Final report

National scale energy system analyses of flexible sector coupling potential through energy storage

The Danish input for the IEA ES Task 35

1. Project details

Project title	EUDP 2019-I IEA ECES Annex 35 - Fleksibel Sektorkobling vha. Energilagring
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Name of the funding scheme	EUDP 2019-I
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Project partners	PlanEnergi
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2. Summary

ENGLISH:

PlanEnergi's work within the IEA ES Task 35 project focuses on national scale energy system analyses to evaluate the influence of different types of energy storages on sector coupling in a fully renewable-based energy system. The analyses are carried out by simulating scenarios for different storage types in the EnergyPLAN modelling tool and comparing them to a reference scenario in terms of costs and energy efficiency. The influence on the energy system is investigated by adjusting the capacity of each of the different types of energy storages.

The analyses show that energy storage can improve the flexibility of sector coupling in the thermal and mobility sectors and cost-effectively increase the energy efficiency in the process, while facilitating the integration of intermittent electricity production units and aiding the transition towards 100% renewable-based energy supply. Moreover, the analyses outline that hydrogen applications and storage play a central role in the system integration of fluctuating renewables, since hydrogen can be used to cover energy demands directly or as an energy carrier when converted to other fuels.

The results from this project can be used as a basis for further research within the field of flexible sector coupling through energy storage, e.g. by in-depth investigation of the role of hydrogen and the necessary infrastructure for its full scale rollout in energy systems. Additionally, the conclusions and policy recommendations from this project can be used directly to facilitate the transition towards fully renewable-based energy systems.

DANSK:

PlanEnergis arbejde inden for IEA ES Task 35-projektet fokuserer på nationale energisystemanalyser for at evaluere indflydelsen af forskellige typer energilagre på sektorkobling i et 100% vedvarende energi-baseret energisystem. Analyserne udføres ved at simulere scenarier for forskellige lagertyper i EnergyPLAN-modelleringsværktøjet og sammenligne dem med et referencescenarie med hensyn til omkostninger og energieffektivitet. Påvirkningen af energisystemet undersøges ved at justere kapaciteten af hver af de forskellige typer energilagre.

Analyserne viser, at energilagring kan forbedre fleksibiliteten ifm. sektorkobling mellem hhv. el og varme- og mobilitetssektorerne, og omkostningseffektivt øge energieffektiviteten i processen. Samtidigt kan lagrene lette integrationen af fluktuerende elproduktion og hjælpe med omstillingen af energiforsyningen til 100% vedvarende energi. Desuden tydeliggør analyserne, at brint – inkl. lagring af denne – spiller en central rolle i systemintegrationen af fluktuerende vedvarende energikilder idet brint kan bruges til at dække energibehov direkte eller som energibærer ved at blive omdannet til andre brændstoffer.

Resultaterne fra dette projekt kan danne grundlag for yderligere forskning indenfor området fleksibel sektorkobling gennem energilagring, f.eks. ved tilbundsgående undersøgelse af brints rolle og den nødvendige infrastruktur til fuldskala-udrulning i energisystemer. Derudover kan konklusionerne og de politiske anbefalinger fra dette projekt bruges direkte til at facilitere overgangen til energisystemer baseret på 100% vedvarende energi.

3. Project objectives

The increase of renewable energy (RE) production capacities in national energy systems, driven by ambitious goals for decarbonisation and reduction of greenhouse gas emissions, poses challenges to meeting the energy demands in the heating, electricity, and mobility sectors without the reliance on fossil fuels. Production from renewable energy sources (RES) is in most cases dependent on external conditions such as wind, sun, etc. The reliance of RES on external conditions can create challenges in matching their production to the energy demands in the system and can lead to increased curtailment of electricity if the mismatch between demand and supply is not properly handled.

Different types of energy storages (ES) can help decouple the RES-based energy supply from the demands in the different sectors within the energy system, and decrease the need for balancing end user demands with intermittent production from wind turbines, solar photo-voltaic (PV) systems, etc.

The value of storages using a single energy source, operating within one sector, is represented by the ability to optimise the operation by enabling flexibility through time. When coupling different sectors, another dimension is added to the storages' ability to allow optimisation of the overall energy system: Storages applied in a flexible sector coupling (FSC) context are able to balance supply and demand across multiple sectors, which improves the system resilience to handle fluctuations in both energy production and demands. Besides this, when storages enable such FSC, the utilisation of an increased number of energy sources may become available. FSC facilitated by various storage options thus represents a pathway to enable a cost-efficient decarbonisation of the energy system.

Hence, by helping to decouple RE supply from energy demands in the different sectors, FSC will have a key role in ensuring that national energy systems are fossil free and CO_2 neutral, while simultaneously helping to decrease curtailment of electricity produced by intermittent RES.

PlanEnergi's work within IEA ES Task 35 involved assessing the influence of different types of storages on FSC in a fully renewable-based energy system through national scale energy system analyses.

The national scale energy system analyses cover most of the FSC configurations presented in the report "Technologies and configurations for national scale flexible sector coupling" (Lund & Sørensen, 2022), conducted by PlanEnergi as a part of this project, and are carried out with the energy simulation software EnergyPLAN. A reference scenario in EnergyPLAN is developed, using the calculation prerequisites described in the above-mentioned report. It is used as a starting point for the comparison to relevant alternative scenarios, each of which focuses on the influence of a different storage type on FSC in a national energy system perspective.

Five different storage types are investigated for their effect on FSC in the context of an energy systems model representing a system similar to what could be Germany in 2050, with large scale integration of renewable energy. Eight different configurations are analysed, as for each of these, a "No storage" and a "Double storage" variation are performed. The scenarios and parameter variations performed in each scenario are shown in the overview in Table 1.

Scenario	Name	Reference	Variation 1 [No storage]	Variation 2 [Double storage]	Variation 3 [Custom]
1a	District heating storage	510 GWh	0 GWh	1,020 GWh	-
1b	District heating storage (no excess heat)	510 GWh	0 GWh	1,020 GWh	-
2a	Individual heat storage Individual heat pumps	1/10-day storage (49 GWh)	0 GWh	1 day storage (490 GWh)	-
2b	Individual heat storage Individual electric heating	1/10-day storage (49 GWh)	0 GWh	1 day storage (490 GWh)	-
3a	Hydrogen storage	3,000 GWh	0 GWh	6,000 GWh	1,500 GWh
3b	Hydrogen storage Double electrolyser	3,000 GWh	0 GWh	6,000 GWh	1,500 GWh
4	District cooling storage	6 GWh	0 GWh	12 GWh	-
5	Smart charge vehicles Battery storage	50% Smart Charge 50% Dump Charge	25% Smart Charge 75% Dump Charge	75% Smart Charge 25% Dump Charge	75% Smart Charge (with V2G) 25% Dump Charge

Table 1: An overview over the scenarios examined and the parameter variations in each scenario, with variation 1 being "No storage", variation 2 being "Double storage", except for scenario 2 and 5, and variation 3 being a custom storage size.

The results from the analyses are quantified in two main analytical indicators: energy system costs and primary energy supply (PES).

The energy system costs include the total annual costs for the operation and financing of the national energy system. These include costs for fuel consumption, operation and maintenance, depreciation of investments, financing costs, etc. The boundary of which costs are included is the same for all scenarios. The change in total system costs in the different scenario variations, compared to the reference, is noteworthy, as this indicates the total cost effect on the energy system of changing the size of the different storage types.

The PES is the total needed supply of energy to an energy system. This includes fossil fuel consumption, bioenergy consumption and power production from renewable sources such as wind, solar and hydro. A change in the PES in the difference scenario variations compared to the reference indicates a change in the overall system efficiency of covering the energy demands as a result from the changes in the size of the different storage types. It is hence a key parameter for monitoring the influence that different storages have on the overall energy system.

4. Project implementation

The project involved energy system modelling and analysis and did not involve any physical experiments or implementation. The modelling and analyses carried out in IEA ES Task 35 subtask 4, which PlanEnergi was the leader of, proceeded largely as expected, as there was agreement on the methodology and scenario analyses after discussions between the project participants at project meetings. Although, some inputs from project partners were delayed, which caused the delay of the work carried out within subtask 4, consequently delaying some of the deliverables to EUDP. The main focus areas of the analyses, as well as how to disseminate the results, was agreed upon by the project group following presentations by PlanEnergi and discussions at project meetings.

