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# Evaluation of Electricity Storage versus Thermal Storage as part of two different Energy Planning Approaches for the Islands Samsø and Orkney

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### Highlights

- Local resources and energy production should be better integrated locally
- Storages can help increase self-sufficiency and independence of islands with RES
- BESS reduce import and export of electricity and can reduce fuel consumption
- TES integrate excess electricity via heat pumps in a fuel-reducing and economic way
- Heat pumps are important for integrating the electricity in the heating sector

### Abstract

Island energy systems should aim for a better integration of local resources and exploit their potential for local energy supply to increase their independence and security of supply besides other benefits. Two trends addressing this problem can be observed: On the one hand, increasing the local use of renewable electricity in the electricity sector by investing in Battery Energy Storage Systems (BESS). On the other hand, the integration of all energy sectors into a Smart Energy System (SES) with the conversion of renewable electricity to heat – thus enabling the usage of Thermal Energy Storage (TES). In this paper, these two potential approaches are investigated through energy systems analyses using EnergyPLAN for the Danish island Samsø and the Orkney islands in Scotland. This investigation shows that BESS tend to address only the electricity sector, while TES furthermore improves issues in the heating sector and enables possibilities in the transport sector. The TES approach results in overall reduced energy system costs, while the BESS has a stronger effect on the exchange of electricity. Depending on the various energy systems, both approaches present potential solutions, while the SES approach with the use of TES demonstrates more advantages for the whole energy system.

### Keywords

Battery energy storage system; thermal storage system; electrified heating; integrating energy sectors; smart energy system; EnergyPLAN analyses

### Abbreviations

| | |
|---|---|
| BESS | Battery Energy Storage Systems |
| DH | District Heating |

| | |
|---|---|
| EU | European Union |
| HP | Heat Pump |
| PV | Photovoltaic |
| RES | Renewable Energy Sources |
| SES | Smart Energy System |
| TES | Thermal Energy Storage |

# 1. Introduction

Islands present special energy systems particularly when either completely disconnected from a larger electricity grid or when having a poor or limited connection, making them vulnerable and dependent on that connection. With or without this connection, islands are generally furthermore depending on other imports to supply the transport or heating sector with the required fuels. Locally produced electricity or biomass barely support these needs for most of the European islands and energy autonomy is rarely reached. Thus, from an economic perspective, islands that may be under economic pressure already need to buy energy and resources from other places.

To address this situation, islands should be encouraged to utilize as much local resources as possible, focusing on renewable energy source (RES)-based electricity production due to a usual abundance of wind and/or solar resources [1], [2]. They should also aim for higher efficiencies and the integration of all energy sectors into a smart energy systems (SES) [3] to reduce overall primary energy consumption. This suggested holistic view on energy system planning contradicts the focus of recent cases of island energy planning, which to a large extent focus only on the electricity sector and in relation to this on batteries as the solution to fluctuating electricity production [8]-[11].

To understand the challenges and opportunities of islands, as well as to increase the shares of RES, they must be investigated and compared. Therefore, the European Union is founding various projects under the Horizon 2020 research programme to study islands, such as the SMart IsLand Energy systems (SMILE) project. In the SMILE project, the focus lies on the electricity sector. To form SES, however, the transition of islands should entail the integration of all energy sectors – electricity, heating, cooling, industry and transport, specifically making use of the access to the RES [3]. With the electricity focus, a core element in the SMILE project is to address electricity storage to improve the integration of locally produced RES. To achieve a SES, however, thermal storage can also be of importance and could be given more attention.

## 1.1. Electric and thermal storage in the literature

For instance, Blechinger et al. [8] look into the energy demand and supply of 1,800 small islands, but focus on the optimization of the electricity sector through integration of photovoltaics (PV), wind power and electricity storage. Alternatively, forecasting and managing RES with algorithms [9] and short-term operation planning [10] could be a solution, which, however, does not solve the dependency on the electricity sector while still neglecting the other energy sectors. The electricity focus of these studies could be attributable to the high wind penetration in these locations, the generally low demands for heating due to the climate or due to simply neglecting other and more difficult sectors, such as the transport sector.

However, Lund et al. [11] put emphasis on the SES by including all the energy sectors and finding the right amount of electrification and storages across sectors, as well as coupling all sectors to mitigate electricity issues. Even if [4]-[10] do not mention significant demands in the heating or transport sector of the respective islands, so must these nonetheless be adapted to the fluctuations of RES production and often the ever-increasing demand from tourism. Furthermore, it can be assumed that some thermal demands are often hidden behind the electricity demand. This applies to for example air conditioning, and the preparation of domestic hot water, which is a demand across climatic regions. Concluding, if other energy demands are to be supplied sustainably at the same time, the focus on electricity and its potential storage does not seem to be the best approach [11].

Gils and Simon [12] present the necessity for cross-sectoral transition of the energy system for the Canary Islands, however, include the implementation of transmission lines between the seven islands. They focus on the tools Mesap-PlaNet and REMix, which focus on demands in industry and transport, while the residual demands are grouped as “others”. This is not optimal for the average European island that often has large heating and cooling demands. A cross-sectoral energy transition, as shown there, however, may require the availability of biomass, which can supply energy for hours without wind and sun, but also for transportation and heating fuel. This brings up the question of the right application of biomass – next to the right way of dealing with electricity – in island systems.

While some of the mentioned studies focus on completely isolated islands without an interconnection to a national grid, the problem of import dependency and vulnerability also appears on interconnected islands. With an increase in RES-based power generation in remote areas and limited transmission capacity [13], [14], all of these island systems are vulnerable to the security of supply. They should therefore aim at integrating their local resources and establishing better local markets to ensure the optimal integration of fluctuating RES [15]. One way to stabilize fluctuating energy production locally is with storage solutions, such as Battery Energy Storage Systems (BESS) and Thermal Energy Storage (TES) solutions.

Kondziella and Bruckner point out the increasing demand for flexibility – as can be provided through storage – caused by the increased share of RES in the European power sector [16]. To avoid curtailment of RES, additional storage is often required. In a study of Aegean isolated islands, RES penetration was found to be maximized “by means of storage possibilities development and installations” to cover both the electricity and heating needs [17]. Perhaps due to the Mediterranean climate, here the electric storage was suggested to be twice as large as the thermal storage.

BESS have gained recent relevance due to technological advances, increased fossil fuel prices and the demand from fluctuating RES. [18] presents various advantages from millisecond to daily optimization by using BESS. In comparison to other power storage systems, BESS performs at rather small capability scales, but can be conveniently distributed or moved. One common technology are Li-Ion BESS batteries, which are very fast-responding and increasing the system’s flexibility better than with pumped storage systems [19]. Particular in isolated power systems, BESS can address the often existing RES curtailment and integrate more RES into the system as Branco et al. studied [20].

