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Published in:
Renewable Energy

DOI (link to publication from Publisher):
10.1016/j.renene.2019.02.140

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Østergaard, P. A., Jantzen, J., Marczinkowski, H. M., & Kristensen, M. (2019). Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems. *Renewable Energy*, *139*, 904-914. https://doi.org/10.1016/j.renene.2019.02.140

Business and Socioeconomic Assessment of Introducing Heat Pumps with Heat Storage in Small-scale District Heating Systems

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This draft presents work that was presented at the 13th SDEWES Conference, Palermo, 2018 and later submitted, reviewed, revised and published in Renewable Energy, Vol 139, 2019
https://doi.org/10.1016/j.renene.2019.02.140

It presents work that is supported by the Horizon2020 research programme through the project SMILE (SMart IsLand Energy systems) under the grant agreement no. 731249.

Abstract

Fossil fuel-based CHP plants have a long history of supplying district heating (DH) in Denmark, however small-scale systems are progressively switching to biomass boilers for economic reasons. Biomass, however, should be reserved for other purposes where a storable fuel is pertinent.

This paper investigates the transition of DH on the Danish renewable energy island Samsø. While already renewable energy-based through the use biomass, the system is neither socioeconomically optimal nor optimal in terms of integrating fluctuating renewable energy sources or using biomass resources appropriately. EnergyPLAN-based energy systems analyses of heat pump (HPs) replacing DH biomass boilers are used to investigate system impacts, the ability to integrate fluctuating renewables and overall systems costs. Secondly, optimal business economic design and operation of the DH plant are analysed using the energyPRO model where plant operation is optimised against an external electricity market.

While heat pumps have a positive impact when factoring in the ability to exploit locally available fluctuating renewable energy sources and local biomass availability constraints, business economic analyses demonstrate a more uncertain feasibility of the potential switch and also demonstrate that significant flexibility through heat storage and overcapacity on heat pumps does not pay.

Keywords

District heating; heat pumps; biomass boilers; energyPRO and EnergyPLAN simulation; business economic feasibility; systems benefits;

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1 INTRODUCTION

Energy systems worldwide are facing an energy transition from being dependent mainly on fossil fuel resources to being dependent on renewable energy sources (RES) [1]. This is mainly due to climate change mitigation[2] as outlined in the Paris Agreement[3]. At the same time, RES are either scarce or of a fluctuating nature calling for these to be integrated well into the energy system to ensure that the different sources' characteristics are utilised optimally - with a view to ensuring that the load-following capability of the energy system is maintained.

Heating (space and domestic hot water) is responsible for one of the main energy demands with a 50% share worldwide (based on [4]) and this has been an object of attention and investigation for several years (see e.g. [5]). Options for the heating sector are many and include end-use efficiency through improved thermal insulation and RES-based supply systems. Biomass boilers, solar thermal collectors, HPs and electric heating based on renewable electricity are among the potential supply system solutions for individual houses. Power-to-heat or even more specifically *Wind power thermal energy systems (WTES)* (see e.g. [6]) are terms gaining importance in the literature.

For DH systems, the same RES are candidate solutions but there are also other potential candidates only relevant for such large-scale systems. This includes geothermal plants, waste heat from power stations, heat from waste incinerators (albeit, a source that should be avoided[7]), waste heat from industry or service industry – and in the future, waste heat from the production of synthetic fuels for the transportation sector. As noted by several authors, power-to-gas and power-to-liquids are candidates for integrating wind power (see e.g. [8]), but significant conversion losses are inevitable. DH systems, however, can exploit these.

In addition to providing RES-based heating or using waste heat sources, DH plants – or more generally district energy plants – also has a purpose to serve in future energy systems by supplying flexibility to assist the integration of fluctuating RES[9]. More specifically, cheap storage in heating systems[10] combined with power-to-heat technologies may provide needed flexibility for the electricity system.

Several analyses have already demonstrated how HPs combined with heat storage should form a key-component in future RES-based heating systems[11,12] but even so, biomass boilers are still a first choice in many DH systems in Denmark, This is in spite of Gustavsson already in 1994 pointing at gasification and CHP as energy efficient alternatives for introducing biomass into heating.

One problem today is however that particularly small-scale DH plants largely use or switch to biomass boilers in countries like Denmark. Biomass, however, is a restricted RES with better purpose elsewhere in the energy system[13] for instance for use in industrial processes where alternatives are sparse, for supplying electricity when fluctuating RES are affected by low resource availability – or as a source of carbon for producing fuels for e.g. the transportation sector[14].

Likewise, Stephen et al. find biomass attractive as a heating sources for off-grid communities in Canada [15] – while for locations with low coal taxes like the Czech Republic, the economic balance tips away from biomass [16]. Thus, the use of biomass is sensitive to framework conditions. Hvelplund[17] stresses the importance of on the one hand securing public acceptance for e.g. wind turbine investments and on the other establishing local energy markets for integrating fluctuating RES. WTES may serve a dual purpose here.

Samsø has the position of being officially announced as Denmark's Renewable Energy Island, and the island has been the site for many energy innovations which has led to the island being supplied 100% by RES now – however only on an annual basis and only when allowing renewable electricity export to counterbalance any fossil fuel imports for heating and transportation. In academia, Samsø has been the case for investigation on photo voltaic systems[18], carbon balance modelling[19], exergy studies[20] and Sperling used the island to investigate how communities manage to set the energy transition in motion[21]. Brandt and Svendsen[22] analyse which "skills" local "green entrepreneurs" on Samsø have – finding they have "profits, communication, and trustworthiness" to advance the transition. Similarly, Jantzen et al. [23] use Samsø as a case for analysing the connection between social and technological movement and Lin et al. [24] analyse Samsø from a policy and implementation perspective, identifying for instance how local ownership "*assisted by substantial local support as well as responsive energy policies, may lead an island community to successfully implementing a renewable energy system*".

Koigias at al. [25] – analysing islands energy systems – stress the positive economic impacts of local energy production. In this case, since the exploited biomass resources are locally available on Samsø and the wind power for HPs will also be locally available, the difference is unimportant in terms of energy imports. Rather, the difference lies in potential exports – wind power vs biomass.

1.1 Scope and structure

Samsø forms the basis for the analyses in this article, which investigates the transition from biomass-based to HP-based DH. While biomass-based DH may be optimal from a current and narrow business economic perspective and without concern for system integration and better uses of a scarce resource – HPs are better for integrating fluctuating RES such as wind power but are also relatively novel for DH purposes in Denmark and expensive.

This paper investigates the area from a dual perspective. On the one hand, it investigates the potential role of HPs combined with thermal energy storage from an overall energy systems' perspective – and on the other hand it investigates whether a transition from a biomass-based boiler to a HP-based system is attractive under present Danish business economic circumstances. The business economic investigation is based on one of the four DH systems on Samsø – the Ballen-Brundby District Heating System (BBDH).

Section 2 presents the two energy systems analyses models – energyPRO and EnergyPLAN - applied in the article to perform the holistic systems analyses and the business economic optimisation. Section 3 presents the Samsø case in further detail. Subsequently Section 4 and 5 present the energy systems analyses using EnergyPLAN and energyPRO respectively and finally main conclusions are drawn in the final section.

2 METHODS

This section introduces the two models used for analysing BBDH; the EnergyPLAN model used to model the entire Samsø energy system from a holistic socioeconomic perspective and the energyPRO model used for the more detailed business economic analyses of the BBDH plant operating against electricity markets.

2.1 EnergyPLAN for socio-economic energy systems analyses

EnergyPLAN is a model widely used in academia [26], and like energyPRO, it is a priority list simulation model, but generally it is based on endogenously defined priorities. The model may be operated in technical or economic simulation mode. Both are based on minimising primary energy consumption and ensuring the hourly balance between supply and demand within electricity, heating, cooling, transportation and gasses. With economic simulation, units are additionally dispatched according to their economic performance and their operation is optimised against a user-defined electricity market. Thus when prices are higher than the marginal cost of producing on a CHP unit for instance, operation is increased if other restrictions permit so. With endogenously defined priorities, it is not possible to model what could be labelled "suboptimal" operation. I.e. it is not possible (as it is with energyPRO) to assign a lower priority to wind power than to heavy fuel oil-based condensing mode power generation.

The model is hourly, operates on a year basis and is aggregated. Units of a certain type are aggregated into one unit representing the entire stock of the given type – e.g. large scale condensing mode power stations or off-shore wind farms. The model is therefore well-adapted for regional or country-wide studies where focus is not on a particular plant's behaviour. Efficiencies and e.g. the coefficient of performance (COP) of heat pumps are constant throughout the year in EnergyPLAN.

DH in EnergyPLAN is split up into three different groups; 1) systems based on boilers only, 2) systems based on back-pressure CHP and 3) system based on extraction CHP plants. In addition, other sources such as solar thermal, industrial waste heat sources and heat from waste incineration may be assigned to the groups. Groups 2 and 3 may also include DH HPs and heat storage.

EnergyPLAN has previously been applied to analyse energy systems with HPs [27], transportation[28], reverse osmosis[29], integration of wind power [30] and intermittent renewables in general[31] – as well as in a long series of scenario development studies for various geographic regions [32].