The project started at the end of 2019 and was originally scheduled to finish at the end of 2022, since this was the original end date of IEA ES Task 35. Due to the necessity for more time to gather inputs for performing the analyses and to formulate key messages, the project was extended until the end of November 2023. The project phase of IEA ES Task 35 was extended by one year, until the end of 2023, due to delays in the early phases of the task. The project phase of Task 35 was concluded in November 2023 with the final report of the task presented to the ES executive committee. The extension of the project period enabled PlanEnergi to disseminate the results of the project at the Volta-X Energy Systems Expo in Stuttgart, Germany in March 2023.

5. Project results

The scenario analyses in this project take their starting point in the reference scenario which could represent Germany's national energy system in 2050. Eight different scenario analyses each with multiple variations, covering five storage types within the scope of FSC are carried out.

The results present in all cases the main analytical indicators, showing the system costs effect and the primary energy effect in the parameter variations compared to the reference scenario for each analysis. If, for example, the costs effect is positive while the primary energy effect is negative, there is a trade-off between costs and energy efficiency as an outcome from the variation in the storage size. If both analytical indicators are decreased or increased, the change in storage size makes the system simultaneously cheaper and more efficient or more expensive and less efficient respectively.

On top of the costs effect and primary energy effect, supplementing figures are shown for some scenarios to further elaborate certain details from the results.

Methodology, assumptions and results have been discussed with and presented for the network of partners within the IEA ES Task 35 group. Besides this, the results have been disseminated through workshops, conferences while the complete report including both background material, results and policy recommendations are made publicly available online when the overall Task 35 reporting is published.

5.1 District heating storage

There are two alternative scenarios for the DH storage. Scenario 1a uses the reference scenario as a starting point for the adjustment of the storage size, while in scenario 1b the excess heat available for direct utilisation in the DH sector is removed from the reference scenario.

5.1.1 District heating

The reference scenario, where the capacity of the DH storage in the national energy system is 510 GWh, is compared to two scenario variations, where the storage capacity is respectively removed and doubled. The results from the parameter variations in scenario 1a are visible in Figure 1.

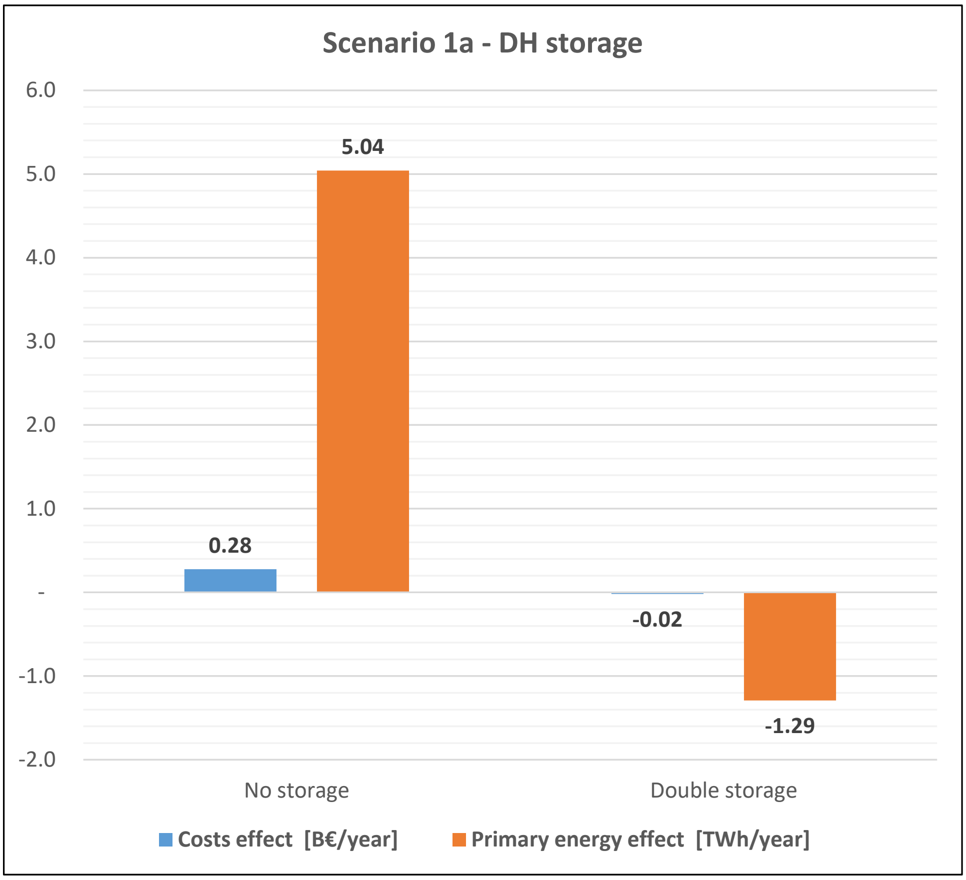

Figure 1: Results for the changes in total costs and PES in scenario 1a (DH storage) by removing and doubling the DH storage, compared to the reference scenario.

Figure 1 shows the costs effect and primary energy effect of removing and doubling the DH storage capacity compared to the reference scenario, i.e. the change in total costs and PES compared to the reference scenario.

It is visible that both total costs and PES are increased considerably when the DH storage is removed. This can be attributed to the lower flexibility of the system, reducing the possibility for the system to effectively utilise the intermittent renewable production. Since their operation is reduced, less efficient production units, e.g. boilers, make up for a larger share of the production portfolio, increasing the PES in the scenario.

Doubling the DH storage has the opposite effect on the energy system. The total costs in the model are slightly reduced compared to the reference. Since a larger storage allows for more flexible operation of intermittent DH production units, e.g. heat pumps, the PES is also reduced compared to the reference.

Results for the DH production in the reference and the two storage capacity variations are visible on Figure 2 and the change in the DH production compared to the reference is shown in Figure 3.

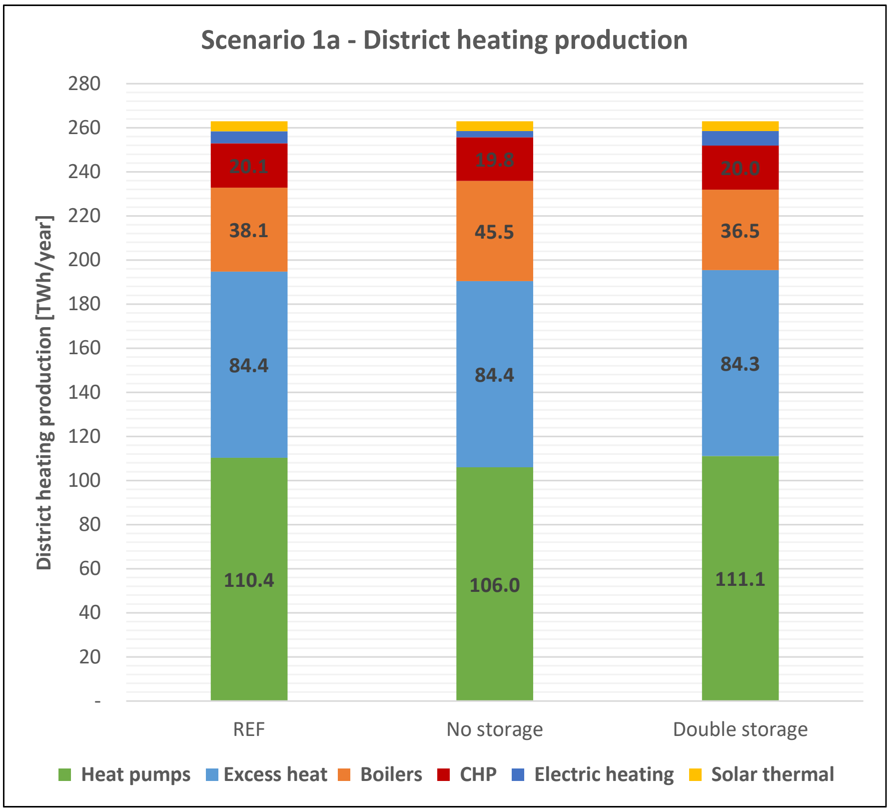

Figure 2: Results for the DH production in the reference scenario and the two variations of the DH storage size in scenario 1a.