While BESS have shown beneficial contributions to various energy systems, this technology is opposing the previously presented suggestion to better integrate the electricity sector with the other energy sectors in a SES. Especially following current trends of supplying heating and cooling demands with electricity, TES can become of great importance.

Arteconi et al. ensure an efficient energy supply through combining the electricity and heat sector with the help of TES [21]. According to them, TES helps "offset the mismatch of availability of renewable electricity and demand for electricity" and heat. Contrary to proposing BESS for wind power curtailment, Jin et al. suggest a better wind power utilization by implementing TES [22]. Even for PV-based power production, TES prove profitable over BESS due to the lower investment costs [23].

To cope with the intermittency of RES even further, district heating (DH) is often suggested to optimize the utilization of the energy stored in the TES [24], [25]. Furthermore, Mathiesen et al. as well as Renaldi et al. propose heat pumps (HP) to charge TES at times with surplus RES, aiming at low carbon DH systems [26], [27]. Alternatively, if TES for DH is not a feasible technology due to limited heat demands, TES can also be filled with a cold substance for district cooling. This is previously analysed in combination with PV potentials and electrical chillers for industrial cooling demand [28], but could be relevant also for residential cooling demands, for example on islands with warmer climates and as an alternative to air-conditioners.

Concluding, the energy systems of islands or remote locations are in need of a transition to enable higher RES integration for a more sustainable future. Various electricity and heat producing technologies can be considered, but often depend on the system's location and resources, while storage technologies are growing in relevance. Both BESS and TES can contribute to the integration of RES, yet in very different approaches and with diverse opportunities. While they may seem like two equal alternatives to storing energy, they should be compared more thoroughly for the specific case of island energy systems to evaluate their potentials in terms of sustainable energy planning.

### 1.2. The islands Samsø and Orkney

The SMILE project addresses the Danish island Samsø, the Scottish Orkney islands and Portuguese Madeira. While they present excellent locations to study technologies and social interaction in a limited scale, all represent "important energy challenges common to several locations in Europe, on islands as on mainland" [29]. For the comparison and evaluation of both BESS and TES, the focus in this paper is on the two first ones, since the potential for DH and hence DH TES on Madeira is limited.

Samsø qualifies for the suggested analysis due to its abundance of RES and the resulting excess of electricity, while other resources are scarce, as has been subject of several previous studies [30]–[32]. On Orkney, the potential of RES is not as extensive, but on the verge of a break-through with the ongoing tests of marine energy, such as wave and tidal powers, besides the already large wind power capacities [33], [34]. Under SMILE, both Samsø and Orkney are mostly looking into the optimization of their energy system through new technologies in the electricity sector and smart grids using BESS.

### 1.3. Scope and structure

In contrast to the above-presented recent studies on island and remote systems as well as various technical investigations, this paper aims at finding the right approach for sustainable energy island planning with the integration of RES in all energy sectors. While this entails a complex and long transition of the energy system with all of its facets, this paper focuses on the current trend of finding and evaluating storage solutions. By doing this, not only BESS, but also TES are investigated. This connects to the ongoing discussion on keeping electricity in the electricity sector versus its integration with other sectors as discussed above by comparing the two different approaches of BESS and TES implementation.

In this paper, the analysis addresses the two trends of storage solutions from the energy planning perspective with the prospect to achieve future sustainable energy island systems. The main focus is on the reduction of electricity exchange with the mainland, aiming at the best local utilization of the locally produced electricity. Therefore, both the import and export of electricity should be reduced to minimize the dependency on the greater grid, and to increase the internal usage of local products.

While this exchange is not a problem in most energy systems, its reduction has a two-fold benefit. Firstly, the acceptance of RES technologies could increase as more of the local energy can be used locally instead of selling it at an often low price and buying expensive electricity or fuels from elsewhere. Secondly, it could result in lower prices, due to the fact that excess RES power is usually adding to the excess production of the mainland, while hours without sun or wind usually also means that the mainland supplies its electricity with alternative means. Especially for islands and remote areas, this focus on local resource utilization is strongly suggested.

To evaluate the two approaches of BESS and TES, both are tested on the two energy systems of Samsø and Orkney. Due to the energy system set-up, as is presented below, additional HPs form an important part of the TES scenarios, as well as the required DH grid. While the electricity focus is, therefore, a rather simple one, the thermal inclusion integrates and changes the heating and electricity sector to a certain extent.

While Samsø may seem like the more obvious place to invest in BESS and TES, doing the same evaluation for Orkney, however, supports the study: On the one hand, Samsø has large amounts of excess renewable electricity production while still importing some electricity throughout the year. On the other hand, there are several existing DH grids and therefore the potential to integrate the excess with HP [35]. Orkney, on the contrary, presents a much smaller amount of excess electricity and furthermore does not have existing DH, and thereby contributes to the evaluation of BESS and TES with its different context, while otherwise seeming similar to Samsø.

The following section presents the applied methods and data for the analysis of BESS and TES in the energy system models of Samsø and Orkney. Afterwards, the results of both strategies are illustrated and compared through various scenarios of storage capacities. In the final part, this is discussed and concluded, after which recommendations for island energy systems are made.

## 2. Methods and data

Samsø and Orkney along with their energy systems are presented in the following, both generally and with their reference energy system models simulated with EnergyPLAN. The modelling tool EnergyPLAN is further described as it is applied to simulate the BESS and TES scenarios. Finally, the BESS and TES specifications for their evaluation is presented. Hence, the methods are introduced alongside the data applied in the analysis.

### 2.1. Scenario evaluation criteria and design

There is a large variety of potential criteria for evaluating optimal RES integration into systems [36]. For island systems, it is particularly relevant to aim for the highest reduction of import, as well as the best integration of the otherwise exported electricity to reach the highest degree of self-sufficiency and internal use of local resources. Further criteria includes low annual costs of the whole energy system and low $CO_2$ emissions.

In the analyses, scenarios are established through a gradual increase of either BESS or TES, in combination with HP capacity. The required DH for the TES approach is already established on Samsø and is simply updated to use electricity through HPs, while Orkney is further studied in this regard to introduce a new DH area on the main island, where a sufficient heat density is given.

### 2.2. Reference energy systems of Samsø and Orkney

Samsø is a small island of around 3,700 inhabitants, lying between the western peninsula and the islands in the east of Denmark. It is characterized by a large share of wind power from local wind turbines, as well as a share of 35% of DH-supplied households. The electricity is otherwise supplied by a small number of (household) PV panels or through a transmission line to the Danish mainland. The fuel for the DH is mainly woodchips and straw, both harvested locally, while the individually heated buildings are supplied by biomass boilers, HP, electric heaters, oil boilers and a few solar thermal collectors. As Figure 1 shows, Samsø is much smaller and simpler in geographical terms than Orkney, with fewer recognized areas for DH, which did not stop the establishment of four grids and not just one as mapped by the Heat Roadmap Europe [37].