2.2 energyPRO for business-economic plant design

The analyses of the business economic feasibility of HPs in DH systems are conducted using the energyPRO model. This model is widely used in consultancies for assessing DH schemes and notably different production technology combinations for such systems operating in different types of energy markets. In addition to being used in consultancies, the model is also used in academia with papers on optimisation against markets[33,34], more holistic regional systems[35], low-temperature DH systems[36,37], and the design of support systems[9].

energyPRO is based on a priority list simulation system. Marginal production costs of all units are calculated for each time step in the planning horizon – e.g. hourly in a year as also used in the analyses in this article – based on operation expenditures and incomes with e.g. time-varying power and gas prices. Included into the production costs are potential incomes, thus the heat production cost of a CHP unit is a result of fuel costs, variable operation and maintenance costs and incomes from delivering electricity to the grid. The units are then dispatched - or committed - in ascending order of production cost while ensuring that new productions do not interfere with previously planned productions.

energyPRO may model an energy system in any desired level of detail and may thus model individual units in district energy plants. The units are described by e.g. power curves (load-specific outputs) and the operation of particular units may be modelled as being restricted to when other units are not operating (or are operating), partial load may be banned and production to storage may be allowed or disallowed for particular units.

Efficiencies may be modelled as constant, however they maybe also be calculated based on other factors or simply as time-varying. A HP COP may thus depend on time-varying heat resource temperature. This is applied in this paper.

3 Case description – Samsø Renewable Energy Island

This section presents the Danish island Samsø starting with a broad overview of the island and continuing with a more detailed description of its present energy system.

3.1 Samsø in general

Samsø is a 11 by 26 km island in the middle of Denmark - midway between the main peninsula Jutland and the island Zealand - with ferry services both east and west. The current population is 3700[38], which is the lowest level on the records. Depopulation threatens the community, and it is a primary political goal to maintain and increase the population[39].

In 1997 the Danish government appointed Samsø as Denmark's renewable energy island. The islanders then installed biomass-fuelled DH plants, as well as on and off-shore wind turbines [40], and private house owners invested in solar thermal collectors, HPs, and biomass boilers. The island started to produce electricity in the year 2000, and a few years later the electricity production was up to three times the local electricity demand. The resulting large electricity export compensated for the fossil fuels consumed by tractors, buses, cars, and ferries – and by the year 2007 the island reached its 100% renewable energy target. Today, the island is nominally a 100% renewable energy island, however this does not mean the island is self-sufficient; it just means the annual energy demand balances the annual supply from RES. Furthermore, a population density which is a quarter of Denmark's density in general and similarly more coast line per capita results in comparably good wind turbine siting possibilities. To transition the heating and transport sectors would inevitably be harder.

The plan is to act as a pilot case for Denmark and phase out using fossil fuel altogether by the year 2030, twenty years ahead of Denmark. Smart energy is central to the energy plan [41]. Submarine cables connect Samsø with the mainland (Jutland), and electricity flows both ways, but mostly in the export direction. The technical objective of Samsø is to lessen the electricity export by increasing the internal use of renewable electricity. The plan includes a biogas plant, which will convert biomass to gas, electricity, heat, and fertiliser. Since March 2015, Samsø has had a ferry operating on liquid natural gas[42] – the *Prinsesse Isabella*. Ideally, Samsø will produce fuel for Prinsesse Isabella, buses and tractors instead of buying it from outside the island.

There are at least three reasons for working towards a sector-integrated smart energy system on Samsø:

- Excess wind power and limited biomass availability, where wind could free up biomass presently used for heating [43].
- Potential bottlenecks in the electrical transmission network – notably the 40 MW submarine cable.
- Thermal storage is two orders of magnitude less expensive than electrical storage [44]. It is therefore an advantage to produce heat with electric boilers or HPs during periods of excess power generation, rather than having to install electric batteries or capacitors [43].

Samsø has an energy vision with a long-term strategy, based on scenario-making and energy system's simulations [43]. The energy vision analyses various scenarios depending on policy. According to the vision, the island should focus on electrifying the heating sector and promote electric cars. This is also in line with other local initiatives in Denmark[45,46].

3.2 The energy system on Samsø

Samsø municipality updates an energy account (referred to as an *energy balance*) every two years which is published online by the Central Denmark Region together with 18 fellow municipalities from that region[47]. The energy balance is a spreadsheet input-output model [48]. The input side is the energy supply, including import, and the output side consists of various end-use categories. A set of efficiency factors represent energy conversions and network losses. This energy balance forms the basis for the case description in this paper.

Samsø's demand for energy includes electricity, heat, process heat, and transport; the climate renders cooling unnecessary (Figure 1). Wind power - combined with import and export mainly for balancing - covers the larger part of the electricity demand.

Four biomass-based DH plants cover 35% of the heat demand. Individual heating units cover the rest (wood stoves 20%, wood pellet boilers 13%, straw boilers 1%, solar heat 1%, oil burners 19%, electric heaters 5%, HPs 6%).

The two ferry lines, cars, lorries, buses, and tractors account for the transport demand. The demand for process heat is due to food processing and cooking. Power plants, including CHP, are absent as is a natural gas network.

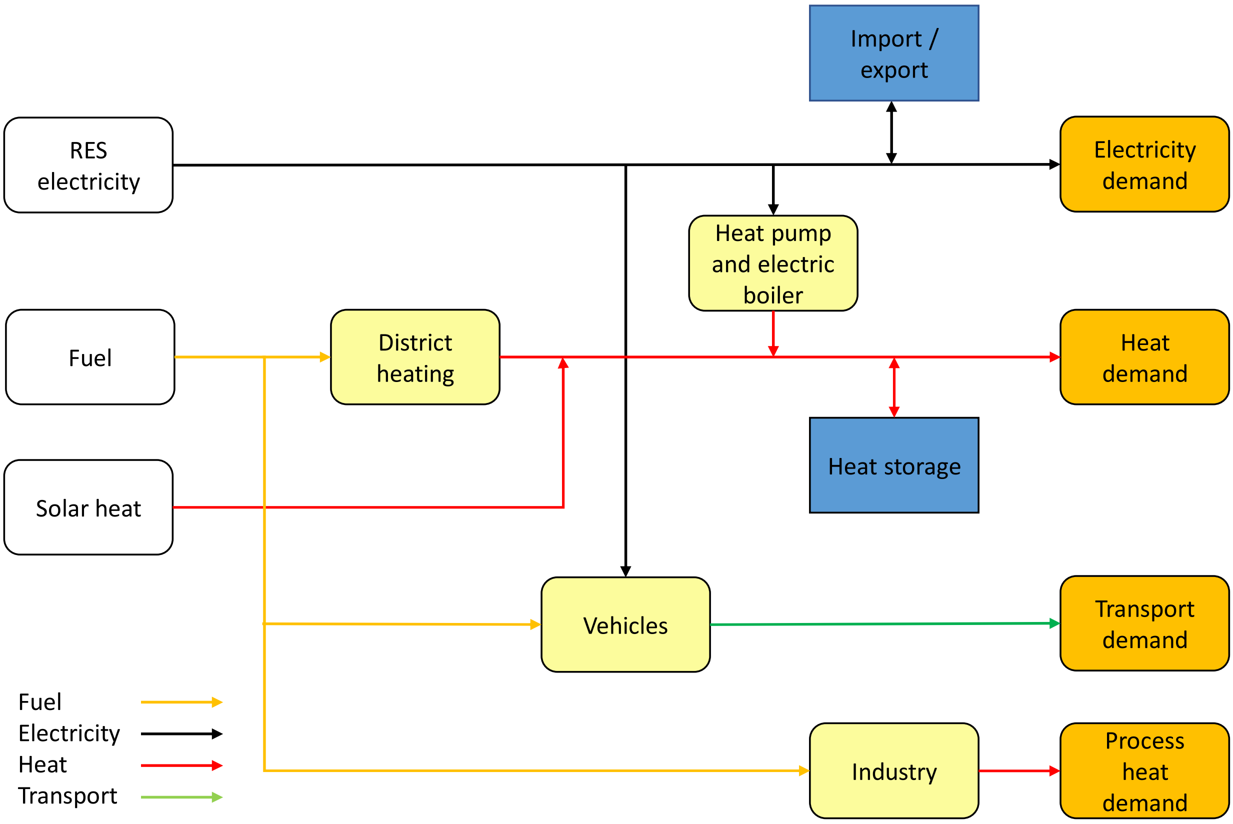

Figure 1. General structure of Samsø's present energy system.

Figure 2 shows the energy balance with respect to RES and fossil energy sources. Clearly, renewable electricity or biomass must replace the fossil-fuelled individual heating. The worst problem, however, is transport, which accounts for 36% of the demand. It is necessary to promote cars based directly or indirectly on electricity and to move biomass to the transport sector using biogas. Industry on Samsø is negligible, fortunately - from an energy transition perspective.

An estimate of the demand for biogas for the westbound ferry Prinsesse Isabella is 4 million m^3 each year [49]. Including 0.67 million m^3 for process heat in the biogas plant itself, the total demand is 4.67 million m^3 or almost 31 GWh. The biogas raw material potential on Samsø consists of liquid matter (manure, waste water) and dry matter (deep litter, surplus straw, cover crops, meadow grass, energy crops, vegetable waste, horticultural waste, and organic household waste). The potential biogas contents amounts to 34 GWh [50], thus sufficient to cover the demand. The surplus may cover the demand from heavy vehicles.

This assessment assumes a contribution from energy crops equivalent to 15% biogas plant input - just below the 18% Danish legal limit. Nevertheless, energy crops require the farmers' cooperation, and they will only grow energy crops, such as grass-clover and perennial alfalfa that fix nitrogen, if the business case is economically viable.