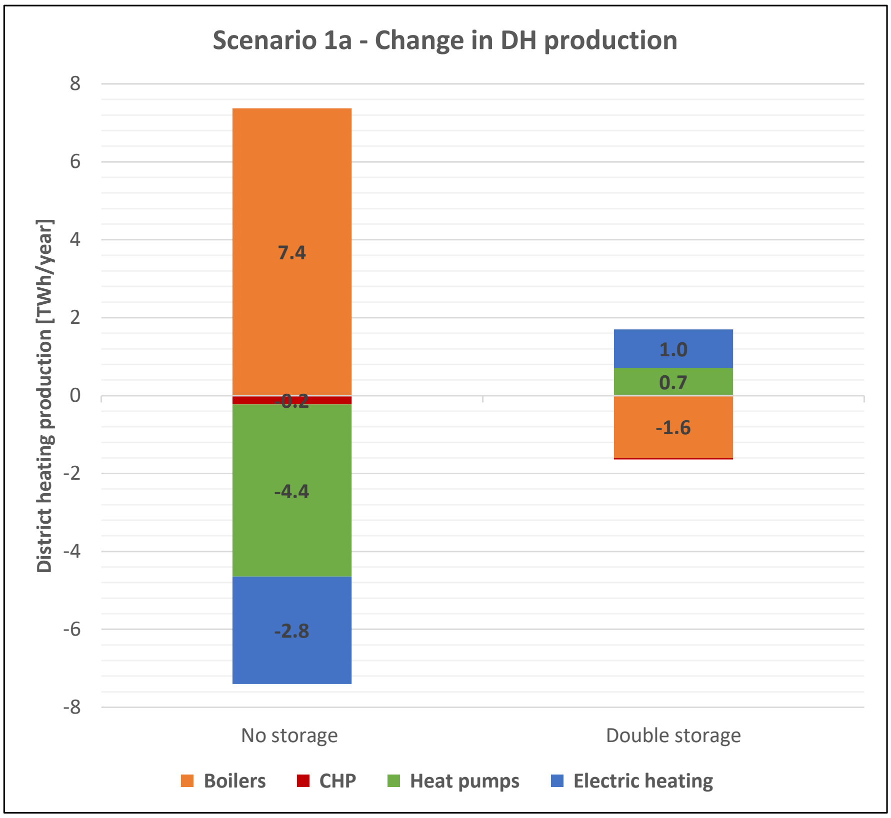

Figure 3: Change in the DH production compared to the reference in scenario 1a with no storage and double storage.

Figure 3 shows that the effect of removing the DH storage on the energy production is quite remarkable, while doubling the storage does not have nearly as large an impact. Hence, there is room in the system for a larger storage capacity, as the increase is almost cost neutral while making the overall system more energy efficient. Removing the storage makes the system both less energy efficient and more expensive.

5.1.2 District heating (no excess heat)

An alternative reference scenario is set up, where the excess heat available for direct utilisation in the DH grids is removed. The storage capacity variations are then carried out based on the adjusted reference scenario. The results for the total costs effect and primary energy effect are visible in Figure 4.

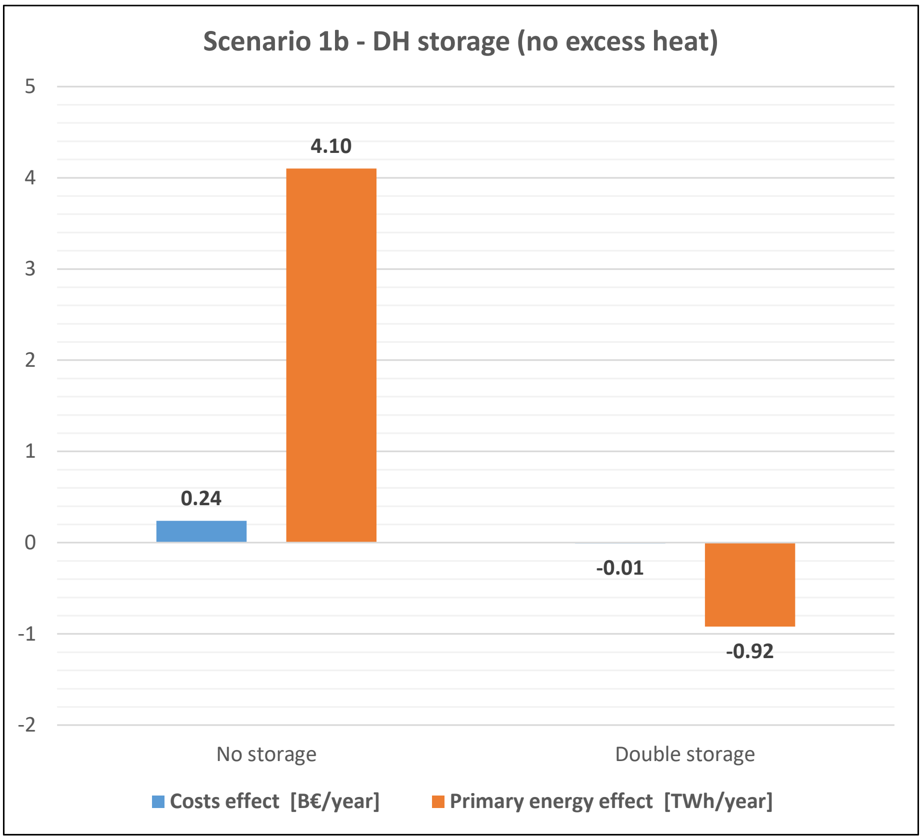

Figure 4: Results for the changes in total costs and PES in scenario 1b (DH storage no excess heat) by removing and doubling the DH storage, compared to the reference scenario.

Figure 4 shows that removing and doubling the DH storage have a similar effect on the national energy system as in scenario 1a. The impact of the changes in the storage capacity on the energy efficiency of the system is lower than in scenario 1a, since excess heat would also be stored at times when the supply exceeds the demand. Moreover, due to the lack of directly available excess heat, a larger share of the DH demand needs to be covered by e.g. CHP units and boilers, making the overall costs in this reference scenario higher than in scenario 1a.

5.1.3 Summary, district heating storage

A general conclusion from the parameter variation of the DH storage is that, regardless of the presence of excess heat in the system, there is potential for further energy savings related to the increase of the storage capacity, which at the same time is cost neutral. Moreover, the lack of a DH storage reduces the utilisation of intermittent renewables, increasing both total costs and PES in the process. Hence, DH storage presents a potential for energy efficiency improvement for the society through the better utilisation of intermittent production units in the heating and electricity sectors.

5.2 Individual thermal storage

Two alternative scenarios evaluating the influence of individual thermal storage on the energy system are carried out. The first assumes that the individual heat supply in the energy system is covered by individual heat pumps, while electric heating is used in the second instead. This is done to investigate the impact of the different production profiles of heat pumps and electric boilers on ES in the individual heating sector.

5.2.1 Individual heat pumps

In the reference scenario, a storage with a capacity equal to approx. 1/10 of the average daily heat demand is used, which is roughly 49 GWh. Parameter variations are then performed, where the storage is first removed and then set to a capacity equal to approx. the average daily demand. Results from the reference scenario and the two parameter variations of the storage capacity are shown in Figure 5.