The second energy system addressed is that of the Orkney islands, which consist of 20 inhabited islands out of a total of 72 islands and islets. With a population of about 22,000 and being located north of the Scottish mainland, the Orkney energy system is largely influenced by the wind and some solar resources, while the large potential of wave and tidal resources is yet to be secured and is therefore not included in the reference. Otherwise, an old Flotta gas turbine present a local power plant with a 10.5 MW grid connection and the two 20 MW sea cables the mainland are providing some electricity to its citizens [14].

It must be noted that the transmission lines within the Orkney islands can present bottlenecks, making the use of local storage or conversion an interesting contribution. Currently – and in the reference scenario – the heating demands on the island are supplied by individual boilers and a large share of individual heat pumps. While Orkney has no current DH grid in either of its larger settlements, this remains the case for the reference scenario. However, studies including Heat Roadmap Europe [37] and the Scottish Heat Map [38] suggest potential heat densities in the two bigger towns of Kirkwall and Stromness on Mainland Orkney. For the purpose of this study, the more likely DH grid in Kirkwall is included in the TES scenarios.

As illustrated in Figure 1, the center of Kirkwall presents high heat densities with the total heat demand of 147 TJ over a small area. This results in a possible share of 33% of the total Orkney heat demand that could be covered with this DH grid. This selected demand includes only the area with the normal threshold of above 120 TJ/km$^2$. Hence, the TES scenarios include the ensuing reduction of boilers in individually heated houses to be supplied from a DH network instead. The resulting demand for this possible new DH grid are presented in Table 1. Furthermore, this DH is to be supplied by both a biomass boiler and a HP, to use the surplus electricity from RES, but not increase the amount of electricity imports. For those hours, the biomass boiler will be modelled to supply the required heat.

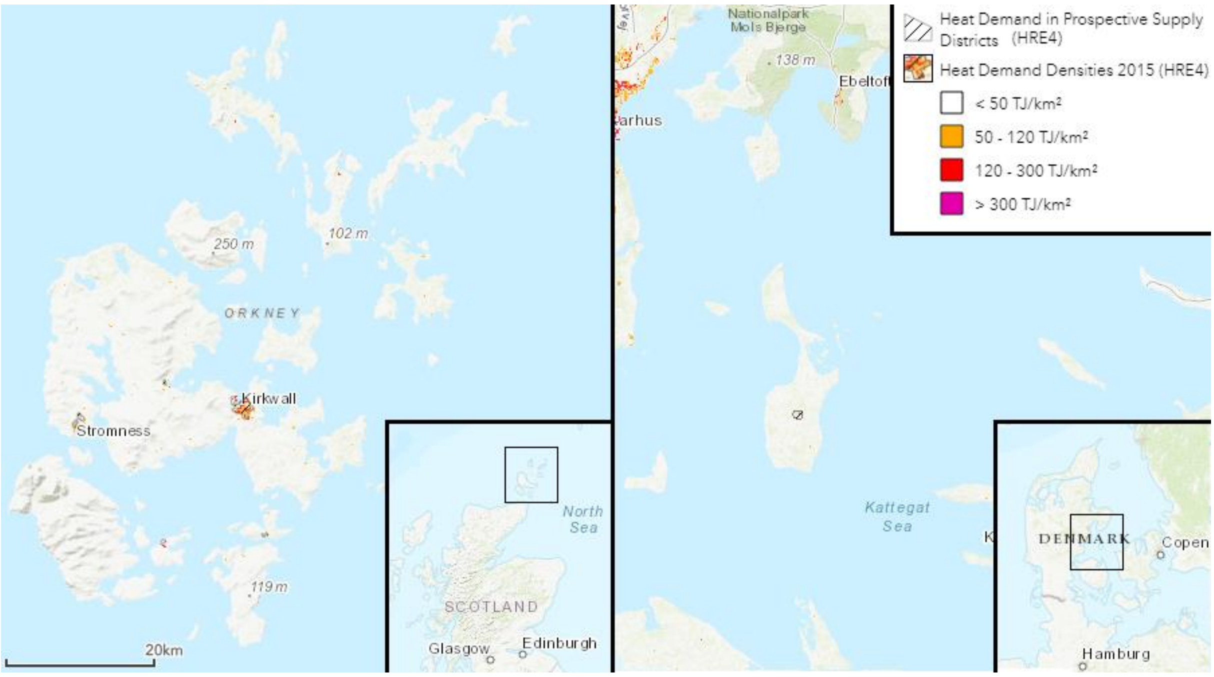

**Figure 1: Geography and size of Orkney (left) and Samsø (right) and the DH potential from Heat Roadmap Europe** [37]**, scale and legend apply to both islands**

The reference as well as the possible future energy systems of Samsø and Orkney consist further of industrial and transportation demands. While Orkney has a larger industrial demand and a local power plant, Samsø has four established DH grids. For the TES, HPs and the DH are an important contribution as indicated in Figure 2, while the BESS interacts only with the electricity sector. In the Samsø case, the already existing DH grids simplifies the possibility of TES, while other islands may need to establish DH first – as it is simulated for Orkney.

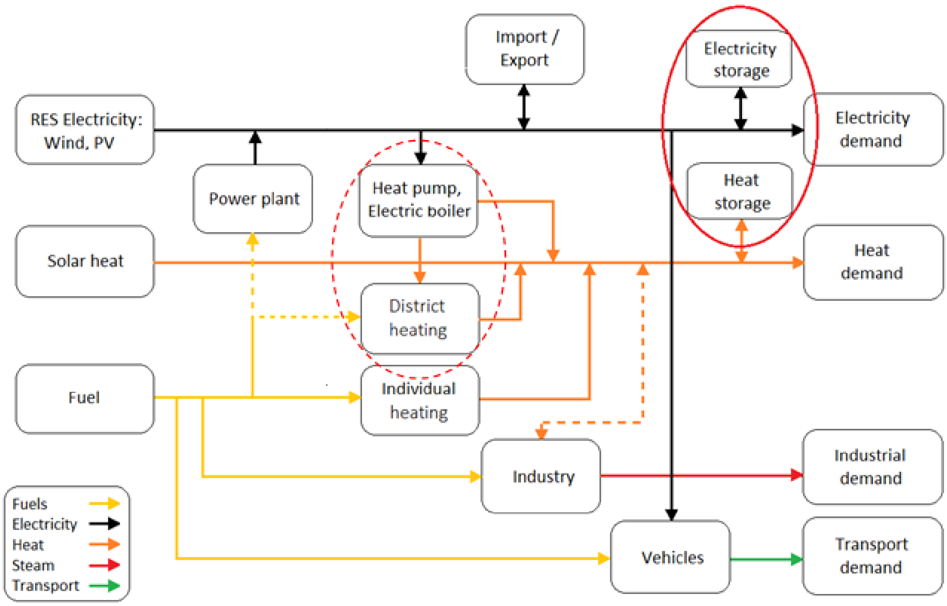


**Figure 2: Simplified energy system structure of Samsø (with existing DH) and Orkney (with power plant) with possible storage extension**

Figure 3, which presents the energy systems separately, emphasizes the large share of currently exported electricity from wind, especially on Samsø and the imports of electricity and fuels for both islands. While the RES productions already covers the demand by 94% and 92% on Samsø and Orkney respectively, it even surpasses the electricity demands in some hours, leading to electricity exports currently, while it could also be better integrated locally.