There are eleven 1 MW wind turbines onshore and ten 2.3 MW wind turbines offshore. Unfortunately, the offshore turbines count only half in the official Samsø energy balance while the other half is allocated to neighbouring municipalities. With this distribution, the total wind production on Samsø in 2015 was 74 GWh.

The annual photovoltaic electricity production is small at 3 GWh, but the potential is large [43]. Counting all roofs with a potential annual production higher than 90 kWh/m^2, the annual potential is more than 60 GWh, almost similar to the current annual wind production on Samsø. In Denmark the average number of full load hours for photo voltaics is 961 [51]. Fortunately, Samsø has more sunny hours and higher solar intensity than average, and the number of full load hours is perhaps 10% higher than the Danish average.

Today, the farmers supply straw to three out of the four DH plants on Samsø (Table 1). The farmers receive about 107 € per tonne of straw, provided the water contents is less than 14%. Normally the rye and wheat harvest provides enough straw, but should the harvest fail, then the farmers are obliged to supply fuel from the mainland. This was a problem after the 2018 European drought. As the Deputy director of the Danish District Heating Association Kim Behnke states, *"On Samsø and other places, they have made straw-based district heating [..] this is a really good idea but it also makes them among the most vulnerable"*[52]. The DH plants have oil burners for backup and for straw shortages – but this is an expensive alternative.

The fourth plant - Nordby-Maarup - operates on woodchips from a local forest together with an array of solar collectors, which supplies 25% of the plant's annual heat production.

The total straw supply for DH on Samsø is equivalent to 22 GWh per year (5500 tonnes/year). This could potentially go to a new biogas plant, while HPs could replace the straw boilers.

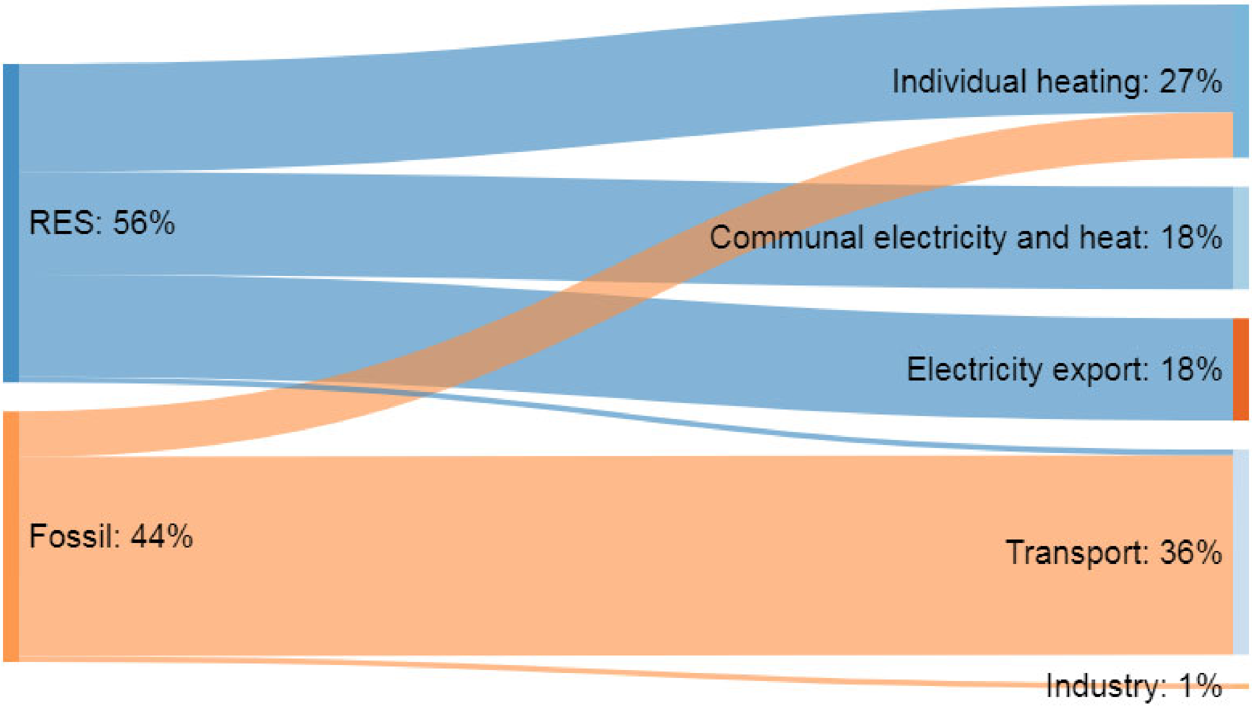

Figure 2. Sankey diagram of Samsø's energy balance 2015. The total energy demand was 548 TJ or 152 GWh.

Table 1. Nominal technology data concerning the four DH plants on Samsø.

	Nordby-Maarup	Onsbjerg	Tranebjerg	BBDH
Size [MW]	0.9	0.8	3.0	1.6
Annual production [MWh]	3600	1500	9500	4000
Villages served	2	1	1	2
Consumers	200	120	400	300
Built [year]	2002	2002	1993	2005
Fuel	Wood chip	Straw	Straw	Straw
Solar collectors	2500 m^2 ~ 2.2 MW	0	0	0
Heat storage [m^3]	800	0	214	0
Annual fuel consumption [t/yr]	1500	400	2600	1100
Efficiency of boiler [%]	93	93	93	93
Efficiency of DH Grid [%]	71	71	71	71
Flue gas cleaning	Condensation	Bag filter	Bag filter	Bag filter
Steady data records	No	No	No	Monthly

3.3 The Ballen-Brundby District Heating plant

The local consumers own BBDH in a cooperative with limited liability. The members both own and manage the cooperative, which is a non-profit organisation (denoted *consumer profit* organisation by Hvelplund in [53]). The plant started operation in 2005 and as of 2017 it had 285 consumers, living in the two villages, Ballen and Brundby, which are two kilometres apart.

Figure 3 shows that the BBDH network is quite outstretched, and the network losses are therefore relatively high (28-36%). The forward temperature is 80°C and the return temperature is around 49°C depending on the season. The plant produces hot water in a 1.6 MW Linka Energy straw boiler operated semiautomatically with an operator visiting once or twice daily to replenish the straw feeder.

Straw is delivered in rectangular 580 kg bales from storages at the farms usually just after harvest in August, and a second delivery in mid-winter. Ash is recycled to the farmers as a fertilizer. Fly ash in the flue gas is withheld in a bag filter, but there is no flue gas scrubber.

The total investment of 2.2 MEUR was partly financed by a 2MEUR municipality-guaranteed loan and a 0.33 MEUR grant from the government. The surplus (0.1 MEUR) was used for buying straw. In 2017 the variable share of the operation and maintenance (O&M) cost was 47 000 EUR, while the fixed share was 70 000 EUR; the total O&M was thus 117 000 EUR, excluding fuel costs. The heat production was 5560 MWh and the fuel consumption 1610 tonnes of straw. Table 2 provides further technology data for simulations.

Table 2. Technology data for the straw-fired BBDH.

Straw boiler	**Standard catalogue data**[51]	**BBDH 2017**
Capacity [MW]		1.6

DH grid loss [%]		33
Technical lifetime plant [years]		25
Technical lifetime boiler [years]		15
Construction time [years]		1
SO_2 [g/GJ fuel]	49	
NO_x [g/GJ fuel]	125	
Unburned hydrocarbon [g/GJ fuel]	0.94	
N_2O [g/GJ fuel]	1.1	
Nominal investment [M€/MW]	0.5-1.1	1.35
Total O&M [€/MWh], fuel excluded	4.0	20.9

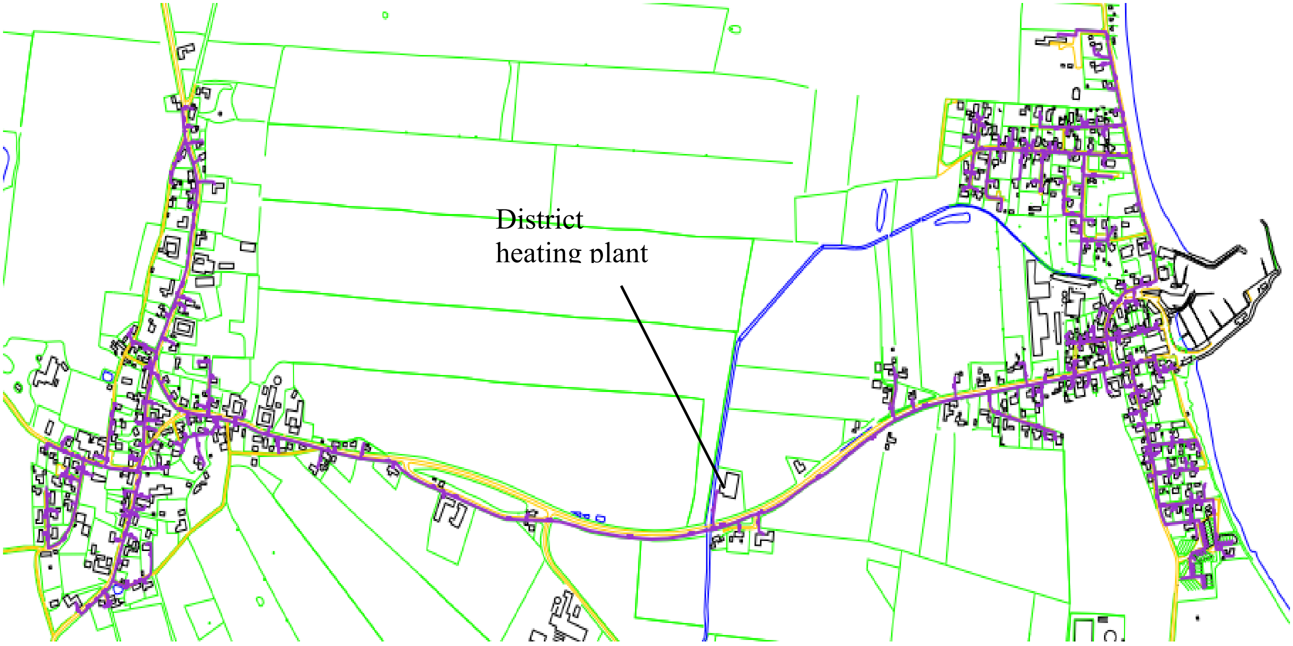

Figure 3: The BBDH network. Map from [54]