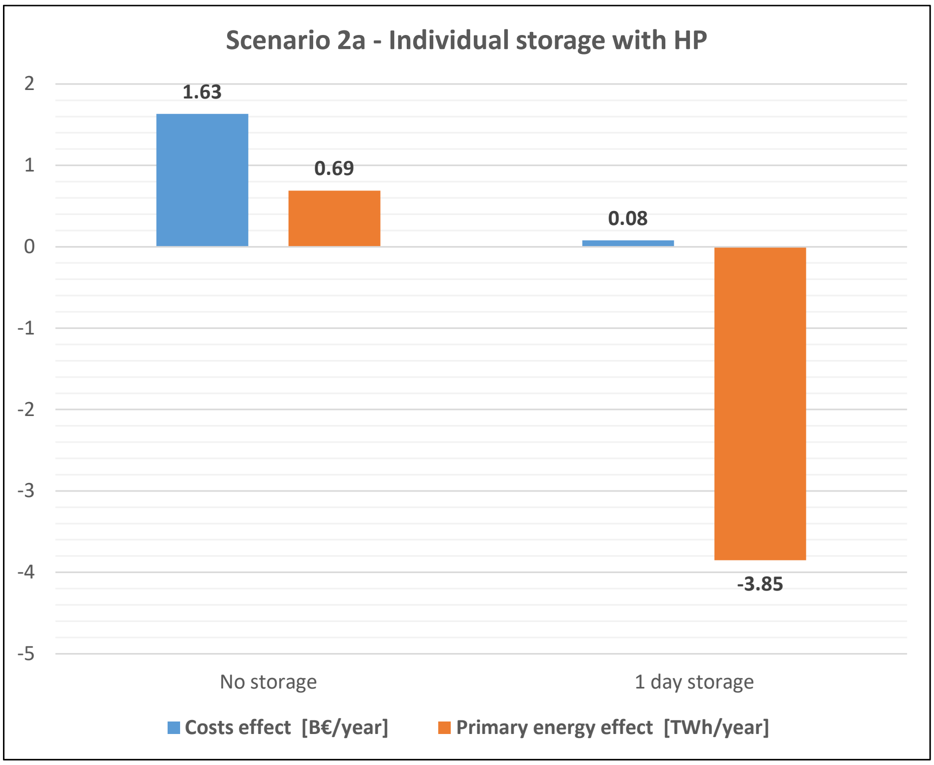

Figure 5: Results for the changes in total costs and PES in scenario 2a (Individual storage with heat pump) by removing the individual storage and setting it to 1 day storage, compared to the reference scenario.

As seen in Figure 5, when the individual heat storage is removed, both the total costs and the PES are increased compared to the reference scenario. This is mainly due to the need for a larger production capacity when there is no storage, to be able to cover the peaks in the individual heat demand throughout the year.

When the individual heat storage capacity is increased, a slight increase in total costs compared to the reference is noticeable, due to the increased investment in the storage. Nonetheless, there are substantial savings of PES, since the system becomes far more flexible, and the electricity supplied to the individual heat pumps can to a higher extent be produced by more efficient production units.

5.2.2 Individual electric heating

Replacing individual heat pumps with individual electric heating somewhat increases the flexibility of operation in the system, since the technical operation of electric heating is not directly dependent on weather conditions. However, electric heating is far less efficient than individual heat pumps, which leads to a much higher electricity consumption in the individual heating sector in this scenario. The results from the scenario analysis in scenario 2b are visible on Figure 6.

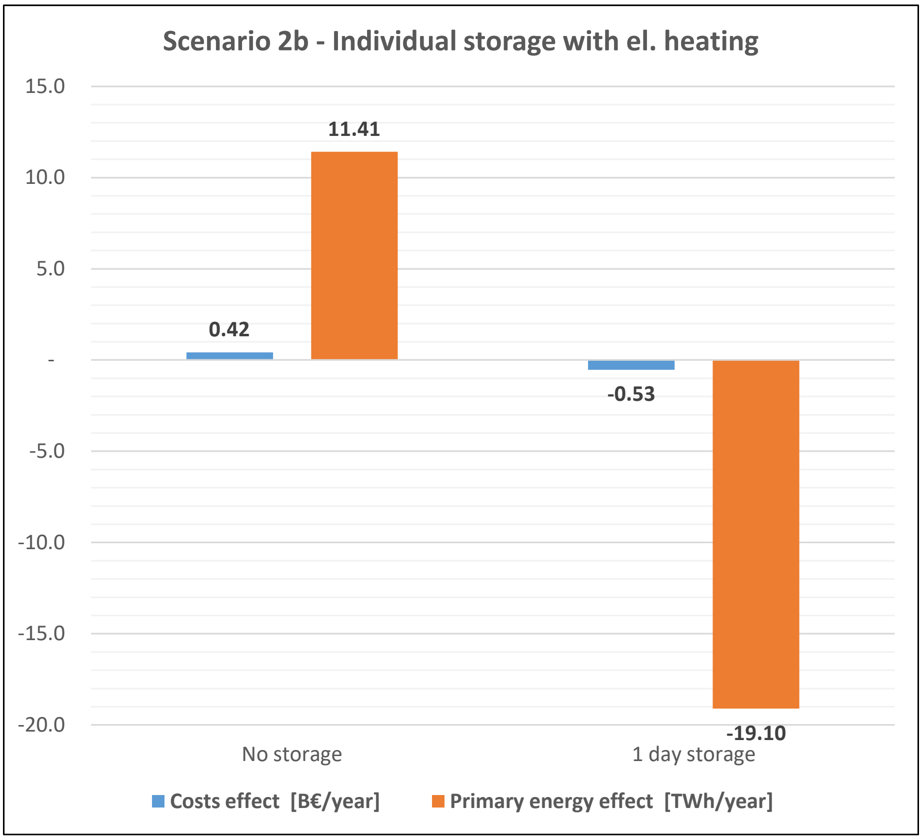

Figure 6: Results for the changes in total costs and PES in scenario 2b (Individual storage with electric heating) by removing the individual storage and setting it to 1 day storage, compared to the reference scenario.

It is clearly visible from Figure 6 that individual heat storage has a large impact on the energy system when it is coupled with individual electric heating. When the storage is removed, there is an increase in overall costs and a noticeable increase in PES.

It is also worth mentioning that the overall system costs are much higher when using electric heating to cover the demand in the individual heating sector than when using heat pumps. This is due to the lower efficiency of electric heating, which requires considerably more electricity to be produced in the system to cover the heat demand.

Increasing the storage capacity shows that there is a larger potential for increasing the storage capacity in the individual heating sector when using electric heating than with heat pumps, since the savings in both costs and primary energy are much bigger. It would thereby make sense to apply larger individual heat storages at consumers with electric boilers.

5.2.3 Overview

Figure 7 compares the PES in the different storage size variations for the scenarios with individual heating based on heat pumps and electric heating. It is clearly visible that the primary energy supply in the system is increased considerably when heat production is based on electric heating rather than heat pumps. As mentioned earlier in this chapter, this is due to the larger electricity consumption of electric heating, due to the lower efficiency compared to heat pumps.

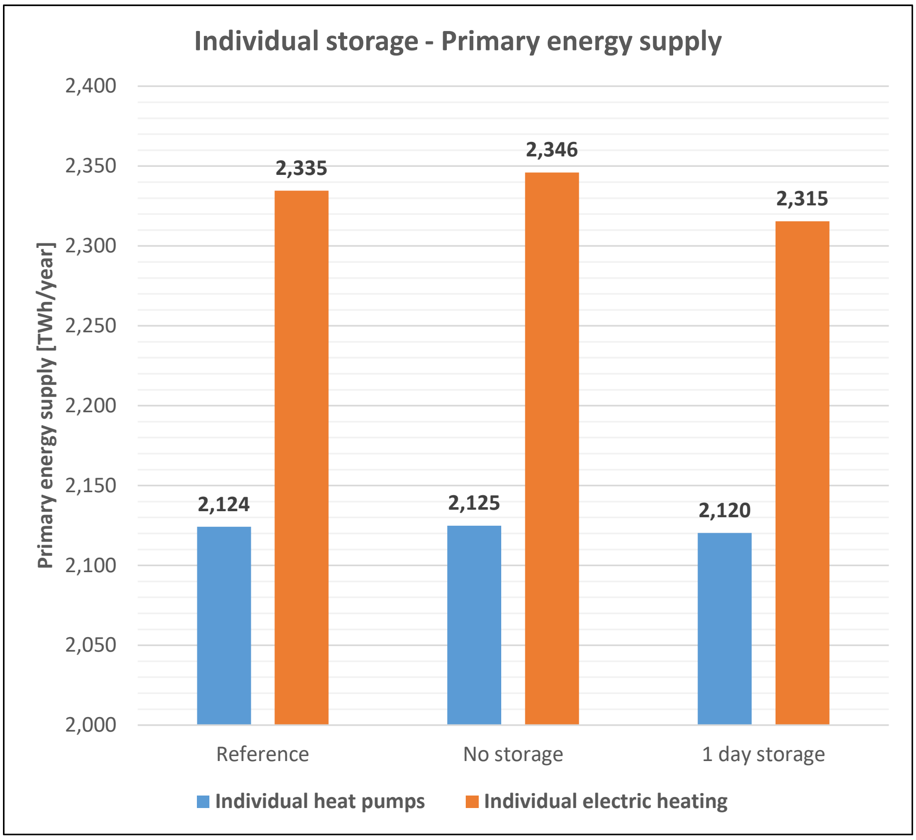

Figure 7: An overview of the PES in scenarios 2a (individual heat pumps) and 2b (individual electric heating) for the reference and the two parameter variations of the storage capacity.

