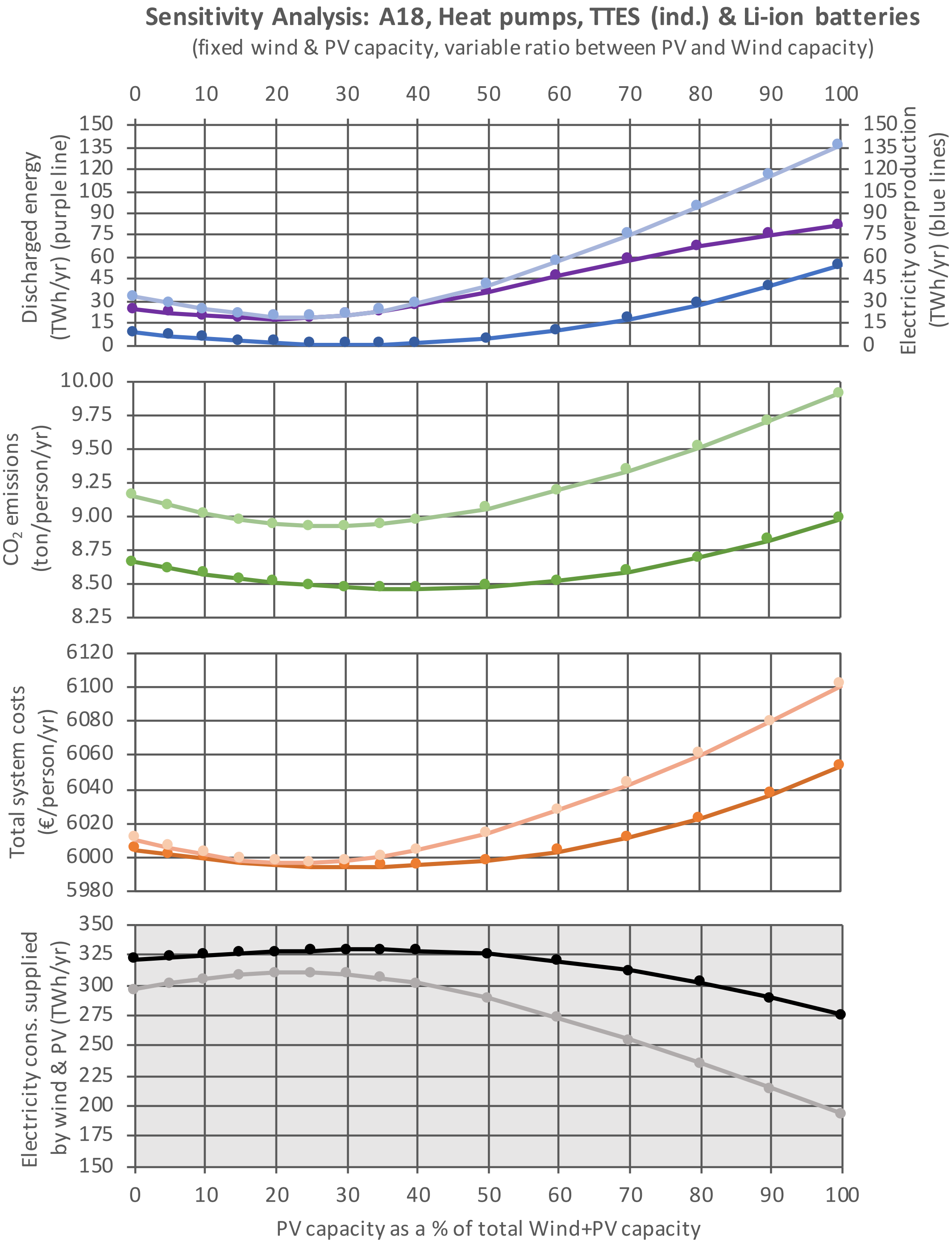


***Figure 7** A variation of the installed PV capacity as a fraction of the total installed wind turbine and PV capacity in the model. This calculation is carried out for scenarios A18 and A0, in both cases with a fixed 330 TWh/yr total electricity generation from wind and PV. The dark coloured curves show the results for scenario A18 and the light coloured curves show the results for scenario A0. The purple curve shows the curve of the discharged energy indicator for scenario A18. The optimal fraction of PV is approximately 35% in scenario A18 but approximately 25% in scenario A0.*

1.5.4 Discussion

1.5.4.1 Modelling Framework Discussion

In this subtask the aim is to identify which combinations of DES technologies and energy system contexts can be technically and economically beneficial for the integration of fluctuating renewable energy generation. This has been performed via scenario-based energy system modelling performed using the energy system simulation software *EnergyPLAN*. In the following, some aspects and implications of this methodology will be discussed, including a discussion of the benefits and drawbacks of the scenario approach and simulation software used in this work.