What can be seen in Figure 3 is a possibility to integrate the (excess) electricity in the heating sector to supply the DH grid, which is currently supplied by boilers in the Samsø case, as well as the individual buildings, as is already applied to some extent on both islands. Also, the large amount of biomass, which is supplying the heat in the Samsø reference energy system is limited and could then be considered for the production of future transportation fuels, as [39] suggests or for back-up power supply [40]. Finally, the losses indicate the comparably low efficiency of boilers compared to electric heat, which further stresses the importance of reducing fuel boilers for heat production. In general, several studies have already pointed to the importance of reserving biomass resources for areas where a storable fuel is required – and heating is not one such.

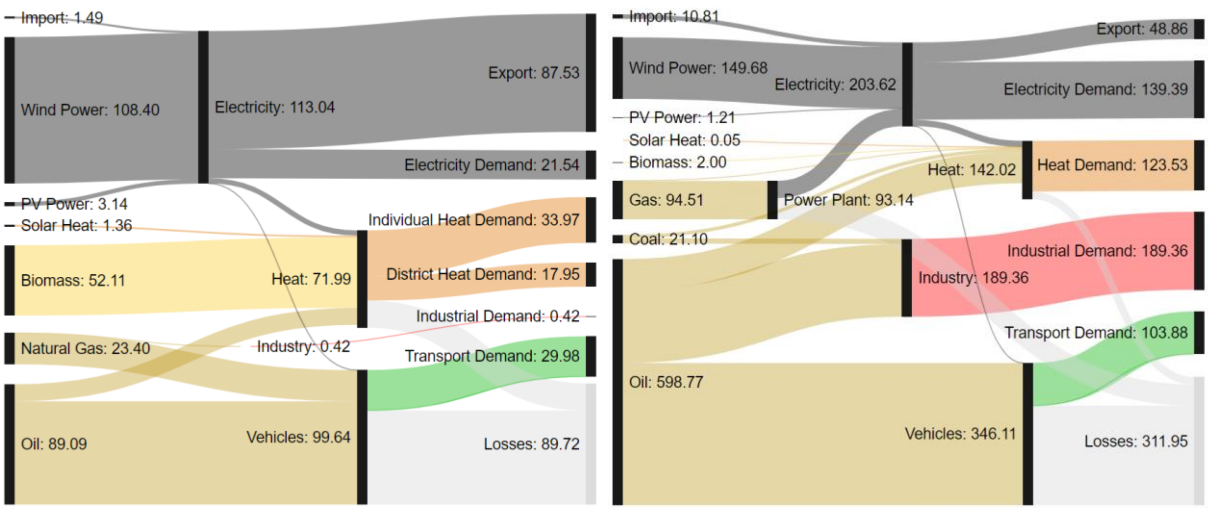


**Figure 3: Sankey diagram of the current energy systems of Samsø and Orkney (numbers in GWh/year)**

The case of Samsø especially stresses the problems of a large RES capacity causing excess wind production and resulting export, while still relying on import of electricity in an eighth of the hours in the reference year. Generally, the idea of storage could also be of relevance in a system with much more import and less export or, on the other hand, in an island system, where RES curtailment and dependence on fossil-fired back-up units is prevailing. For the Orkney case, even a much smaller wind power capacity per capita results in export and even curtailment in certain hours, while it could be integrated better through new storage technologies. While Samsø imports 13% of the hours in the reference year, in Orkney it is modelled to be importing electricity 30% of the time. This equals 6% of the absolute electricity demand on Samsø and 7% on Orkney.

### 2.3. EnergyPLAN reference models

To perform the energy system analysis presented in this paper, the modelling tool EnergyPLAN is used. This is a widely known and applied tool to make both market economic and technical simulations for the whole energy sector including heating, electricity, transport and industry [41], [42]. EnergyPLAN is able to analyse all energy sectors with all inputs and outputs of the energy system, including balancing and storage options, which are relevant for this evaluation.

EnergyPLAN is an hourly simulation model based on endogenously defined priorities. It is an aggregated model where each type of technology is an aggregation of all units of the particular type – i.e. one off-shore wind power description to represent the entire stock of off-shore wind power in the given system. EnergyPLAN is described more thoroughly in e.g. [30]. Based on the ability to present the holistic energy system of a defined geographical region whilst keeping the ability to track required imports, EnergyPLAN is well suited for the comparison of BESS and TES for the islands of Samsø and Orkney. Hence, the reference models for each island are either updated and improved – as in the case of Samsø – or newly created for the purpose of this analysis – as in the case for Orkney.

Several publications using EnergyPLAN for energy systems simulations refer to its ability to adequately depict existing systems for reliability and validation of the model [43], [44], while the developer of the model takes the discussion to a higher level in [45]. From a general discussion based on one of the important works in the field of model validations [46], arguments are presented in [45] on how a model can be validated. Here, the model may be validated through a) its ability to model a large variety of energy systems (see a review in [42]) and its pubic procedures [47]; b) its ability to adequately reflect a given system; and finally c) the quality of the data for the storage systems in question. For the purpose of the analyses presented in this paper, the combination of EnergyPLAN, scenario data and storage data is considered adequately validated and reliable.

The EnergyPLAN reference model of Samsø, which is applied in this analysis, has already been subject of a study regarding various BESS capacities in combination with PV [30]. It presents Samsø and its demands for the reference year 2015, based on the latest official published energy balances for the municipality [48]. While the previous study focused on mere technical aspects for residential BESS and PV systems, this article includes further data on annual socio-economic costs of the energy system.

The Orkney reference model is based on data from 2014 and was created with help of the Orkney Energy Audit [14] as part of the SMILE project [49]. The energy system Sankey diagrams in Figure 3 include all production and consumption data that either supply or result from the EnergyPLAN reference models.