Figure 8 compares the total costs in the different storage size variations for the scenarios with individual heating based on heat pumps and electric heating. Intact with the increase in PES, there is also a cost increase related with using electric heating instead of heat pumps, as electricity costs are higher and there is a need for considerably higher electricity production capacity.

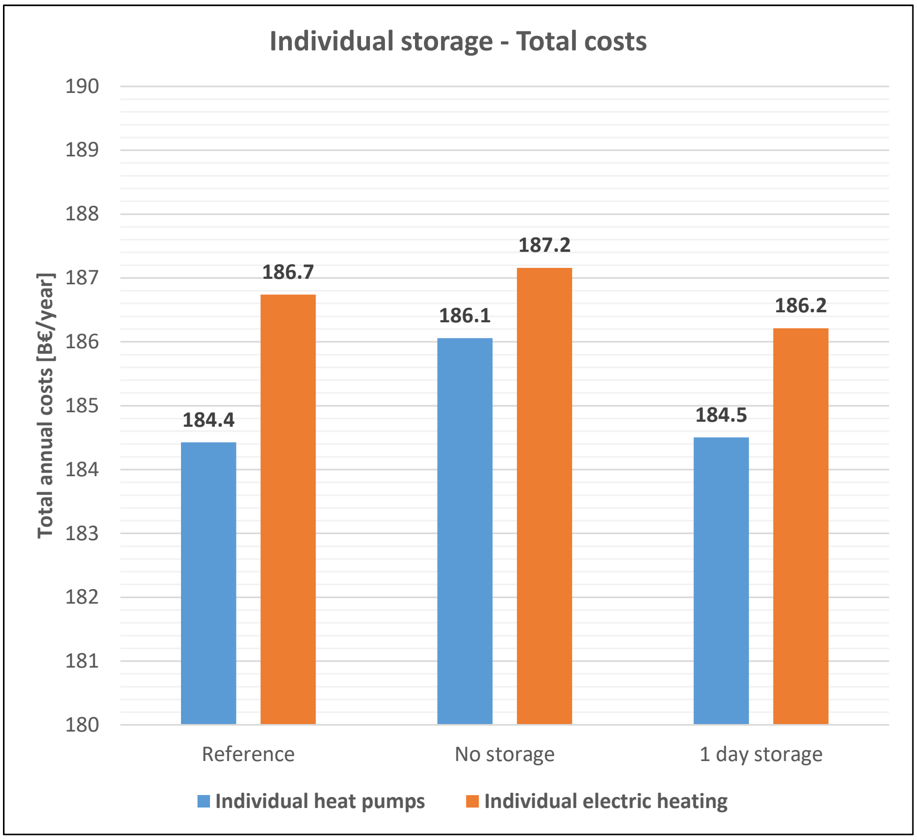

Figure 8: An overview of the total costs in scenarios 2a (individual heat pumps) and 2b (individual electric heating) for the reference and the two parameter variations of the storage capacity.

5.2.4 Summary, individual thermal storage

The results from the analysis show that individual heat storage reduces both PES and total costs in the energy system, thereby making it beneficial to society. Individual heat storages are scalable, as the analysis identifies further energy savings when increasing the storage capacity, which is almost cost neutral.

It is overall cheaper and more energy efficient to use heat pumps in the individual heating sector, rather than electric heating. The potential for thermal energy storage is remarkably larger in systems with electric heating, but the general cost level of the system is significantly higher, making it more economically feasible to use heat pumps for individual heating.

5.3 Hydrogen storage

The hydrogen storage in the reference scenario is set to 3,000 GWh. Three parameter variations are performed in the scenarios, as the storage is removed, halved, and doubled, compared to the reference scenario. The hydrogen storage is assumed to be equally distributed between regular gas tanks and salt caverns.

5.3.1 Hydrogen storage

The parameter variations of the hydrogen storage compared to the reference scenario are visible in Figure 9.

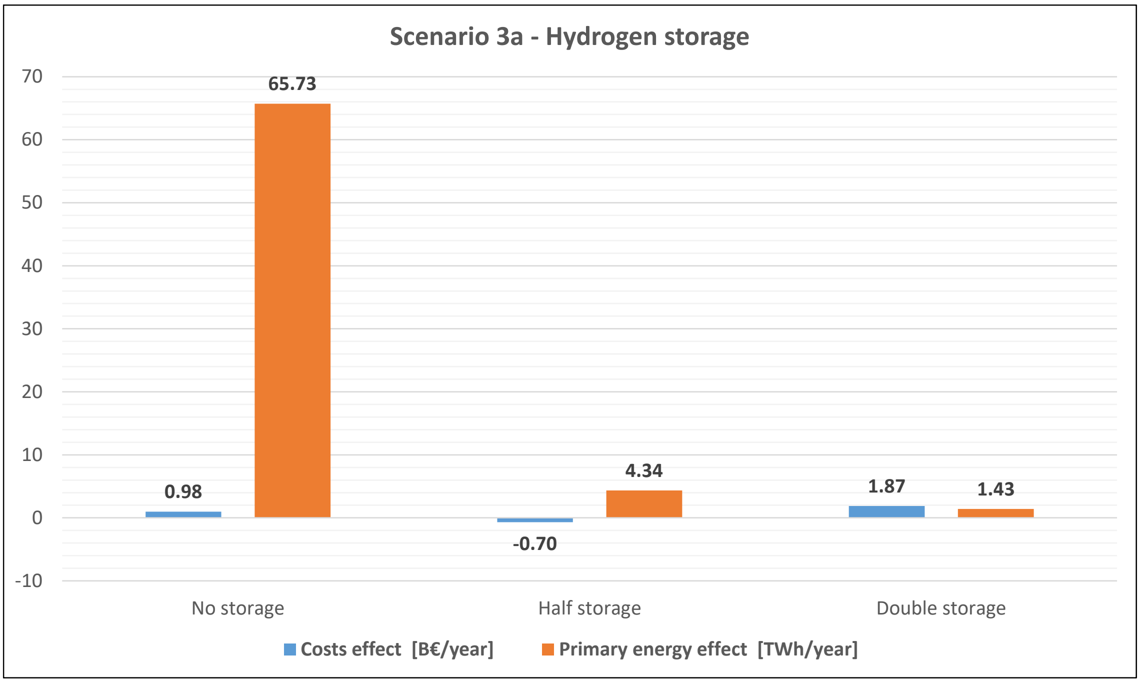

Figure 9: Results for the changes in total costs and PES in scenario 3a (Hydrogen storage) by removing, halving, and doubling the hydrogen storage, compared to the reference scenario.

The results in Figure 9 show that the removal of the hydrogen storage has a very large impact on the energy efficiency of the system. The utilisation of VRES (e.g. PV), which are dependent on weather conditions to cover the electricity demand for hydrogen production, becomes less flexible and thereby less efficient. Hence, there is a necessity for considerably larger PV capacity to meet the demands in the system.