The *EnergyPLAN* energy system simulation software used for the modelling is an aggregated model, mainly designed for the modelling of large (e.g. regional, national or continental) energy systems. The tool enables the modelling of all sectors of the energy system and their interactions. The model is an aggregated, copper-plate model, but is computationally very fast and therefore well suited for modelling a large array of scenarios. The aggregated, top-down approach means that the model is suitable for assessing the total, big-picture impact of introducing a DES technology (or other technologies) in the energy system as a whole, but is not suitable for modelling the more detailed effects they have on the local energy systems in which they are implemented. The copper-plate approach means that the model is suitable for assessing the impact of the technologies in an energy system setting where transmission and/or distribution grid capacities are not assumed to be limiting factors, but it is not capable of taking the impacts of DES technologies (or other technologies) on any congestion problems in the transmission or distribution systems into account. For more detailed modelling of local impacts of DES and their impacts on congestion problems, further work with other modelling frameworks that are more dedicated for these tasks, is needed.

Another consequence of the aggregated, copper-plate approach is that no information is obtained in this modelling about where the energy supply and demand balancing solutions and the fluctuating RES generation should be located geographically within the modelled energy system. This should be considered in further analyses for the introduction of DES, especially when considering specific cases and countries.

The estimated investment in the expansion of the electricity grid has been taken into account in the results. This is in particular relevant in scenarios with EVs, power-to-heat and or power-to-gas, as the peak electricity load in these scenarios is higher than in the remaining scenarios. There are of course substantial uncertainties connected to the estimated grid investment costs. Those costs furthermore depend on how great the already existing overcapacity is in the energy system.

The *EnergyPLAN* model simulates an energy system with a perfect knowledge of all the modelled parameters, including a knowledge about the fluctuating RES generation profiles, the energy demand profiles and the electricity spot price profiles, which are all input in the model in the form of hourly time-series for a whole year. The model is then capable of simulating the most rational operation of the energy system under the constraints and equations that govern the model. In reality, such perfect operation of the system cannot be replicated but only approached, because energy system operators must deal with uncertainties about future prices, generation profiles, demands and more.

In the *EnergyPLAN* tool, specialised technical aspects of the energy conversion and storage technologies in the model cannot be modelled in full detail. This is often a necessary trade-off in energy system modelling, because including very technology specific details on all energy conversion and storage technologies of a whole nation-wide energy system model is neither practically nor computationally feasible. The technical model input parameters for electrical energy storages are the installed storage injection and extraction power capacities, the injection and extraction and efficiencies, the storage energy capacity. For thermal energy storages, the technical model input parameters are the storage energy capacity and the storage strategy (e.g. daily, weekly, seasonal storage cycles). The energy losses for thermal energy storages are calculated in the model based on the storage strategy. For power-to-heat and power-to-gas, the technical model input parameters are the installed energy conversion power capacity and the conversion efficiency. In all cases, the economic model input parameters are the specific investment costs of the storage or conversion unit, its operation and maintenance costs (O&M) and its technical lifetime in years.

The relatively simple representation of the storages in the model has some implications regarding the choice of the which energy storage technologies to include in the modelling and which to exclude. As an example, two battery technologies with different chemistries but identical efficiencies, costs and technical lifetime cannot be distinguished in the model. It would therefore not be necessary to include separate model scenarios for these two technologies, as the modeller knows beforehand that the results for both technologies would be identical. If one of the battery technologies was more expensive and less efficient than the other, the modeller would furthermore know beforehand that the model result would show that this battery technology was less economically and technically feasible than the other technology. After performing a literature study on the costs and efficiencies of different DES technologies, these considerations can be used for choosing which technologies to include in the modelling (the cheapest and most efficient technologies in each category) and which technologies to exclude (the ones that are more expensive and/or less efficient than the most promising competing technology in each category). These considerations have been used when choosing which technologies to include in the scenario modelling.

1.5.4.2 Scenario-Analysis Methodology Discussion

In the methodology chosen for the scenario modelling in this work, it is not feasible to investigate all possible combinations of energy storage (or conversion) capacities and fluctuating RES generation capacities. The results and conclusions in this work are therefore based on calculations performed for some specific combinations of these capacities. The investigated capacities are defined *a priori* by the modeller, and are not outputs of the model. The installed capacities for the energy conversion and storage technologies in each variation of each scenario are, furthermore, defined based on the best judgment of the modellers regarding how much energy supply and demand balancing capacity is needed in each case.