Table 1 presents the main characteristics of the electricity and heating sectors, which form the core of the analysis. As might be noted, all production and consumption is grouped – meaning for example that DH is seen as one block in the energy system with general biomass as fuel, even though it consists of four smaller DH grids and various heating units. The main area of interest is the *Electricity export* and *import* as it indicates the potentials for this analysis.

**Table 1: Electricity and heating data for the reference energy systems**

| | Samsø | | | | Orkney | | | |
|---|---|---|---|---|---|---|---|---|
| | **Total (GWh)** | **Min. (MW)** | **Avg. (MW)** | **Max. (MW)** | **Total (GWh)** | **Min. (MW)** | **Avg. (MW)** | **Max. (MW)** |
| **RES production** | 111.5 | 0 | 12.7 | 33.6 | 150.1 | 0.1 | 17.2 | 49.4 |
| **Electricity demand** | 25.5 | 1.6 | 2.9 | 4.5 | 139.9 | 8.5 | 15.9 | 25.0 |
| **Electricity export** | 87.5 | - | 9.8 | 31.1 | 48.9 | 0.0 | 5.6 | 38.0 |
| **Electricity import** | 1.5 | 3.7 | 0.1 | - | 10.8 | 0.0 | 1.2 | 14.7 |
| **DH production**<br>**[possible new DH]**<br>**(total heat demand)** | 25.5<br><br>(59.4) | 0.9<br><br>(1.2) | 2.9<br><br>(6.8) | 5.5<br><br>(13.4) | 0.0<br>[28.6]<br>(123.5) | 0.0<br>[0.4]<br>(0.6) | 0.0<br>[3.3]<br>(14.1) | 0.0<br>[6.1]<br>(28.5) |

While the export listed in Table 1 could, on the one hand and as described previously, be stored in a BESS to reduce the import, it could, on the other hand, also be integrated in the heating sector via HPs and through the support of TES to reduce the fuels used there. These two approaches are further explained in the following section.

Otherwise important in the reference model are the annual $CO_2$ emissions of 29 kt and 186 kt for Samsø and Orkney respectively, as well as annual system costs of 15,669 k€ and 55,136 k€, which includes investments converted to annual costs, operation and maintenance (O&M) costs, fuel costs for transportation and heating and the resulting $CO_2$ costs. The applied cost data of the relevant technologies for the analysis can be found in Table 2. Other system costs are included in the total costs presented later, but are not specifically changed for the analyses.

**Table 2: Cost data of relevant technologies**

| | **Basic costs** | ***Lifetime*** | ***Ref.*** |
|---|---|---|---|
| **$CO_2$ price** | 20 €/t | | |
| **Boiler investment** | 490 €/kW$_{th}$ | 20 years | [50] |
| **Boiler O&M /year** | 0.08% of investment cost | | |
| **HP investment** | 2,640 €/kW-e | 25 years | [50] |
| **HP O&M/year** | 0.3% of investment cost | | |
| **TES investment** | 3,000 €/MWh$_{th}$ | 20 years | [50] |
| **TES O&M/year** | 0.7% of investment cost | | |
| **BESS investment** | 600 k€/MWh$_e$ | 30 years | [11] |
| **BESS O&M/year** | 0.5% of investment cost | | |
| **DH grid investment** | 150 €/MWh$_{th}$ | 40 years | [51] |
| **DH stations** | 190 k€/MW | | |
| **DH O&M/year** | 1% of investment cost | | |

## 2.4. BESS specifications

Similar to an earlier approach to BESS evaluations [30], the following analysis is made. With BESS showing round-trip efficiencies of 75-77% [52] and latest test even showing efficiencies above 90% [53], both round trip efficiency is adjusted to an annual constant of 85%. The charging and discharging powers are set to a typical value of 66% of the BESS capacity [30], [54] – corresponding to a charging/discharging time of 1.5h if fully charged/discharged. In the analyses, the total capacity of the BESS is gradually increased from 0.001 to 50 $MWh_e$ with 0.66 to 30,000 kW powers.

With the above-mentioned electricity demand of Samsø, a 10 $MWh_e$ BESS could supply electricity for 2-6 hours depending on the exact time and a 30 $MWh_e$ BESS stores electricity for up to 12 hours. The same sizes are used for Orkney to keep the technical investigation comparable, where the BESS would be able to supply comparably less hours, due to the larger electricity demand. The investigated maximum of 50 $MWh_e$, therefore, supplies for up to 17 hours of the average demand (10-30 hours for extremes) for Samsø and around 3 hours (2-6 hours) for Orkney, making the BESS in either studied island a short- to mid-term storage system, supplying electricity for minutes and up to more than a day.

### 2.5. TES specifications

The TES is modelled in the same steps of energy content as the BESS, meaning up to 50 $MWh_{th}$, which is small in thermal storage terms, while 50 $MWh_e$ is large for electricity terms. However, by this, the evaluation of BESS and TES becomes comparable in terms of technical storage sizes for both island.

In the case of Samsø, with similar quantities of electricity and DH demand, also similar durations can be covered, as can be expected from the heat demands in Table 1. This entails that the DH grids are considered as one or the TES is split proportionally between the individual DH systems, as EnergyPLAN models the DH in one single aggregation. Therefore, while the 10 $MWh_{th}$ storage could cover between 1.8 and 10 hours of the heat demand in DH, a 30 $MWh_{th}$ TES can supply heat for up to 12 average hours and 50 $MWh_{th}$ equals up to 50 hours (low demand).

While the total heat demand on Orkney is correspondingly larger than on Samsø, the DH potential demand of Kirkwall center is modelled at a comparable level to that of the total DH production of Samsø, hence the TES can supply about the same amount of hours to the DH grids. Due to the slightly milder climate on Orkney, and longer periods of small heat demands, the TES might be able to supply more than 50 hours if it were to be the same low demands for hours at a time.

Contrary to the BESS, the TES is considered to operate loss-free. Furthermore, the TES scenarios require additional power-to-heat units to qualify for a heat storage in connection to excess electricity production. This is due to the biomass boiler, which otherwise simply operates according to the heat demand and without any connection to the electricity system. However, with the aim to both reduce the biomass usage and to increase the currently unused wind power, a HP is added to the TES scenarios.

The reduced biomass consumption on Samsø is planned to be used for a future biogas plant [55], while the excess electricity from wind is currently exported instead of being used locally. Therefore, for Samsø, different sizes of HPs from 250, to 500 and 1,000 $kW_e$ are added; with the larger capacities to fit with the larger storages. On Orkney, the newly introduced DH is to be able to be supplied by boilers and HP of the same thermal capacity, fitting the respective heat demand. In both cases, the HP is set to only operate during excess local electricity production and to let the biomass boiler operate when electricity is imported. Furthermore, the coefficient of performance (COP) of the HP is set to a constant 3.