3.4 Temporal demands and productions

An operator console at BBDH shows various production data real-time, but unfortunately without logging these. Instead, for these analyses weather data are used as a proxy for the temporal heat demand distribution, where it is assumed that the heat demand follows the outdoor temperature in terms of degree hours. To calculate degree hours, 17°C is taken as the base temperature, which is the assumed outdoor temperature at which the household thermostatic valves turn off. Heating degree hours are then defined as the function max(0, 17 – T), where T is the average temperature of the hour. The Climate Forecast System provides temperature data on an hourly basis.

Figure 44 shows the hourly heating demand profile. EnergyPLAN can load such a heating degree hour profile and distribute the aggregated user-given annual demand. EnergyPLAN thus uses the shape of the profile; the absolute numbers are not important.

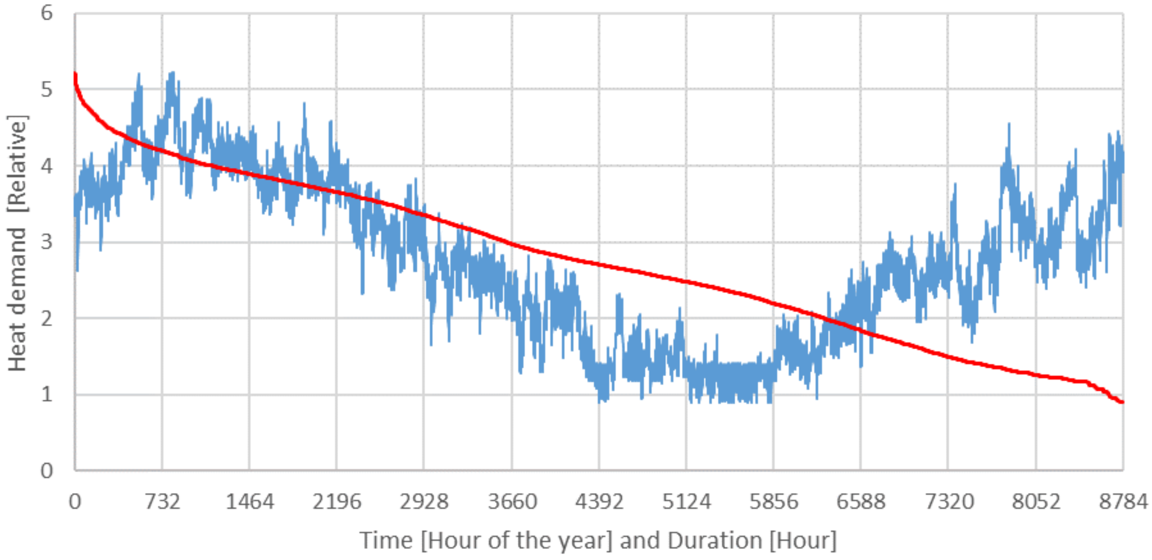

Figure 4. Hourly heat demand profile for one year and duration curve of heat demand.

It is not surprising that the heat demand is higher during the winter than during the summer, but the reason for the noticeable heat demand during summer is the production of domestic hot water alongside with DH grid losses.

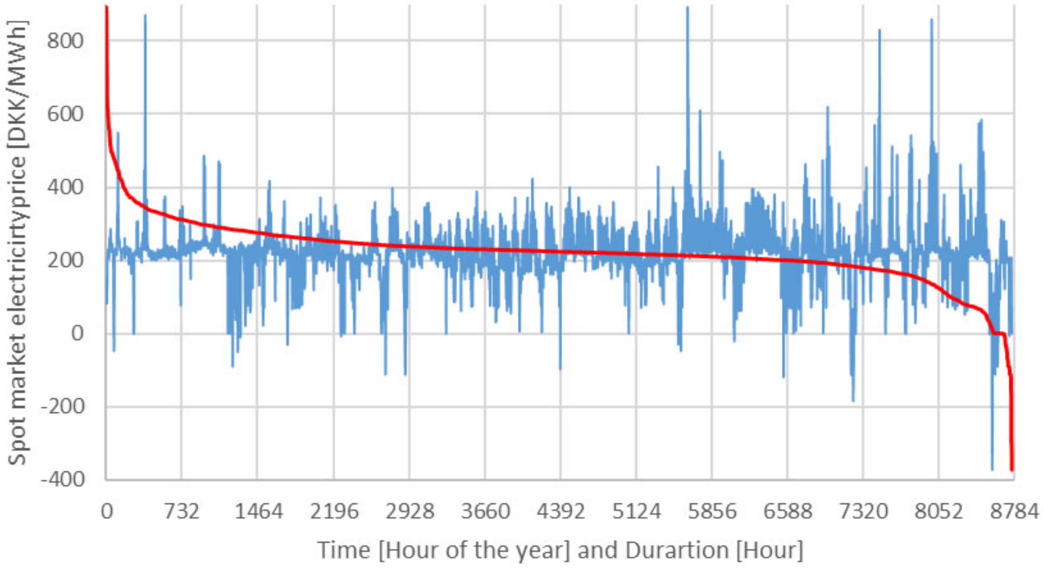

Figure 5: Hourly spot market electricity price pricing areas DK1 for 2017. Data from [55]

Figure 5 shows the hourly spot market electricity price variation of a year. Note that the market permits negative prices.

4 The role of heat pumps in energy island scenarios

Three characteristics of Samsø's current energy system call for a change of the energy system: (1) The production of renewable electricity is large, (2) three out of four DH plants use straw, and (3) the straw is needed in a future biogas plant. The last is based on wood chip that may also have a more valuable role in the energy system. The objective is to move the straw from DH to biogas, and instead generate heat by means of HPs using locally generated electricity. It is time to consider scenarios for the replacement of the DH plants anyway, as they are getting old.

1. *Scenario 1: Replacing all DH boilers by HPs*. This should increase the demand for electricity, but create a better balance between production and demand of electricity by decreasing the electricity export.
2. *Scenario 2: Adding thermal storage to DH systems*. It should be possible to absorb fluctuations in renewable energy supply by means of storage. If the electricity export is decreased by means of thermal storage, it will be a clear demonstration of the benefits of the sector integration through the smart energy approach. The size of the storage will be varied and effects on electricity export and systems costs will be observed.

The first scenario clearly replaces biomass by electricity. There are other advantages, such as fewer emissions of SO_2, NO_x, unburned hydrocarbon and N_2O from the combustion process, lower operation and maintenance costs, and digital monitoring and control. Due to the asynchronous electricity production mainly from the wind turbines, some electricity must be imported though.

The second scenario tests the hypothesis that thermal storage can absorb some of the fluctuations in the renewable electricity production.

4.1 The reference model

The reference model uses data from the year 2015 corresponding to the previously displayed energy balance (Figure 2). The total DH demand is 25 GWh/year.

Table 3 lists the main parameters related to DH and electricity. Transport demand and individual heating is left out of the table for brevity.

An EnergyPLAN simulation of the Samsø reference model yields an electricity export which is 87.5 GWh/year while the import is 1.5 GWh/year. The import is thus below 2% of the export, and in that respect negligible. The costs consist of variable costs, fixed annual costs, and annualised investment costs. The total cost is 22.6 M€. This is used as a reference in the following scenarios.

As a first approximation, the DH demand would be covered by 7.7 GWh/year of electricity using HPs with a COP of 3.25. Compared with the electricity export of 88 GWh/year, the potential reduction of the export is thus approx. 9%.

4.2 Scenario 1: Adding heat pumps

All four DH plants taken together correspond to a thermal capacity of 6.3 MW (Table 1). The current version 12.1 of EnergyPLAN is unable to fully replace biomass boilers with HPs; HPs can only be included as a supplement. Thus HPs with the same capacity, and COP of 3.25 are added. Using the market economic optimisation EnergyPLAN prioritises the HPs over the biomass boilers most of the time (HPs produce more than 99% of the DH).

As a result, the electricity export is reduced by 7.2%, which is close to the first approximation (9%). The electricity import increases a little, but it is negligible compared with the export as mentioned previously. Compared with the reference, the variable costs are 7% less, the fixed costs increase marginally by 0.6%, and the investment costs increase somewhat (6.6%). Altogether, the total costs increase by 1.5%.

Obviously, adding HPs requires some investment, but operation and maintenance is less expensive. In the long run HPs seem to be more expensive, depending on prices, but they have other advantages as mentioned previously.