In Figure 9 it can also be seen that when the hydrogen storage is halved, the total costs are decreased, due to the high investment costs in the storage, at the expense of an increase in PES compared to the reference. This is due to the smaller system flexibility and necessity for larger RE capacities in the system. The half storage variation represents therefore a trade-off between costs and energy efficiency as the trend of the two parameters point in different directions. Doubling the storage capacity results in an increase in both total costs and primary energy, which indicates that the storage capacity in this parameter variation is larger than necessary in the system. This indicates how it is relevant to consider jointly the demand for hydrogen storage, the availability of cheaper salt caverns as opposed to more expensive hydrogen storage options such as tanks, and the options to transfer the hydrogen to other fuels such as ammonia, e-methanol etc. where the storage, distribution and use may in some cases be more suitable.

Figure 10 shows the change in the electricity production compared to the reference for the three parameter variations in scenario 3a.

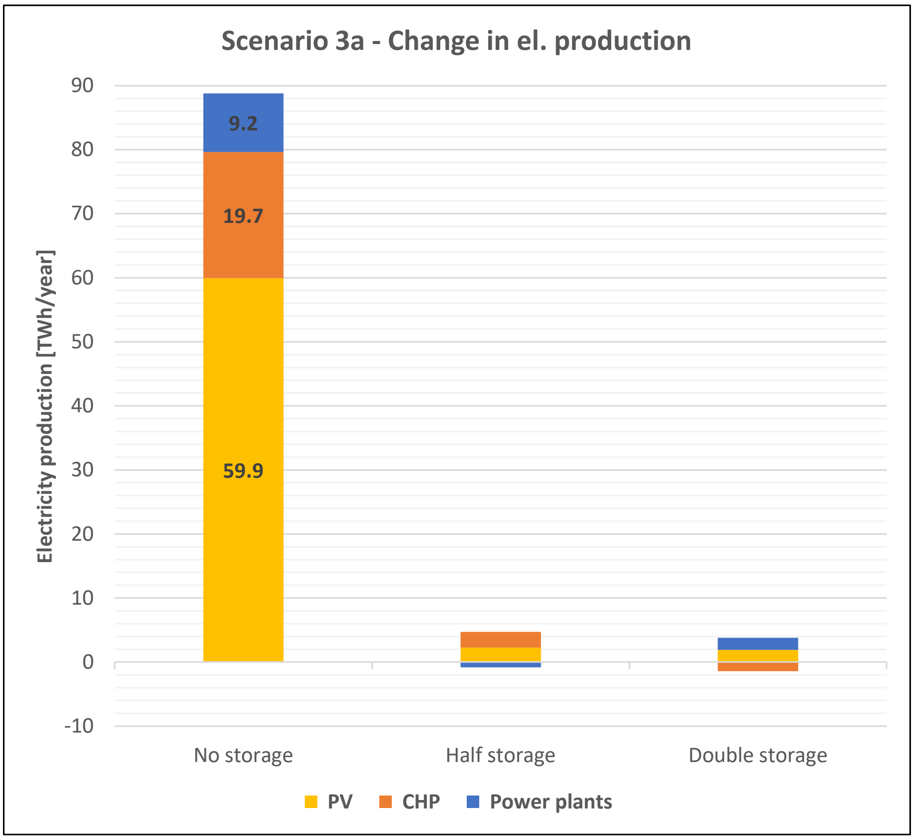

Figure 10: An overview of the change in electricity production compared to the reference for the three storage size variations in scenario 3a (Hydrogen storage).

As seen on Figure 10, since it is not possible to decouple the electricity production from PV from the hydrogen demand in the system without a hydrogen storage, the operation of other production units (e.g. CHP and power plants) is increased at times when there is no electricity production from PV. In addition, the lack of a hydrogen storage increases the total costs in the system, due to the necessity for larger production capacities and the increased production from electricity production units, which are more expensive to operate. Since hydrogen plays a key role in covering demands both directly and by using it for production of other fuels, having a hydrogen storage facilitates the more efficient integration of fluctuating renewables through FSC. This can be in the form of direct hydrogen storage or as an alternative hydrogen-based fuel.

5.3.2 Hydrogen storage - double electrolyser

In this scenario variation, the electrolyser capacity in this scenario is doubled compared to scenario 3b, from 400 to 800 GW-e. The results from the parameter variations in this scenario, compared to the reference, are seen in Figure 11.

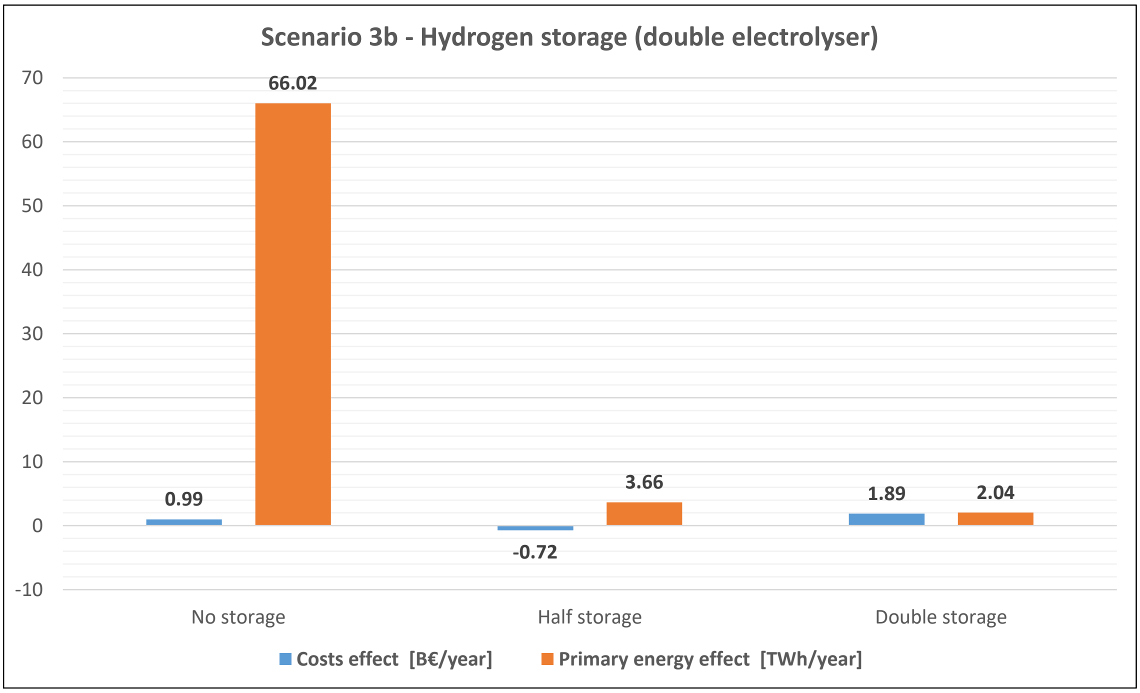

Figure 11: Results for the changes in total costs and PES in scenario 3b (Hydrogen storage double electrolyser) by removing, doubling, and halving the hydrogen storage, compared to the reference scenario.

The results from the parameter variations in scenario 3b show conclusions similar to those for scenario 3a. However, the total costs in this scenario are considerably higher than in scenario 3a, due to the capital costs associated with the larger electrolyser capacity. The effect of changing the storage capacity is slightly larger, but the possible effect of larger electrolyser capacity leading to lower need for storage is not identified. The need for storage in this regard seems more connected to the direct and indirect demand for hydrogen in the system, and the periods of fluctuations in production and demand it responds to do not require larger electrolyser capacities. From an economic standpoint there might also be room for further reduction of the electrolyser capacity assumed in the reference.

5.3.3 Summary, hydrogen storage

Generally, the analysis in this section shows that the presence of a hydrogen storage in an integrated energy system is very important for maintaining an energy efficient supply, in a system with a very high share of fluctuating renewables. Hydrogen storage thereby facilitates the efficient integration of high shares of VRES in the system. Compared to the PES impact, the cost effect of the storage, however, is relatively small, even in the “No storage” scenario.

The results indicate that the presence of a storage in connection to the production of hydrogen to a large extent enables flexibility in the system, which is required especially in 100% RE-based energy systems. This way, these storages facilitate the sector coupling between fluctuating electricity production and various demand types (covered by hydrogen directly or by a hydrogen-based fuel). However, a storage smaller than in the reference case could be sufficient for providing the desired flexibility. Further analysis on the availability of cheap and most suitable hydrogen storages, relevant distribution options as well as the most suitable fuel type for storing, distributing and utilizing green hydrogen can enable the most energy and cost efficient use of hydrogen.