## 3. Results

This section presents the analysis and evaluation of firstly the BESS and secondly the TES for both Samsø and Orkney. For the TES scenarios of Samsø, the criteria of different HP capacities is further presented. Afterwards, a comparison of the options leads to the conclusion.

### 3.1. BESS analysis

In the first part of the analysis, a small BESS is added to the EnergyPLAN reference models, and then its capacity is gradually increasing. The charging and discharging powers change in accordance to the BESS specifications presented above. This is illustrated in Figure 5 in comparison to the same gradual increase of TES capacity, however, with various HP capacities in the Samsø and one in the Orkney evaluation.

As Figure 5 shows, the expenses increase gradually for the first few $MWh_e$ of BESS capacity with a similar decrease of the electricity exchange. With a larger capacity, however, the prices increase more drastically while the electricity exchange drops less significantly. At 50 $MWh_e$, the total annual costs have increased by 10% from the reference for Samsø and 3% for Orkney's reference system costs. Also for the final scenario, the total electricity exchange has decreased by 3% and 12.5% respectively. Of that electricity exchange, on Samsø the import of electricity is reduced by 87% (-1.25 GWh) and the export by -2% (-1.5 GWh), while the changes on Orkney with the same BESS are a bit smaller: 3% (0.3 GWh) and 10% (5.1 GWh) respectively, largely due to the different initial amounts and available excess electricity.

Regarding the rest of the energy system, not many changes can be observed. The fuel consumption for the heat and transport sector is the same on Samsø since the BESS merely interacts with the electricity supply and demand. For Orkney, the BESS also reduces the electricity production of the local power plant, resulting in less local fuel consumption and $CO_2$ emissions.

The increase of the annual total costs for Samsø results from an 8%-increase of the system's fixed operation costs and a 29%-increase in the investment costs, while no direct fuel savings are achieved. On Orkney, the BESS causes a 15% increase in investment costs and a 5% increase in total operation costs. For both cases, the fuel for producing the electricity outside the islands is not considered. The reduced expenses from buying electricity for Samsø is similar to the reduced income from potential sales, resulting in the absolute annual system costs of 17,315 k€ – or a 1,646 k€ (10%) increase. For Orkney, the smaller share of excess electricity leads to a comparable higher reduction of incomes through electricity sales, but also imports are reduced to some extent, resulting in total system costs of 56,581 k€ – or a 1,445 k€ (3%) increase.

### 3.2. TES analysis

In the second part of the analysis, the TES is added gradually to the reference systems. Furthermore, a HP is replacing some of the heat production from biomass boilers, enabling and encouraging the utilization of the TES whenever excess electricity is available locally.

The size of the HP effects the results of this analysis strongly and should be kept in mind for the Samsø results.

The largest improvements to the reference system can already be seen in Figure 5 by adding a small TES capacity and a HP. An increase of TES capacity at a constant HP capacity (250 $kW_{el}$, for Samsø) barely changes the results in terms of electricity exchange and costs. Therefore, for the Samsø case, the HP capacity is increased from 250 to 500 $kW_e$ and to 1,000 $kW_e$ after three TES sizes each to show the impact of HP sizing, as explained in the following. This detailed evaluation is not chosen for Orkney, but rather a fixed HP is selected to focus on the TES evaluation as such.

For Samsø, with a HP of 250 $kW_e$, already 19.6% of the heat demand is supplied by the HP with a 1 $kWh_{th}$ TES, while an increase to 2.5 $MWh_{th}$ increases this share to only 20.7%. This results from the HP running at full capacity only during the hours of excess electricity production, therefore fuelled only by local RES-based electricity. To increase the share of heat from the HP and the utilization of the TES, an increased HP capacity is required. Otherwise, the TES is not able to fully charge and discharge at a feasible rate.

This is illustrated with a screenshot of the EnergyPLAN results, as seen in Figure 4, where a 50 $MWh_{th}$ TES is modelled in combination with a 250 and a 1,000 $kW_e$ HP. The yellow area is the resulting heat from the HP with a maximum capacity of 750 and 3,000 $kW_{th}$ in the left and right charts of Figure 4 respectively, showing the HPs' and TESs' impact on the overall heat production. The lower charts of Figure 4 presents the operation of the same TES with a 250 and a 1,000 $kW_{th}$ HP. While the 250 $kW_e$ HP is able to fill up the storage 25 hours of the year, while completely discharging once (18 full-capacity[1] cycles), the 1,000 $kW_e$ HP is able to fill it up more than 1,500 hours with fully charging and discharging more than 37 times (43 full-capacity[1] cycles).

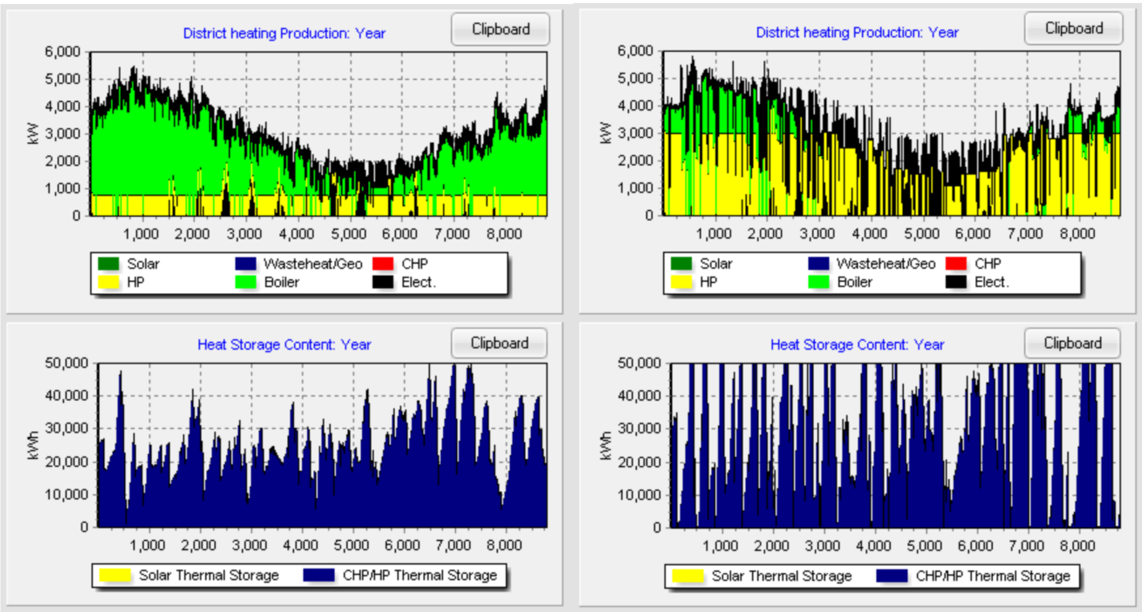


**Figure 4: EnergyPLAN screenshots from the Samsø case of a 50 MWh TES with a 250 (left) and 1,000 $kW_e$ HP (right), producing 750 and 3,000 $kW_{th}$**