4.3 Scenario 2: Adding thermal storage

Evidently, HPs use some of the exportable electricity. The question now is whether storage reduces export even more. Scenario 2 is based on Scenario 1, but adds a thermal storage, which is then increased in steps. The initial step is 25 MWh capacity, which corresponds to roughly 0.1% of the annual heat demand. On average, that corresponds to a residence time of 8.8 hours. The next step is twice the previous, and so on until storage size 3200 MWh, which is considered a realistic upper limit for hot water storage.

Technically, a storage may save the HP some start/stop cycles and thereby prolong its lifetime. This effect is not factored into the analyses

The plot in Figure 66 shows a linear increase of the total cost with increasing storage size. EnergyPLAN assumes linear investment costs and linear operation and maintenance costs (Table 3). The plot also shows that the electricity export decreases, but not linearly. That is, the saved amount is less as the size of the storage increases. This is an example of diminishing returns.

Going for the full storage of 3200 MWh – corresponding to a residence time of approximately 1½ months, electricity export is reduced by 8% - comparable to the effect of replacing biomass boilers by HPs in the DH systems on Samsø. There is obviously a trade-off to be made between the size and the cost of the storage on the one side – and the benefit to the wider system on the other side.

Table 3. Main EnergyPLAN parameters regarding DH.

Parameter	Setting	Comments
Simulation type	Market economic	
Electricity demand [GWh/year]	21.5	
Onshore wind power capacity [KW]	11359	
Onshore wind production [GWh/year]	27.5	Capacity factor 0.29
Offshore wind power capacity [KW]	23000	
Offshore wind production [GWh/year]	80.9	Capacity factor 0.41
Photovoltaic capacity [kW]	1337	
Photovoltaic production [GWh/year]	3.14	Capacity factor 0.27
DH demand [GWh/year]	25.46	
Boiler capacity [kW]	6300	Biomass boilers
Boiler efficiency	0.927	
Solar thermal input [GWh/year]	1	Nordby-Maarup
DH network losses	0.295	

Interconnection capacity [MW]	40	
Storage investment cost [EUR/MWh]	7292	(See Table 4)
Storage operation cost [% of investment/year]	3.66	

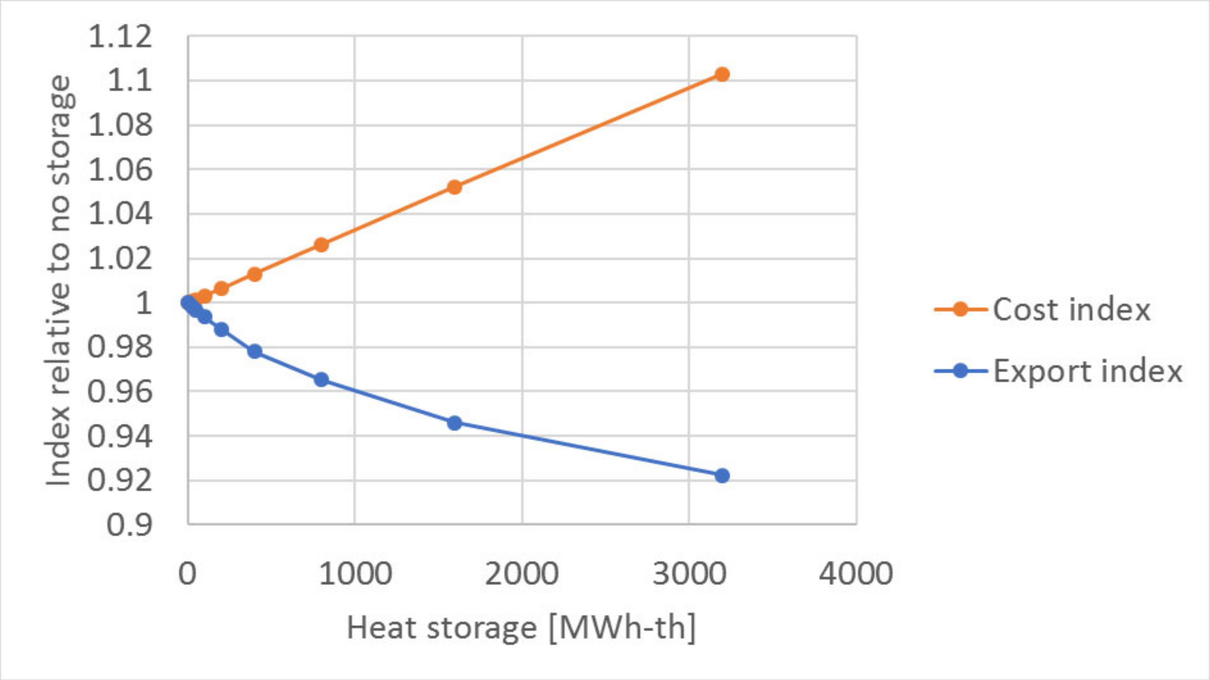

Figure 6. The effect of heat storage size on total cost and electricity export.

5. Business economic assessment of investments in heat pumps

This section explores the business economic feasibility of supplementing or supplanting the DH straw boiler by a HP and a heat storage. The business economic feasibility of HP and storage depend on electricity prices and levies, which are considered in this section. Current political negotiations aim to reduce the levy on electricity for heating purposes gradually over three years starting in 2018, however this has not been considered, but may eventually improve the feasibility.

5.1 Common data for the energy systems analyses

Tables 4 and 5 contain the main characteristics applied in the energyPRO simulation. Note that investment costs are not included in the operation simulations that solely depend on the marginal operation costs. Investment costs as well as fixed operation and maintenance costs are only included in the invest comparisons.

Table 4: Heat storage data for a steel tank

Characteristic	Comment
Temperature levels	Corresponding to DH levels; upper / lower temperature 80°C and 45°C
Energy contents	48 kWh/m^3
Utilisation rate	90% (not 100% due to nozzles/diffusers/imperfect stratification)
Investment cost	350€/m^3 ~ 2530 DKK/ m^3 [56] (Technology 61). The main data in the reference are for applications > 1000 m^3 where prices are listed as 160-260 €/m^3. For smaller steel tanks, specific cases list prices as 350 and 200 €/m^3. As the analyses include relatively small sizes, the upper range price of these is used, though it should be stressed that it is an area of little empirical evidence and certainty.
Loss	Negligible

Table 5: System characteristics with focus on parameters included in the operation optimisation. Notes and sources: [a]EMD International; [b]Danish Energy Agency[51]; [c]BBDH [54]. Costs based on 104000 DKK per year fixed and variable; [d]Provided for reference only; [e]Danish Ministry of Taxation[57]; [f]Danish Ministry of Taxation[58]

	Straw boiler	Heat pump
Fuel / electricity cost	0.82 DKK/kg[c]	Hourly DK2 Spot market price 2017. For this time series, prices fluctuated between -372.5 and 892.6 DKK/MWh with an average of 223.6 DKK/MWh
Fuel heating value	4 kWh/kg[c]	
Fuel / electricity taxes	27 DKK/Ton straw (Sulphur Tax)[e] 6.8 DKK/Ton straw (NOx)[f]	258 DKK/MWh (electricity levy) [a] 147 DKK/MWh (PSO levy) [a] 135 DKK/MWh (distribution grid fee) [a] 83 DKK/MWh (Transmission grid fee) [a]
Variable operation and maintenance costs	0.6€ = 4.5 DKK/MWh[b]	15 DKK/MWh[b]
Fixed operation and maintenance costs	80000 DKK/year[c] + 250000 DKK/year operating staff[c] 52892€=396690 DKK/MW/year[bd]	2000 € = 15000 DKK/MW$_h$/year [b] + 50000 DKK/year operating staff[c]. If combined with straw boiler, then operating staff is zero
Investment cost	6.83 MDKK/MW[b]	0.7 M€ = 5.25 MDKK/MW$_h$ [b]
Efficiency	0.8683[c]	Dependent on resource temperature (Lorentz efficiency and a system efficiency of 50%). COP 3.6 with DH water heated from 45°C to 80°C with a resource cooled from 12.5°C to 10°C Using sea water as heat resource, the weighted average yearly COP is 3.25
Operating restrictions	Minimum 1h consecutive operation Minimum 1h consecutive off Production to storage not allowed Partial load operation allowed	Minimum 1h consecutive operation Minimum 1h consecutive off Production to storage allowed Partial load operation not allowed

5.2 Scenario 1 – Heat pump and straw boiler operated in conjunction

For the first scenario, the existing straw boiler is maintained and supplemented by a HP as detailed in Figure 7.