5.3.4 Discussion of the role of hydrogen

As shown in this section, the hydrogen storage has a different role to the other storage types in the overall system because the volume of energy flow is large compared to the other energy carriers in the system. Moreover, a large share of the produced hydrogen does not cover a direct hydrogen demand in the system but is utilised as input for further processing and conversion to other fuels. All the above clearly indicates that green hydrogen plays a key role in the decarbonisation of the energy system through FSC. It also shows how the overall system can benefit from avoiding the “silos” of considering ES only within each sector individually, but rather applying storages where they are most valuable. By means of FSC, the storages can be linked to the conversion of energy thereby enabling the introduction of storage at the point in time, place, and with the type of energy carrier which result in the largest system benefit.

An important part of covering the energy demands in the transport sector in this model is the production of synthetic fuels, using hydrogen as the energy carrier. The amounts of energy and demands for these purposes, is in this report assumed to correlate with the overall transport demands. However, the general need for transport, including heavy road transport, shipping, and aviation, might be reduced in the future. The transport sector might also have a higher integration of direct electrification, through overhead power lines, batteries, or other technologies, so that the fuel consumption is considerably reduced. This will intact reduce the need for hydrogen production and possibly for hydrogen storage, thereby potentially reducing the benefit to FSC in the process.

Hydrogen as a central energy carrier in national energy systems is not yet realised in practice, compared to electricity, heat or gas, which brings a large uncertainty regarding its exact implementation. Some technologies are not fully developed and tested in the scale assumed to be necessary in 2050 in the analyses carried out in this report. This uncertainty means that both the costs related to the establishment of the necessary infrastructure and the specific processes related to it are still unclear. Consequently, this can have an influence on where in the energy supply chains it makes sense to have storage, e.g. to minimise the costs for more expensive production or conversion elsewhere in the system.

5.4 District cooling storage

The cold storage for district cooling is assumed to be a combination of ice storage and aquifer storage. The storage capacity of 6 GWh in the reference is respectively removed and doubled in the two parameter variations. The results from the analysis in scenario 4 are visible on Figure 12.

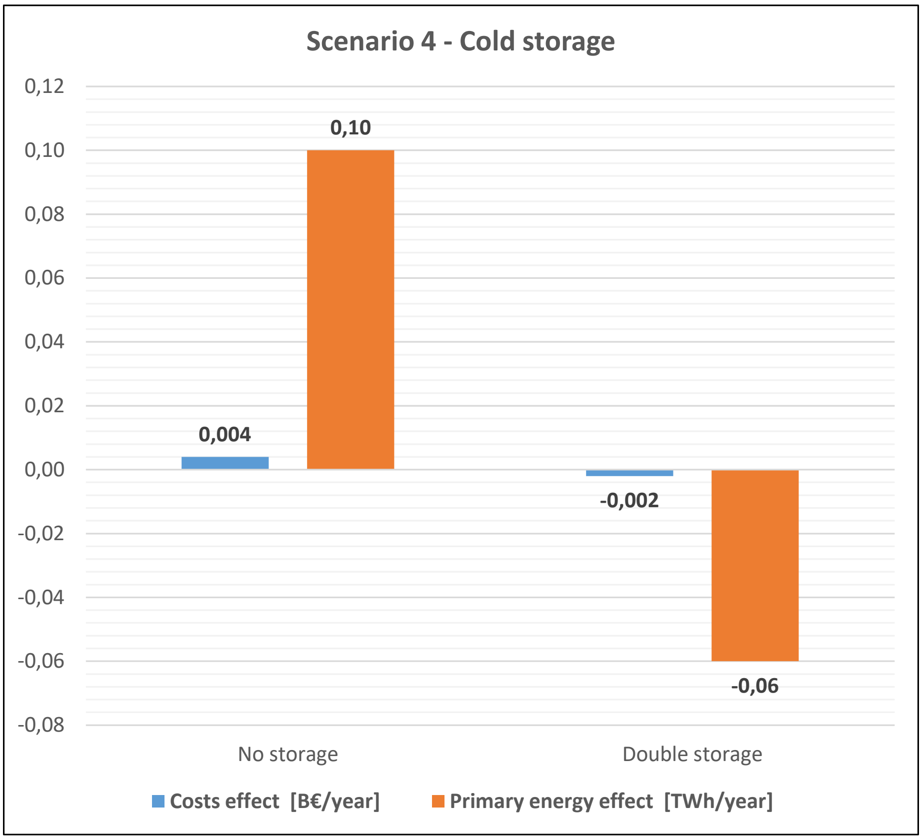

Figure 12: Results for the changes in total costs and PES in scenario 4 (Cold storage) by removing and doubling the district cooling storage, compared to the reference scenario.

As seen on Figure 12, removing the district cooling storage has a negative impact on both the overall costs, which are increased compared to the reference, and on the energy efficiency of the system. In contrast, doubling the district cooling storage capacity leads to a reduction of both PES and total costs. The conclusion, which can be drawn, is that district cooling storage can reduce the overall costs and increase the energy efficiency of the energy system.

The results indicate that cold storage can have a relevant role in providing flexibility from district cooling systems, but also that the total potential may be larger than indicated here. This can be seen through the fact that both the cost effect and the primary energy effect is negative in the double storage variation. However, the EnergyPLAN model is not well suited to model cold storage in district cooling, hence some aspects and details of the technology-specific modelling may not turn out to represent the actual options in a future energy system. Besides this, the development in district cooling demands is a significant uncertainty. A further investigation of future cooling demands, load profiles and cooling demand densities together with different cold storage technologies would be beneficial for the better evaluation of district cooling storage potential.

The overall potential in terms of capacity in district cooling is relatively low in the modelled energy system, but the potential relative to the storage capacity is similar to that of district heating. The lower potential in absolute terms relates to the lower demand for district cooling in the model. District cooling is different from district heating, as the number of cooling sources is lower than those for heating. Hence, the flexibility provided by that storage can move the production of e.g. a chiller from one hour to another, but rarely replace it with a more efficient production unit, as is the case for district heating.

5.5 Electric vehicle battery storage

The impact of adjusting the flexibility of the battery storage in electric vehicles is investigated through three different parameter variations. In the reference scenario, the distribution between smart charging and dump charging electric vehicles is assumed to be equal (50% smart charging and 50% dump charging). In the first two parameter variations smart charging is respectively reduced to 25% and increased to 75%, with the rest being dump charging. In the third variation, V2G is added as an additional option to the 75% smart charging, with the remaining 25% being dump charging. The results from the parameter variations of smart charging in BEVs, compared to the reference, are shown in Figure 13.