As a result of this methodology, it is by no means certain that the results of the scenarios represent the optimal performance of the energy storage or conversion technology in the given energy system configuration. There are almost certainly other combinations of storage (or conversion) capacities and fluctuating RES capacities that are slightly more economically and/or environmentally feasible than the combinations included in the current modelling. This is in particular true for combinations that include individual heat pumps, as all scenarios in this modelling work that include individual heat pumps are found to be technically and economically beneficial. This is not expected to change the general trends and conclusions obtained from the model results. A more comprehensive optimisation of the capacities is outside the scope of this work but would, however, be a useful addition in further work and when studying specific DES usage cases. It should also be noted that, although the different technologies are modelled one by one in technology-specific scenarios here (in order to investigate their effects on the system), reality will almost certainly include a combination of all (or most) the technologies included in this work.

An implication of the methodology used in this work is that the installed capacities of the different energy storage and/or conversion technologies cannot be compared across scenarios. It is e.g. not possible to say how much heat pump capacity in DH would be needed in scenario 5 to equal the installed Li-ion battery capacity in scenario 9; this would be comparing apples and oranges. For this reason, the results are suitable for identifying the general trends for one technology at a time on each of the three indicators, but a comparison of the numerical values of the indicators across scenarios is not applicable.

Similar considerations are also true for the comparison of the results of the scenarios across configurations (A-E). Comparing the absolute values of the indicators between configurations is not applicable, due to the very different starting points (baseline scenarios) of the configurations. The results of the economic and environmental indicators are therefore only presented relative to the corresponding baseline scenarios when comparing across configurations.

The technologies included in the modelling are divided in four categories; distributed EES, distributed TES, energy conversion technologies and alternative methods for balancing energy supply and demand. The different categories each have somewhat different roles in the system. The EES technologies operate within the electricity sector and have the potential of storing overproduction of electricity from fluctuating RES for use at later times, thereby lowering or avoiding the consumption of fuels for supplying the demand during low production from fluctuating RES. The TES technologies play a similar role, but within the heating sector (either in DH or individual heating). The energy conversion technologies have a somewhat different role, as they can be used for reducing the overproduction in one sector by enabling the usage of this energy in another sector (where it may be used immediately or stored e.g. as a synthetic fuel). The alternative methods for balancing supply and demand included here have similar effects on the system as EES, but do this by shifting the demand in time or influencing the total demand by import or export of energy.

In all cases, the introduction of the technologies in the model in this work aims at moving the overshooting fluctuating RES production to hours of lacking RES production, compared to the demand. A technically successful implementation of this will reduce the demand for fuels in the system and increase the share of renewable energy, thereby reducing the total system CO_2 emissions. In the method used here, an economically successful implementation of this will reduce the total socio-economic costs of the energy system (i.e. how much it costs society as a whole to fulfil its demand for energy services, disregarding all taxes and subsidies). As shown in the results, the scenarios where this implementation is most technically and economically successful is often where storage technologies and conversion technologies have been combined in a flexible sector coupling solution.

It is worth noting that the CO_2 emission values in the different scenarios range from approximately 11 ton/person/year to 7 ton/person/year. This means that the maximum reduction in CO_2 emissions observed in the model only corresponds to around 35% of the total CO_2 emissions in the model. This means that 65% of the CO_2 emissions are not affected by the introduction of more RES, the implementation of the recommended energy system redesign measures or by the introduction of the energy supply and demand balancing technologies. This includes e.g. CO_2 emissions in the industrial and mobility sectors, as well as the fraction of the electricity, heating and gas sectors where it is not possible to replace fuel usage even though all recommended measures in this work are carried out. This pointed out here to illustrate the complexity and scale of the emission goals and climate challenges that lie before us. The introduction of DES or other energy supply and demand balancing technologies for the integration of large amounts of RES is only one part, but an important part, in the transition towards a sustainable and environmentally responsible energy supply.

1.5.4.3 Model-External Uncertainty Factors

The technologies included in the modelling have a number of properties and uncertainty factors that are not included in the model. These can be referred to as model-external uncertainty factors. Some of these factors are mentioned in Table 6 through
Table 10.