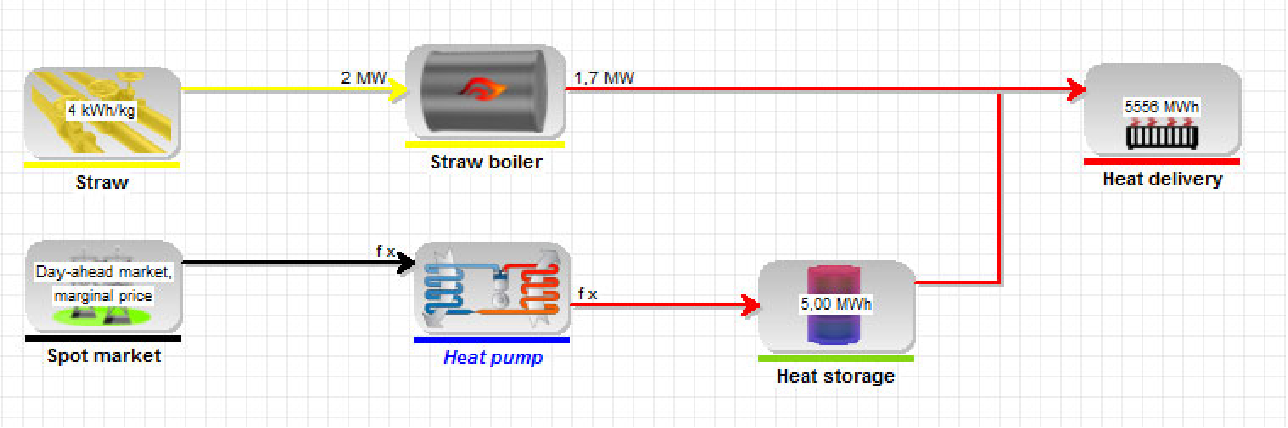

Figure 7: Energy system with HP, straw boiler and storage. The HP is 200kW$_e$ with a thermal output determined by the Lorentz efficiency and limited to 1MW$_{th}$.

When operating the HP and the straw boiler in conjunction – with priority depending on the marginal production cost, HPs are more expensive in the winter time than the straw boiler due to a lower marginal production costs on the straw boiler. This is caused by a higher resource temperature and a higher Lorentz efficiency during the summer giving a smaller electricity demand.

Figure 8 shows how this results in a break-even electricity spot market cost between the straw boiler of approx. 75 DKK/MWh$_e$ during the winter and 275 DKK/MWh$_e$ during the summer. Thus, the HP is considerably more competitive during summer.

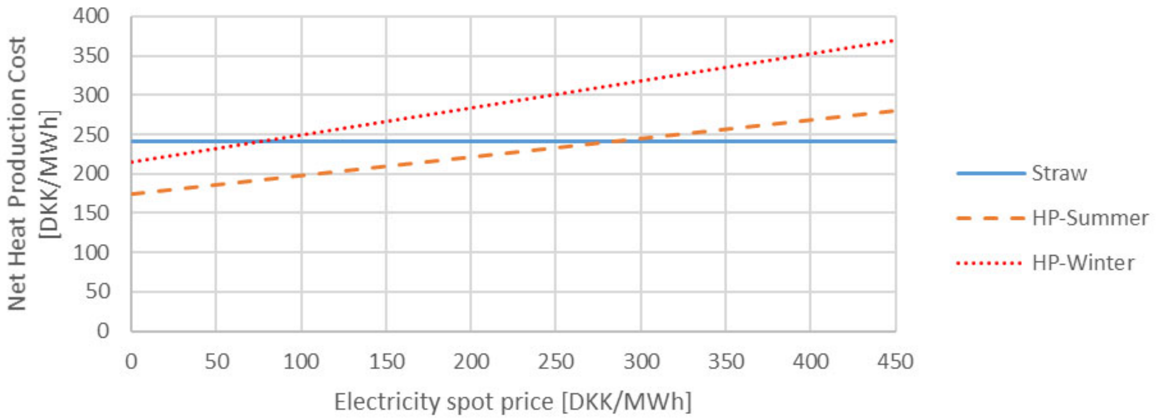

Figure 8: Net heat production cost vs electricity spot market prices for the system shown in Figure 6 for January and July.

In terms of operation of the system, the effects are noticeable from Figures 9 and 10 showing the operation of the individual units. In January, there are only two operation periods for the HP while in July there are numerous – at which time there is only limited use of the straw boiler.

In January, the storage is never used. This is because the system is operating almost exclusively on the straw boiler – where partial operation is allowed. There is no economic incentive to shift boiler production from one hour to another using the storage, so this has not been allowed in the modelling. At the same time, the HP at the modelled size is insufficient to meet the demand – thus there is no overcapacity to store. As a sensitivity analyses, a 0.5 MW_e HP has been tested and this does make use of the storage in January – but it does not result in new HP production periods. On a yearly basis, increasing the HP size does result in HP heat production increasing by 17% from 1247.1 MWh to 1457.5 MWh – the remainder of the total annual demand of 5556 MWh in either case produced by the biomass boiler.

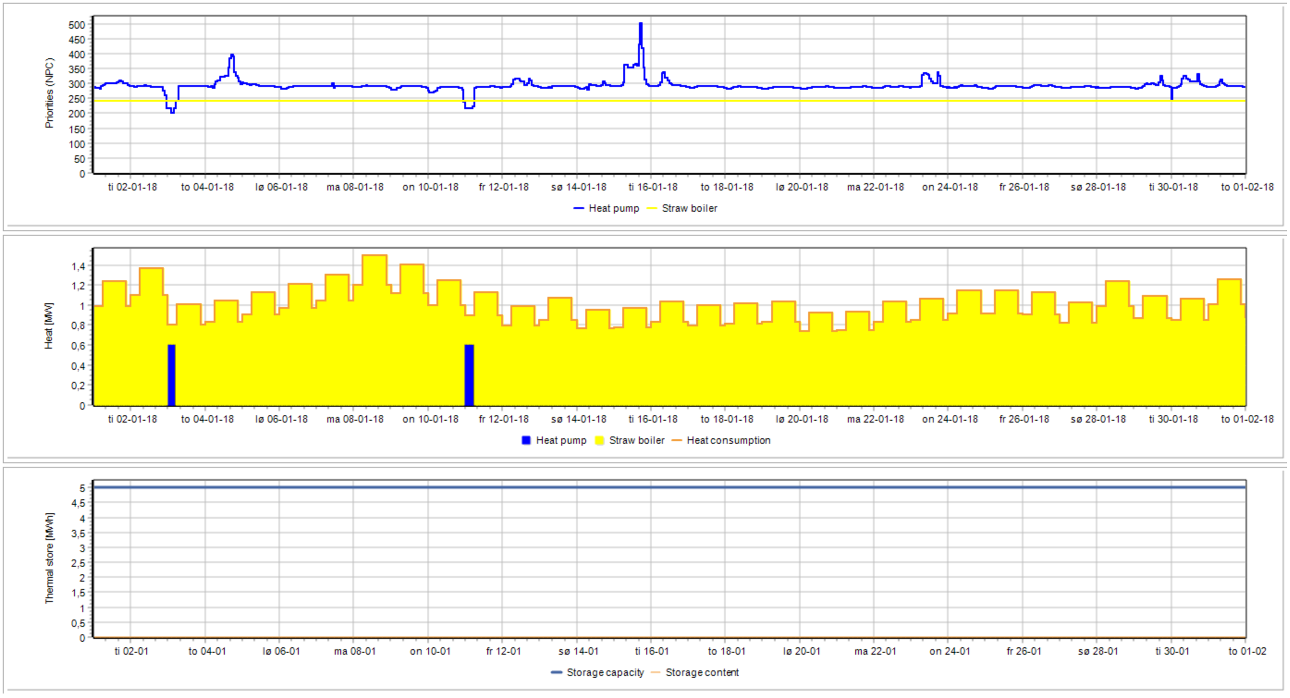

Figure 9: Production profile for January for a system with a HP and a straw boiler. The priority panel at the top shows production priorities equal to marginal production costs. Note that the storage is not used in this period

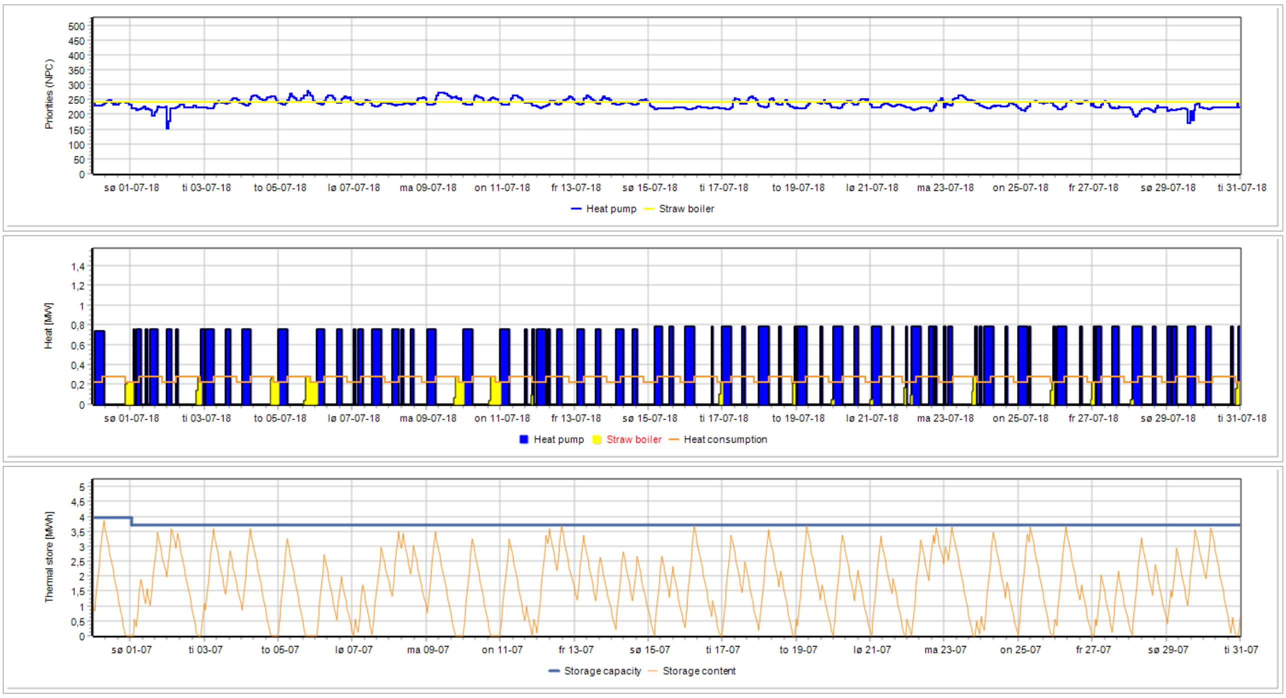

Figure 10: Production profile for July for a system with a HP and a straw boiler. The priority panel at the top shows production priorities equal to marginal production costs.