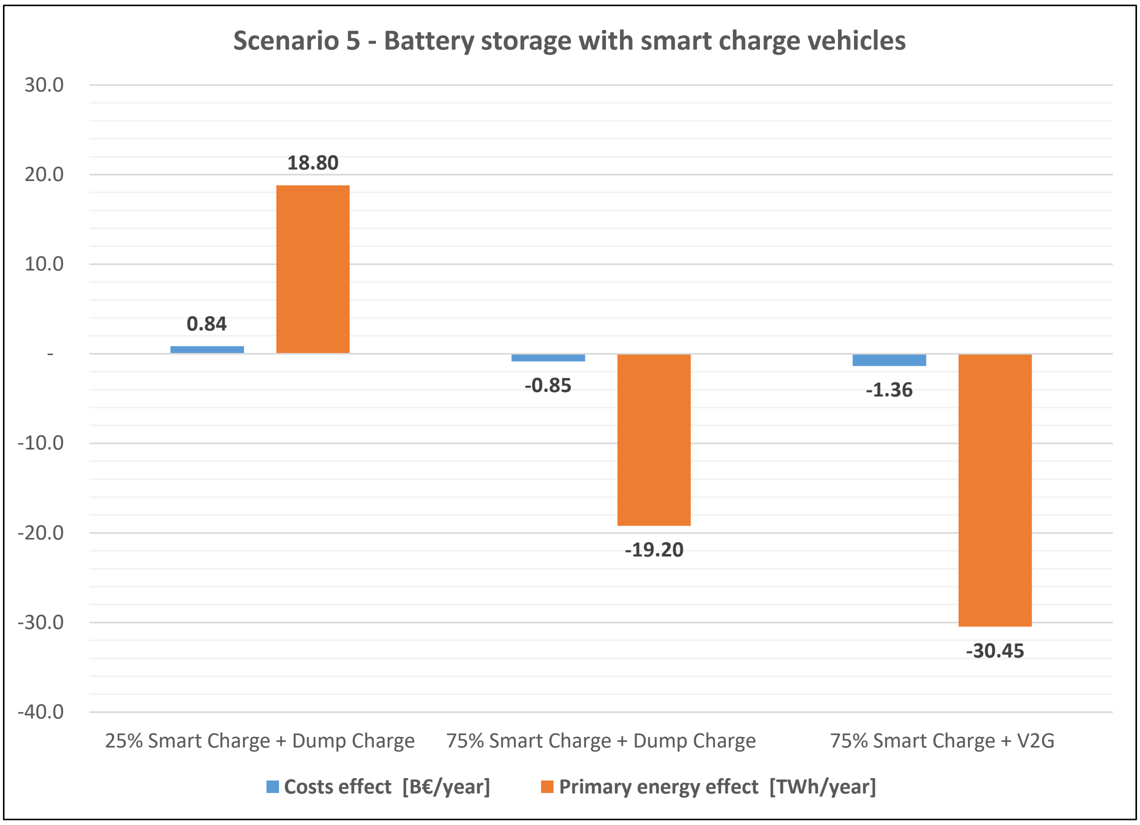

Figure 13: Results for the changes in total costs and PES in scenario 5 (Battery storage) by setting smart charging to 25%, 75% and 75%+V2G of the overall distribution of BEVs, compared to the reference scenario.

Figure 13 shows that reducing the smart charging share of electric vehicles increases both the total costs and the PES compared to the reference. On the contrary, an increase of the share of smart charging BEVs results in a decrease of both overall costs and PES, compared to the reference. The decrease in costs and increase in energy efficiency is even more significant, if a V2G is enabled on top of the increased share of smart charging vehicles. The reduction in costs and PES in the second and third variation are due to the energy system becoming more flexible and better able to utilise intermittent electricity production throughout the different sectors.

It is visible that the change in PES and total costs from 25% smart charging, through the reference (50% smart charging) and to the 75% smart charging, is almost linear. The assumption that 50% of the cars in the reference can use smart charging, may not be exact, and it might vary throughout a day or a year how large a share of the vehicle fleet is allowed by their users to apply a smart charging scheme. However, the results show that there is positive effect on both costs and energy efficiency to have the ability to charge flexibly according to the fluctuations in renewable electricity production.

The effect of also allowing the charger to deliver electricity from the vehicles back to the electricity grid (V2G) is also positive, but the relative effect is lower than the possibility of smart charging. Changing from 50% smart charging to 75% smart charging saves almost 20 TWh PES per year, whereas adding V2G on top of 75% smart charging saves additionally about 10 TWh/year. This indicates that the effect of changing the charging scheme for a car from dump charging to smart charging has a larger impact than changing from smart charging to smart charging + V2G, even though both actions contribute positively from both an energy efficiency and economic perspective.

Hence, smart charging in BEVs can lower the total system costs and improve the energy efficiency of the system. A V2G option in addition to smart charging is also a feasible initiative, but with lower relative impact.

6. Utilisation of project results

- *Describe how the obtained technological results will be utilised in the future and by whom.*
- *How does the project results contribute to realise energy policy objectives?*
- *If Ph.D.'s have been part of the project, it must be described how the results from the project are used in teaching and other dissemination activities.*

The project results can be utilised by both researchers and policymakers. The conclusions from the report can be used as a starting point indicating relevant pathways for further research e.g. on the role of hydrogen and the necessary development of hydrogen infrastructure to ensure the transition towards fully renewable-based energy systems.

Moreover, policymakers can use the recommendations mentioned below to facilitate the transition towards more efficient and less costly fully renewable-based energy systems.

6.1 Policy recommendations

- **Flexible sector coupling:** When coupling electricity and thermal energy, energy storages can be implemented where it is most cost-efficient. The analysis shows how cheap thermal storages combined with an increased share of district heating can enable the kind of flexibility which is highly needed when increasing shares of fluctuating renewable energy are included in the energy system. Provable emission reductions caused by the implementation of storages could be eligible for support schemes in place for renewable or energy savings measures.

- **Consumer flexibility:** Consumers should be encouraged to provide flexible demand where possible. Flat rates should be replaced with differentiated electricity prices, taxes and levies for both private households and industries to represent the value of a shift in demand away from peak load hours.

- **Energy incentives:** It is important to ensure incentives for smart charging as opposed to simply promoting BEVs alone. Similarly, short-term thermal storages and intelligent control mechanisms for individual heat pumps should be encouraged to also enable a flexible electricity demand in the individual heating sector.

- **Supporting green fuels:** With electrofuels becoming a key energy carrier in future decarbonised energy systems, support for demonstration of replicable solutions is relevant. This includes both flexible production and storage options to test and prove in which context various fuels, production methods and storage options are most suited. This includes evaluating the utilisation of excess heat from such electrofuel production processes where relevant.

7. Project conclusion and perspective

- *State the conclusions made in the project.*
- *What are the next steps for the researched technology area?*
- *Put into perspective how the project results may influence future development.*
- *For ExCo delegates: list meeting attendance for meetings during the project period.*

The analyses carried out in this report show that energy storage can improve the flexibility of sector coupling in the thermal and mobility sectors and cost-effectively increase the energy efficiency in the process. Instead of considering energy storage in “silos” of each sector individually, the storages can be linked to the conversion of energy thereby enabling the implementation at the time and place, and with the type of energy carrier where they are of greatest value for the system.

Thermal storage in electrified district heating production can create a synergy between intermittent electricity production and electricity consumption units. This is important for ensuring a cost-efficient, decarbonised district heating supply, while facilitating the integration of large quantities variable renewable energy production in the system. In addition, thermal storages are important for the utilisation of excess heat in central heating systems, thereby reducing the overall costs and maintaining an efficient energy system.

Heat production from individual heat pumps is considerably more expensive without thermal storage, due to the need for a larger electricity production capacity, indicating a clear advantage of establishing individual heat pumps together with a thermal storage. The economic potential for thermal storages is relatively larger when they are connected to direct electric heating compared to heat pumps in individual buildings. However, the general cost level of the system is significantly higher, thus arguing for the promotion of the more efficient use of electricity by means of heat pumps rather than direct electric heating.

Hydrogen applications and storage plays a central role in the system integration of fluctuating renewables, as hydrogen can be used to cover demands directly or be converted to other fuels, thereby simultaneously creating a flexible link between electricity and both the thermal and mobility sectors. Moreover, storage of hydrogen is important to ensure a fully renewable-based energy system. Without hydrogen storage (directly or indirectly in the form of electrofuels) the system is much less efficient, and needs significantly higher renewable energy production capacities, which increases costs considerably.

Cold storage for district cooling can reduce system costs and primary energy consumption. Although the overall potential of cold storage for cost reduction and improvement of energy efficiency is lower than of other storage types, the potential relative to the storage capacity is comparable to the one of district heating storage. Hence, the cold storage aspect is relevant to consider as the future cooling demands increase.

Smart charging in battery electric vehicles can facilitate the integration of intermittent renewables and make their operation more efficient, reducing the total system costs in the process. Battery electric vehicles with a vehicle-to-grid option in addition to smart charging can further reduce energy consumption and total costs, but the majority of system benefits are associated with the shift from dump charging to smart charging.

8. Appendices

- *Add link to Annual reports that are published in the project period.*
- *Add link to other relevant documents, publications, home pages etc.*

The full report on PlanEnergi's contribution to IEA ES Task 35, containing detailed description of the methodological approach, can be found on the following site when the overall Task reporting (i.e. the combined IEA ES Task 35) is published:

https://planenergi.eu/projects/flexible-sector-coupling-iea-eces-annex-35-eudp-supported/