For electrical interconnections, it is not clear how reliable the electricity exchange with the neighbouring countries is. The development of electricity spot prices is uncertain, and so is the ability or willingness of the neighbouring countries to exchange when needed in the national system (as overproduction and underproduction may coincide in neighbouring systems with a similar RES mix). Fundamental national security of energy supply may also be a concern when relying greatly on electrical interconnectors to abroad.

Electric heat pumps require an external heat source, but no assumptions are made in the model regarding what this heat source should be. The potential for external heat sources that are suitable for electric heat pumps has also not been estimated in this work. The coefficient of performance of electric heat pumps also depends on the heat source and its temperature, but an average constant COP of 3.0 is simply assumed in the model. Furthermore, heat pumps may have a very long peak-demand periods during long cold periods of the year, which may decrease their potential for flexible operation unless connected to a sufficiently large TES.

These aspects must be investigated in more detailed when preparing case-specific studies of the implementation of electric heat pumps.

The magnitude of the available potential for flexible electricity demand is not clear, and depends on the willingness of electricity consumers to be flexible. This willingness again depends on the business models and technical solutions that are available for making the demand flexible. It is also uncertain if or how much the electricity consumers would need to be compensated for their flexibility. The costs of any such compensation are not included in the model.

For the power-to-gas-to-power and power-to-gas technologies, the development in the costs, scaling and reliability of the electrolysis and methanation technologies must reach the assumptions used in the model. The choice of modelling solid oxide electrolysers and fuel cells here, rather than the more conventional alkaline cells, was taken based on the development potential of this technology. The technology has the potential for reaching the assumed maturity, but only with concentrated research, development and demonstration efforts and if the market for these technologies increases. In case the solid oxide technology fails to reach these targets, the performance of the P2G2P and P2G scenarios will be worse than in the results shown here.

The same uncertainties apply to the battery prices for Li-ion and Vd-redox batteries. Li-ion batteries are proven technology with prices that have rapidly fallen in recent years. This development is anticipated to continue such that the investment costs for battery systems (including power electronics, inverters and casing) can reach the assumed level within the next 5-10 years. The Vd-redox battery technology is not as mature, and both technology development and price reductions are needed for them to reach the maturity assumed in the model. Similar to the solid oxide cells, this requires a concentrated research, development and demonstration effort and the development of a larger market for Vd-redox batteries.

The nuclear power plants included in configuration E are assumed to operate as inflexible baseload electricity generation. Technological advancements may lead to increased flexibility of nuclear power plants. This would enable increased integration of fluctuating RES in energy systems with nuclear power.

The transition away from ICE vehicles towards electric vehicles has already begun. As seen by the results of configuration D, electric vehicles can be very useful for cost effective integration of fluctuating RES. This assumes that all EVs are charged in smart (flexible) way. Measures should be taken to ensure that smart charging will be the standard method as the transition towards electric vehicles advances. A failure to implement smart charging infrastructure (and some incentives for the vehicle owners to make use of this) would lead to less feasible results in the model scenarios in configuration D.

Many of the energy storage or conversion technologies modelled in this work have a potential of yielding ancillary services to the electricity grid, in addition to providing the modelled balancing of supply and demand. These ancillary services include frequency regulation and primary reserve supply. The provision of these services could reduce the need for other reserve capacity in the system and improve the economy of the storage or conversion technology. These electricity system service aspects were not included in this subtask but should be looked into in future studies focussed on distributed electrical energy storages.

1.5.5 Project expectations and success

The objectives of the project, described in subsection 1.4.3, were realized. The technical and the economic potential for the usage of DES for the integration of renewable energy have been estimated for 19 scenarios (with different DES technologies, alternatives to storage or combinations thereof) and for 5 different energy system typologies. For specifically addressing the question of if and/or how these technologies can facilitate the integration of fluctuating renewable energy sources, the amount of the electricity generation from such sources has been varied in a large range in all modelling scenarios. The total potential of the DES solutions has been analysed for the different energy system typologies. The results of these analyses have been summarized in Table 6 - Table 10. A full version of the project results, including additional graphs for the technology specific scenarios, can be found in the full version of the report at www.planenergi.eu/desire.

The project has resulted in the building and gathering of state-of-the art knowledge in the field of energy storage for both PlanEnergi and AAU. The project has played a part in enabling PlanEnergi to hire an additional employee during and after the project period. It is expected that the increased expertise in the field could enable PlanEnergi's involvement with more projects in the fields of energy storage and sector coupling, which could increase the turnover, employment (and exports, in case of projects abroad) of PlanEnergi in the long term. Besides this, PlanEnergi will be able to use this knowledge in guiding other stakeholders in the energy sector in terms of how RES can be integrated to a large extent in future energy systems.