5.3 Scenario 2 – Straw boiler operated alone

Without a HP in the system (Figure 11), the storage may also be removed as the boiler is modelled not to produce to the storage. Even if allowed to use the storage, there would be little if any incentive to move production through the use of the storage. In this case, the boiler simply follows the heat demand throughout the year as indicated for January in Figure 12.

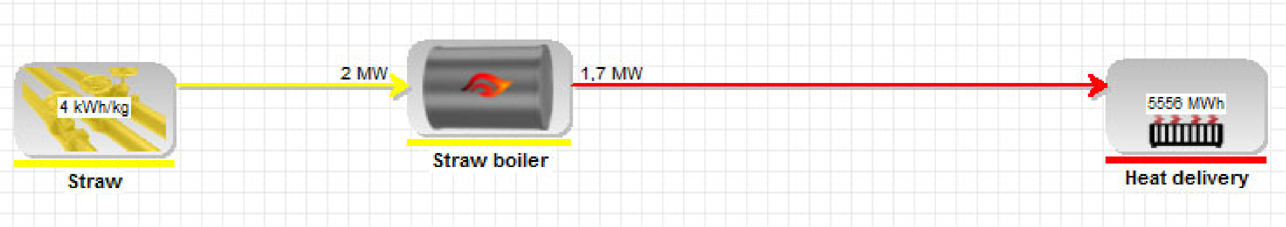

Figure 11: System configuration for system with straw boiler only.

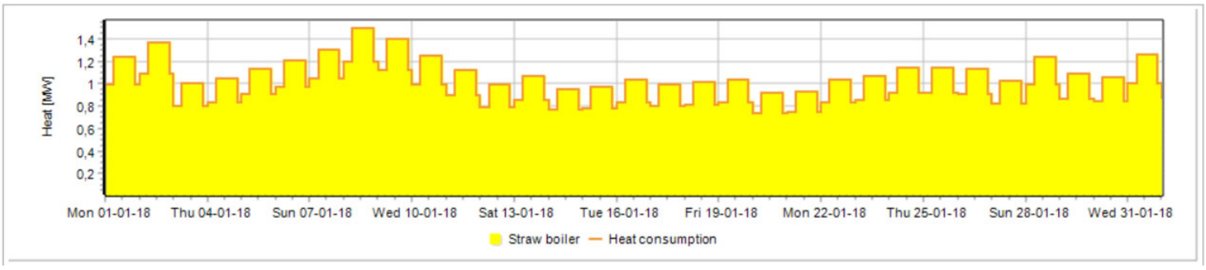

Figure 12: Production profile for January for a system with a straw boiler. Note that the storage is not used in this system configuration.

No further results are shown for the operation in this scenario.

5.4 Scenario 3 – Heat pump operated alone

With the same HP size as in Scenario 1, demand will not be met when the straw boiler is not available. This is even the case with a storage corresponding to the annual heat production as the HP simply does not suffice.

For contingency reasons an electric boiler is added to the system. This unit has variable operation and maintenance of 3.75 DKK/MWh (0.50 €/MWh); Fixed operation and maintenance of 8250DKK/MW/Year (1100€/MW/Year) and an investment cost of 1.125 DKK/W (0.15€/W) (Data from [56] - Technology 41). It is calculated with an efficiency of 100% and is subject to the same electricity prices and levies, as the HP. In the existing configuration in the DH plant, an oil boiler serves this purpose, however for a future renewable energy-based system, this will not be available. Thus, a full-sized electric boiler is included.

With the same size HP as in Scenario 1, this will function nearly as base-load for a large part of the year. Figure 13 shows the production profile for January and it is clear from observing the energy contents in the heat storage that the system operates with a some degree of flexibility against the hourly electricity prices. The heat boiler is only used seldom. In the summer period, it will operate with more flexibility.

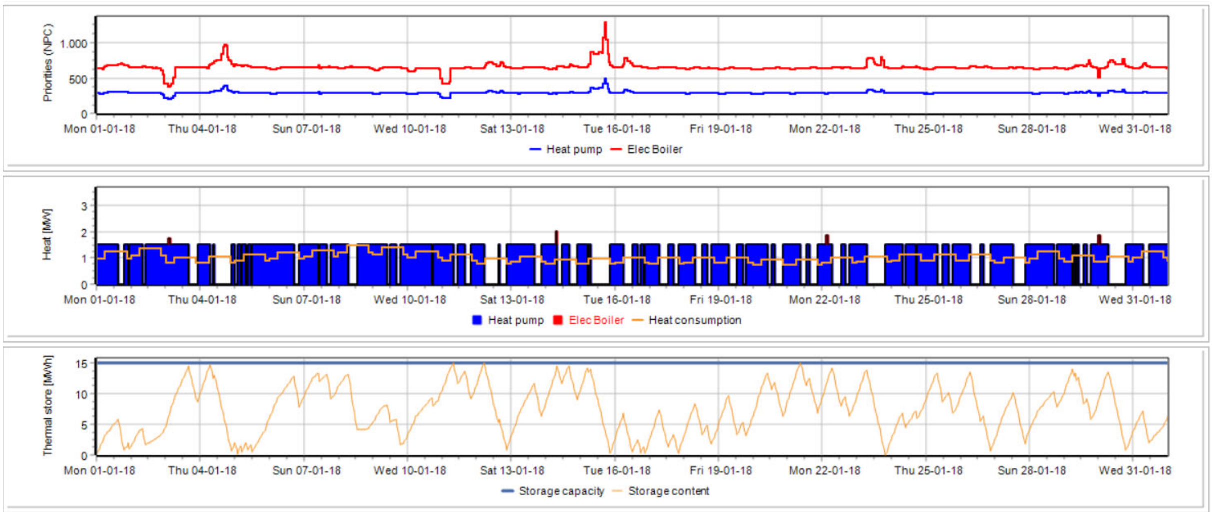

Figure 13: Production profile for January for a system with a 0.5 MW$_e$ HP and 15 MWh of heat storage. The priority panel at the top shows production priorities equal to marginal production costs.

Figure 14 shows the results of a comparison between different sizes of heat storage and different sizes of HPs. In all cases, HPs may not operate in partial load but are allowed to produce to the storage. This has the effect that only the smallest size HP gets any production without a storage. With partial load disallowed, the other HPs are simply too large.

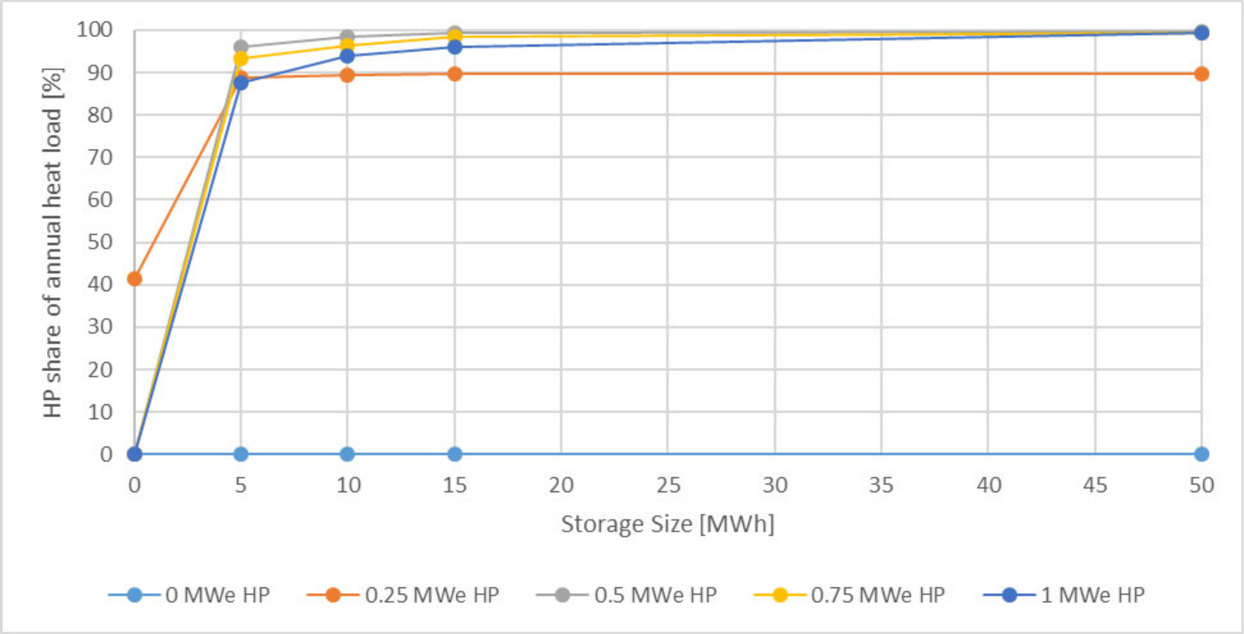

Figure 14: Production share of HPs in BBDH with sizes ranging from 0 to 1 MW$_e$ for storage sizes ranging from 5 to 50 MWh. The storage corresponds to between 8 and 80h of average load. Thermal HP capacity varies according to temperatures but the COP is restricted to maximum 5.