[1] Calculated with discharged MW per installed capacity, does not necessarily reflect full charging cycles

Based on the best compatibility of small-scale HPs with small TES capacities and vice versa larger HPs with larger TES, the following combinations are chosen for the evaluation of Samsø:

- HP of 250 $kW_e$ and TES of 0.001, 1.0 and 2.5 $MWh_{th}$
- HP of 500 $kW_e$ and TES of 5.0, 7.5 and 10 $MWh_{th}$
- HP of 1,000 $kW_e$ and TES of 15, 20, 30 and 50 $MWh_{th}$

While the 250 $kW_e$ HP can supply up to 21% of the DH demand, the 500 $kW_{th}$ supplies between 40 and 41.5% and the 1,000 $kW_e$ supplies 71 to 75%, presenting different options for Samsø. The smallest constellations of HP and TES reach a reduction of up to 2% in the electricity exchange, 4% in the second and above 7% in the constellation with the largest capacities. Hereby the TES surpasses the BESS in electricity exchange reduction already at a low capacity. However, this is only due to the decrease of excess production, while the import of electricity remains the same. This is due to the inflexible and exogenously given electricity demand for electrical devices in the reference model, which cannot be addressed with this approach. The 50 MWh TES in combination with the 1 MW HP results in -7.9% export (-6.1 GWh), while the import stays the same.

While the Samsø evaluation presents alternative HPs and its impacts, the trend towards larger HP suggest generally more savings. For Orkney, the evaluation therefore addresses one size of HP, largely due to the trend shown with Samsø and to focus on the TES evaluation instead. With the suggested DH in Table 1 and the maximum hourly heating demand of 6,081 $kW_{th}$, both the biomass boiler and the HP are chosen to be producing 6 $MW_{th}$, depending on the availability of excess electricity. This constellation of DH production units is tested for the different TES sizes as in the Samsø evaluation. The results of this are presented in the next section.

### 3.3. Comparison

Regarding the annual costs for Samsø, the TES leads the comparison with BESS from the first scenario, as can be seen in the upper part of Figure 5. Even though the total annual savings are just around 3% at the largest TES and HP, the reason and its consequences (fossil fuel and emission reduction) are important for the energy system. Similarly to the BESS, the operation and investment costs in the TES analysis increase when compared to the reference system, but by a comparably low share (0.4 and 1.2%), while the costs in fuel consumption decrease the most with 7.8%. The result is a total annual cost of the energy system with TES on Samsø of 15,188 k€. Compared to the reference system, the total costs of the energy system are reduced by 3.1% (481 k€ annually) with the 50 $MWh_{th}$ TES/HP, compared to the increase of 10% (+1,646 k€ annually) for the BESS scenarios of 50 $MWh_e$ storage.

The total annual system costs on Orkney are reduced by 2% with the 50 $MWh_{th}$ TES compared to the reference system without DH and storages, which amounts to -1,187 k€ annually, while the 50 $MWh_e$ BESS scenario increases the annual costs by 1,445 k€, as the electricity sales would go down by 10%. As to be expected, investment costs for the TES go slightly up (1.4%), but all other costs (operation, fuels, $CO_2$ costs) are reduced, despite the new investments in DH grid and boilers, besides the increase in biomass consumption.

Not only can money be saved with the second approach, but also the fuel use. For Samsø, on the one hand, this leads to available biomass for other purposes. In total, the biomass consumption is reduced by 39% (20 GWh) through the integration of electricity in the DH sector of Samsø through HPs. Additionally, some of the oil in the back-up heating units can be saved, influencing the $CO_2$ balance and the costs further.

For Orkney, on the other hand, the introduction of DH leads first of all to a reduction in the use of individual boilers based on various fuels. Instead, the consumption shifts to biomass and/or electricity for the HP, depending on the availability of excess renewable electricity. This leads to a substantial amount of biomass required, which is between 18 and 33 GWh annually, depending on the HP and TES. But at the same time, the consumption of coal (-3 GWh) and oil (-25 GWh) is substantially reduced. Therefore, the newly required biomass should be considered a good exchange for reduced fossil fuel imports and dependence.

In comparison, the total $CO_2$ emissions of both the BESS and the TES analysis are not very substantial. While the BESS does not show any reductions on Samsø, the TES scenarios lead to a yearly reduction of 22 t or 0.1%. For Orkney, also the BESS reduces the $CO_2$ emissions by 1,807 t (1%) due to the reductions in the productions of the gas-based power plant. The TES, however, can reduce the annual emissions by up to 7,736 t (4%) on Orkney. An overview of the results regarding electricity exchange, costs, emissions and energy system evaluation criteria is summarized in Table 3.

**Table 3: Overview of results of selected BESS and TES scenarios**

| **Storage type (and size)** | **Reference Samsø** | **BESS (1)** | **BESS (50)** | **TES (1)** | **TES (50)** | **Reference Orkney** | **BESS (50)** | **TES (50)** |
|---|---|---|---|---|---|---|---|---|
| **BESS [$MWh_e$]** | 0 | 1 | 50 | 0 | 0 | 0 | 50 | 0 |
| **BESS power [MW]** | 0 | 0.66 | 33 | 0 | 0 | 0 | 33 | 0 |
| **(DH-) HP capacity [$kW_e$]** | 0 | 0 | 0 | 250 | 1,000 | 0 | 0 | 2,000 |
| **TES [$MWh_{th}$]** | 0 | 0 | 0 | 1 | 50 | 0 | 0 | 50 |
| **Import [GWh/year]** | 1.5 | 1.4 | 0.2 | 1.5 | 1.5 | 10.8 | 10.5 | 10.8 |
| Δ | | *-7%* | *-87%* | *+/- 0* | *+/- 0* | | *-3%* | *+/- 0* |
| **Export [GWh/year]** | 87.5 | 87.4 | 86.1 | 85.9 | 81.4 | 48.9 | 43.8 | 44.3 |
| Δ | | *-0.1%* | *-1.6%* | *-1.8%* | *-7.9%* | | *-10%* | *-9.4%* |
| **Total annual costs (M€)** | 15.67 | 15.70 | 17.32 | 15.54 | 15.19 | 55.1 | 56.6 | 53.9 |
| Δ | | *+0.2%* | *+11%* | *-0.8%* | *-3.1%* | | *+2.7%* | *-2.2%* |
| **$CO_2$ emissions [Mt/year]** | 28.51 | 28.51 | 28.51 | 28.50 | 28.49 | 186.0 | 184.2 | 178.3 |
| **RES share of PES [%]** | 59.5 | 59.5 | 59.5 | 58.7 | 56.2 | 17.6 | 17.8 | 19.8 |
| **Total fuel consumption [GWh/year]** | 164.6 | 164.6 | 164.6 | 159.3 | 144.0 | 716.4 | 707.6 | 704.1 |
| **Total electricity demand [GWh/year]** | 25.5 | 25.5 | 25.5 | 27.2 | 31.6 | 154.7 | 154.7 | 159.3 |

As Table 3 shows, the BESS has advantages in regards to import and some export reduction, if that is targeted, but the disadvantage is the increase of costs – the bigger the system, the bigger these trends. Other effects on the energy system of Samsø cannot be observed, while the operation of the local power plant of Orkney decreases as well.