1.5.6 Project dissemination

Throughout the project, three open expert meetings have been held at the IEA in Paris. These meetings have been open to all interested parties, thereby providing dissemination of the progress and results of the project to the IEA and to the scientific and/or industry community.

The project and its preliminary results were presented at a public workshop hosted by PlanEnergi in Copenhagen in April 2017. Speakers at the workshop were both international expert participants in IEA ECES Annex 28 and Danish experts in the field of energy system analysis and energy storage, including experts from PlanEnergi and AAU. The workshop provided a forum for exchange of Danish and international knowledge and experiences. The workshop was attended by approximately 40 participants, mainly from Danish research institutions and industry.

The results of the project were presented at an oral presentation at the International Renewable Energy Storage Conference (IRES) in Düsseldorf, Germany in March 2018. The presentation, held by Dadi Sveinbjörnsson from PlanEnergi, was titled "*Identifying the Potential of Renewable Energy Storages for Integrating Fluctuating Renewable Energy Sources*". The presentation was co-authored by PlanEnergi and AAU.

Besides this, the results of the project were presented at an oral presentation at the 4th International Conference on Smart Energy Systems and 4th Generation District Heating (4DH) in Aalborg in November 2018. The presentation, held by Daniel Trier from PlanEnergi, was titled "*Sector Coupling and Distributed Energy Storages for the Integration of Renewable Energy Sources*". The presentation/corresponding abstract was co-authored by PlanEnergi and AAU[1].

An article on the project and its main results is prepared by AAU and PlanEnergi. The article will be submitted to an international peer-review scientific journal in the field of energy system analysis.

1.6 Utilization of project results

PlanEnergi will utilize the results for updating its knowledge on distributed energy storage systems, where such systems could be feasible and what the feasible alternatives to energy storages could be. This can be directly utilized and implemented in PlanEnergi's consulting work regarding e.g. pit thermal energy storage and heat pumps, enabling PlanEnergi to identify and recommend solutions based on the most recent knowledge in the field.

Aalborg University will utilize the energy systems modelling work and results for further improvement of the *EnergyPLAN* energy systems modelling software. AAU will also use the results to update its knowledge on DES systems.

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[1] See www.4dh.eu/images/Book-of-Abstracts-2018_online_version.pdf and www.4dh.eu/images/Daniel_Trier_PlanEnergi_2018.pdf respectively.

Both PlanEnergi and AAU are planning to continue collaborating with international stakeholders in future annexes e.g. within the IEAs ECES and DHC programmes. The results and knowledge obtained in the current project will be used by PlanEnergi and AAU in the definition and working phases of such upcoming projects for further development of flexible energy systems with high shares of renewable energy. This way the knowledge from the project can be disseminated further and used directly in future research.

This R&D project of the IEA is based on calculations and modelling of DES and does not involve the development of a single technology or component. As such, the project contributes to the development of energy storages and the integration of renewable energy solutions in general, but does not directly lead to new commercial activities, business plans, products or patents for the project participants.

1.7 Project conclusion and perspective

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:

1.7.1 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.

1.7.2 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.

1.7.3 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.

1.7.4 Perspective

In this work, the technical and economic feasibility of DES technologies and other technologies for balancing energy supply and demand has been assessed for the energy system as a whole. More detailed modelling of some aspects of distributed energy storages, such as how they may help relieving congestion in distribution grids and how they may be useful for providing ancillary services to the electricity grid, requires further work in other, more specific modelling frameworks.

One of the main results of this work is that flexible sector coupling, e.g. through flexibility in the electricity sector and/or the heating sector (e.g. through energy storage) with a coupling between them in the form of power-to-heat technologies, is very beneficial for the system as a whole. Other beneficial flexible couplings between other sectors that were not looked into in this work may also be possible. Further research into which combinations of flexibility and sector coupling could be most useful for integrating renewable energy and lowering the CO_2 emissions of the energy system should be carried out.

References

[EnergyPLAN 2018] *EnergyPLAN | Advanced Energy System Analysis Computer Model.* Web site: *energyplan.eu*. Visited 01.02.2018. Department of Development and Planning, Aalborg University, 2018.

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Annex

The full report on PlanEnergi and AAUs contribution to IEA ECES Annex 28 that contains all details on the energy system modelling work, including the analysis assumptions and detailed results for each scenario, is available here:

www.planenergi.eu/desire

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