When operated with an electric boiler, it is clear that the HP dominates, and that increasing storage sizes enables the HP to reach higher production shares. The marginal value of increasing the storage beyond 5 MWh is characterised by a diminishing return situation though.

The operational expenditures (variable operation and maintenance and electricity costs) follow the HP production share; the higher the HP production share the lower the operational expenditures as shown in Figure 15. Thus, if investments have been made in storage and HP, then the storage will be used.

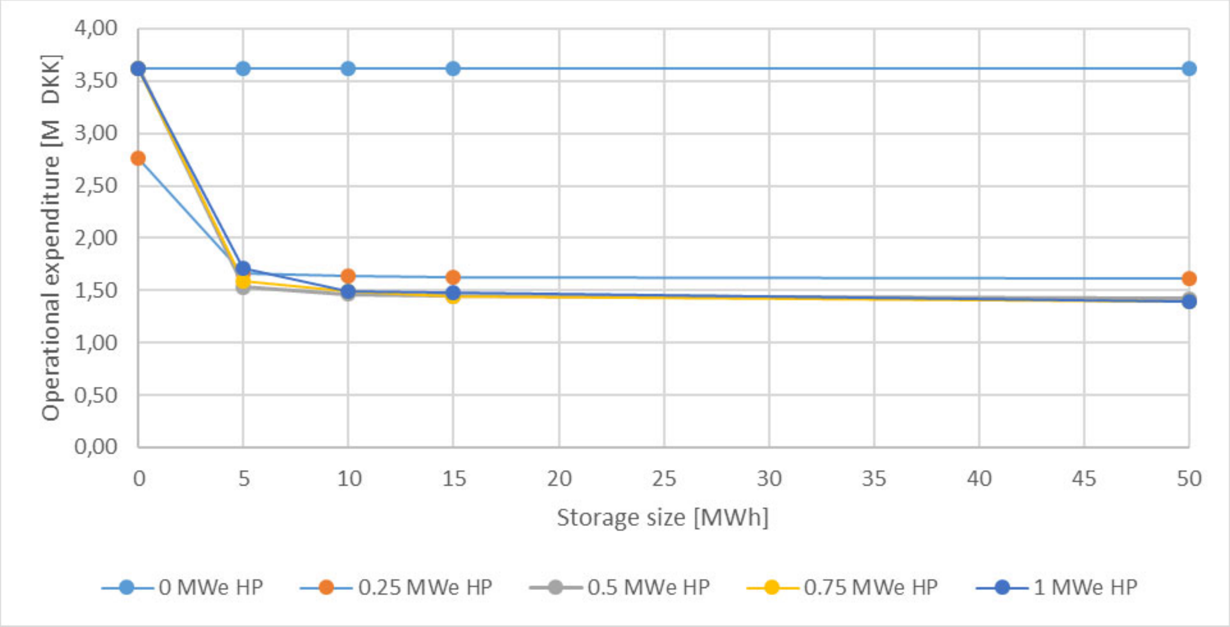

Figure 15: Operational expenditures for BBDH as function of HP and heat storage size under the same conditions given in Figure 13.

Factoring in investment costs and fixed operation costs as relevant for an investment decision however shows that the optimum is around 10-15 MWh of thermal storage capacity - which is barely discernible in Figure 16. This corresponds to 16 to 24h of average thermal output from the production units or 7 to 10h at maximum yearly load. This means that the HP – thermal storage combination only renders limited flexibility when an investment configuration is optimised. When optimising according to the business economic feasibility of the plant, only limited investments in storage are carried out while on the other hand Figure 5 demonstrates that larger storage sizes have a positive impact on the system’s ability to integrate locally produced fluctuating renewable electricity production.

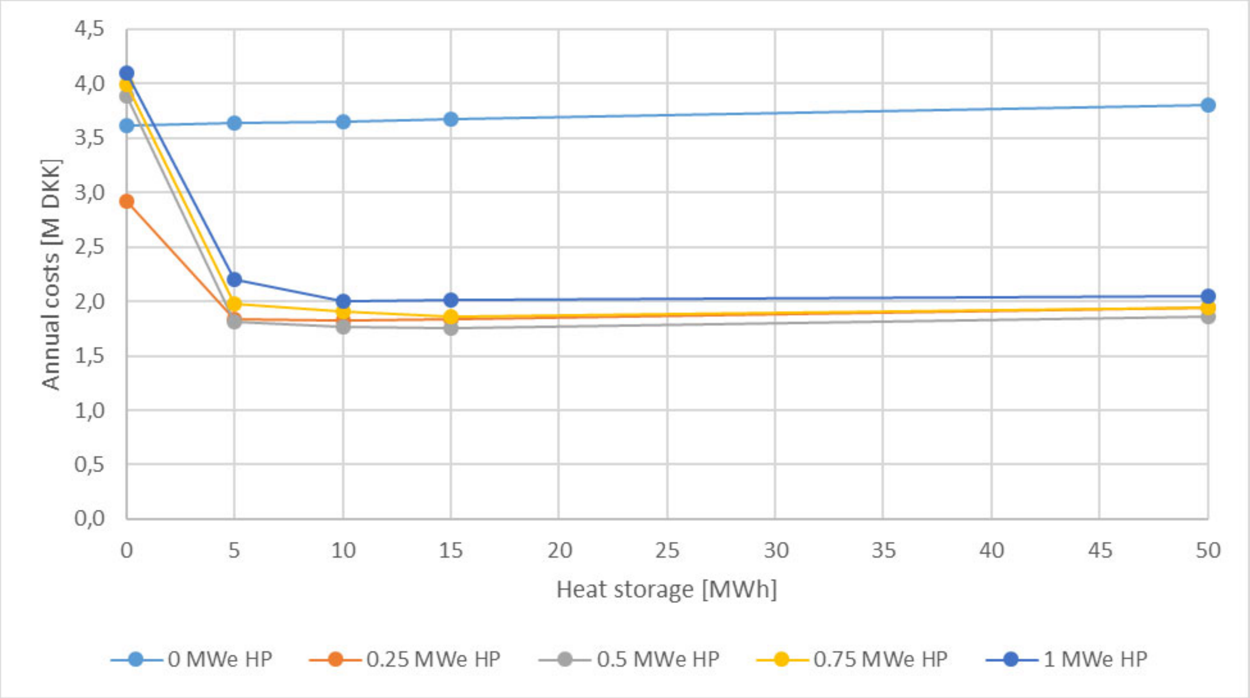

Figure 16: Total annual costs (operational expenditures, annualized investment costs and fixed operation and maintenance) for BBDH as a function of HP and heat storage size under the same conditions given in Figure 12. Based on technical life-times of 25 years for the HP and 30 years for the heat storage. Annualized investment costs and fixed operation and maintenance costs for the electric boiler are not included. These are identical across scenarios.

6 CONCLUSIONS

Heating systems need to adapt to renewable energy sources, and biomass resources should be reserved for purposes where a storable fuel is pertinent or where a carbon source is required for the production of synthetic fuels. Heating systems thus need to convert to renewable energy sources that are typically of a fluctuating nature.

At the same time, DH systems have the ability to assist in the integration of fluctuation renewable energy sources, exploiting the circumstance that storage is cheap in DH system as opposed to within electricity systems.

Using the island Samsø as a case, this article has demonstrated how HP-based DH systems combined with heat storage can assist Samsø in utilising wind power locally and free biomass resources for other purposes. With an aim to be a truly 100% renewable energy-based island, importing and exporting large amounts of electricity is not an example that can be followed by other areas in the future.

Meanwhile, business economic analyses show that while the HP / heat storage combination is interesting from an overall systems side where focus is on various societal aspects, only limited HP and storage capacity is feasible from a business economic perspective.

Also, in a system with HPs, storage and a straw boiler, the HP will not be economically feasible to operate during most of the winter and only becomes feasible due to the higher COP value during the summer. Thus, the straw boiler will outcompete the HP.

If the straw boiler is not available and an electric boiler is introduced as backup to the HP, then the HP will cover most of the heat demand. In the analyses, partial load operation was disallowed, thus production was limited by the availability of a demand or of a storage. With these design choices, the results indicated that on the one hand it does not pay to invest in much overcapacity – which would be required to make full use of excess power generation during the hours this occurs – and on the other hand it does not pay to invest in much storage capacity. In fact, storage is only relevant up to a size of 24 hours' of production – and far less than what was interesting from the island perspective when factoring in other aspects. Thus, there is a misalignment between what is relevant from a societal perspective and from a plant operator perspective that needs to be overcome.

Acknowledgements

This paper presents work that is supported by the ERA-Net Smart Grids Plus through the project MATCH (Markets – Actors – Technologies: A comparative study of smart grid solutions) as well as by the Horizon 2020 research programme through the project SMILE (Smart Island Energy systems) under grant agreement no. 731249. The article is based on a manuscript first presented at the 13th conference on Sustainable Development of Energy, water and Environment Systems (SDEWES) held in Palermo, Italy, September 30th – October 4th 2018.

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