The TES scenarios generally show positive effects on the export reduction, but also reductions in costs, $CO_2$ emissions and total fuel consumption. On the negative side, the import of electricity is not addressed with TES and the total electricity consumption even increases. Since the latter can be supplied by local RES, it does not have an effect on the costs or emissions, making it an acceptable downside.

As referred to earlier, Figure 5 shows the trends of electricity import and export as well as annual system costs for both Samsø and Orkney in the presented steps from no to gradually increasing storage capacities up to 50 MWh. While Figure 5 shows the tendency towards TES, both regarding electricity exchange and costs, it further suggests the importance of HP, as a main factor to integrate the excess electricity in another energy sector. This becomes very clear with the upper right chart, which presents the TES scenarios for Samsø and the high impacts the HP can have.

In terms of suitable sustainable energy planning approaches, both the BESS and TES have potential to improve the integration of locally produced renewable electricity. While the BESS impacts the electricity exchange more, the TES enables improvements also in the heating and transport sector. When addressing the overall energy system in a SES context, the capability to increase RES integration while keeping costs and resources limited is best presented in the TES scenarios. The analysis therefore evaluates the choice of storage technology as important and the SES with TES approach as most suitable to enable sustainable energy planning for islands, which could also be valuable for other remote regions.

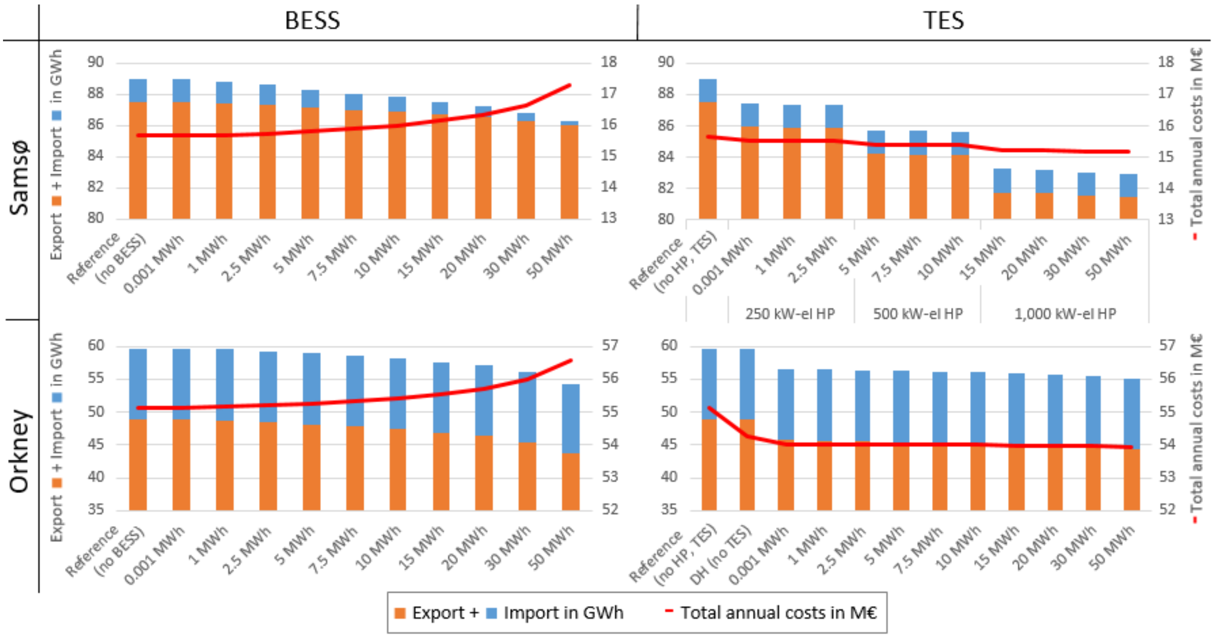


**Figure 5: Results of electricity exchange and costs for Samsø (upper charts) and Orkney (lower charts) for the BESS (left) and TES (right) scenarios**

## 4. Conclusions

The evaluation of the two storage solutions BESS and TES for the islands of Samsø and Orkney addresses the problem of vulnerability and dependency of island energy systems. By comparing electricity versus thermal storages in two different cases, the electricity sector-focused improvement is opposed to a SES approach, combining electricity with heating through HP and TES and linking to the transport sector. This presents two different potential solutions for the planning of sustainable energy systems for islands and possibly other remote regions.

The analysis shows the tendency to the advantage of the latter solution by combining energy sectors and utilizing TES. In the EnergyPLAN energy system models of both islands, the BESS tends to solve problems in the electricity sector only, while the TES addresses some of the issues in the electricity sector by also improving the heating sector and enabling further possible enhancements in the transport sector by freeing biomass resources.

Both BESS and TES approaches show a big variety in options, including material, set-up, requirements and operation specification. While both storage types require investments and higher operation costs in the energy system, the TES scenarios result in a reduction of the total systems costs, while the BESS leads to increased overall costs. For BESS, the positive effects can be found in reduced import and export, as well as some reduced fuel consumption for Orkney, while the TES scenarios improve exports and fuel consumption for both cases and more significantly. However, the addition of a HP and its specifications influence the operation of the TES, as well as make the comparison not a true comparison of storages, but two different optimizations of an energy system. In this regard, also the operation of the HP is of interest, as this simulation utilized the HP only during hours of RES overproduction. To turn off the HP when electricity would otherwise have to be imported would require a smart operation of the HP. Therefore, for the sector integration through HP and TES, this paper also showed the role of HP to be important.

The fact of only looking at two small island energy system with their characteristic wind power productions and demands influence the results. While the same tendency can be assumed for other places, a further study of other islands and energy system configurations is suggested. This way, other energy systems and their problems and opportunities can be addressed and the BESS and TES evaluated on their terms, enhancing the comparison. For the future energy systems of islands, local renewable resources should generally be strategically utilized and sector-integration made to the best extent possible. Storage technologies should only be aimed for after resources and sectors are well integrated and further excess electricity could otherwise not be used.

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