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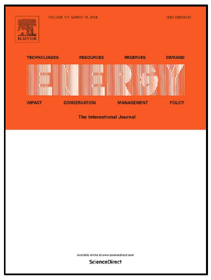

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Dynamic exergoeconomic analysis of a heat pump system used for ancillary services in an integrated energy system

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Keywords: Dynamic exergoeconomic analysis, integrated energy systems, heat pump, flexibility, ancillary services

Abstract

The integration of different energy sectors, such as the electricity and heating sector, is an effective way to integrate large shares of renewable energy into the energy system. Heat pumps allow efficient heat production based on electricity. As such, they may be used to provide two different services - the generation of heat and the provision of demand flexibility as ancillary services for the power system. The paper presents a method to assess the impact of providing demand flexibility on the performance of the conversion system based on a dynamic exergoeconomic analysis. A way to allocate the cost of heat and flexibility products based on the difference in exergy destruction was proposed. The method was applied to a case of a groundwater-source heat pump system supplying a district heating island system. It was found that providing demand flexibility causes higher exergy destruction, mainly due to heat losses during storage and the need to reheat the fluid using an electric heater. The major part of the additional exergy destruction was not related to heat pump regulation. When providing flexibility the overall cost of the system increased and according to the proposed allocation, demand flexibility accounted for 12 % of the overall cost.

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1 Introduction

The future Danish energy system will be characterized by high shares of transient renewable power production [1]. One of the main challenges imposed by this is to design future energy systems to be able to balance high shares of fluctuating power and to achieve an efficient use of the energy available. This challenge may be met by integrating the power, heating and mobility sectors. Synergies can be exploited, and it is expected that it will be possible to allocate higher shares of renewable energy, increase the overall energy efficiency of the system and help to ensure a reliable and resilient energy system [2].

The heating sector can absorb large amounts of electricity and additionally offers the possibility to store the energy as heat in heat storages, buildings and district heating systems [3]. Different technologies are available to couple the heating and electricity sector by converting one energy form into another, such as heat pumps and electric heaters. Mathiesen and Lund [4] found that large scale heat pumps are especially promising to efficiently integrate large amounts of renewable energy into the system. However, the ability and limitations of large heat pumps to provide demand flexibility need further investigation [5].

In this study, we focus on the integration between the heating and the power system by analyzing a heat pump system supplying a district heating island system. Further, the system acts as a controllable load in the power system, i.e. the heat pump electricity consumption changes according to signals from the power system operator [6]. Previous studies showed that the integration of the electricity and the heating sectors offers the possibility to decouple electricity supply and demand constraints and can provide balancing service to the power sector [7]. Stinner et al. [8] confirmed that balancing services from lower voltage levels are necessary in energy systems with a high share of renewables to balance the distribution and transmission grids. Further, controlling the load of heat pumps flexibly can reduce

CO_2 emissions and lower CO_2 abatement cost, while the overall electricity consumption may increase [9].

The considered conversion system provides two different products – the heat supplied to the district heating grid and the ancillary service to the electricity grid. This has several consequences for the operation of the heat pump. Firstly, the operation strategy has to take the demand of heat and power regulation into consideration. Secondly, the ability to provide flexibility comes at the cost of increased investment cost for a larger conversion system. Thirdly, the flexible operation leads to additional losses in the conversion system. The three consequences open for investigations of the valuation of the different products and the additional cost of flexible operation.

Ulbig & Andersson define the operational flexibility of a power system as the technical ability of a power system to modulate the power feed-in or load over time [10]. Extending this definition to integrated energy systems, we propose to define flexibility as the technical ability of a energy conversion system to adapt the power feed-in, load or conversion into other forms of energy in order to optimize security of supply, cost and/or environmental impact of the overall energy system.

Different studies have been carried out in an effort to determine the value of flexibility provided by heat pumps and electric heaters. Three general approaches were identified.

The first approach is to define an average flexibility value by considering the differences between supply and demand [7], [11], [12]. This approach is based on the idea that the unit that adapts to the state of the system, and thus decreases the difference between supply and demand, provides a balancing service to the system.

The second approach takes the specifications regarding ramping rates and capacities of the different components into consideration. In this way it evaluates the actual potential of a component to react to regulation needs of the system at a certain point in time with respect to the current state of component operation [10-12].

The third approach is to evaluate the flexibility of a unit by evaluating the cost effectiveness of an increase of flexibility. Blarke & Lund [15] defined the cost effectiveness of the storage or relocation option as the shadow cost associated with increased flexibility of a certain unit. Meibom et al. [16] propose to evaluate the impact of heat pumps and electric boilers according to their influence on the price of regulating power.

All these approaches value flexibility according to the benefit of the power system or of the overall energy system. However, it is important to assess which cost is associated with providing ancillary services for the heat pump system operator, as this is valuable information when deciding on the operation strategy and the system design. The analysis of the actual changes induced to the conversion system and the associated costs requires a more detailed method than suggested by the above references.

In the present study, the performance of a conversion system was analyzed using an exergoeconomic approach. A dynamic model of the system was simulated and a dynamic exergoeconomic analysis was conducted in order to reveal the exergy destruction connected to the flexible operation of the system and where and when it occurs. The method of exergoeconomic analysis is a combination of an exergy analysis and economic principles and is used to obtain information about how to design and operate energy conversion systems in a cost-effective way [17]. It enables the allocation of cost to multiple products of any energy conversion plant based on a framework that consistently connects economics and thermodynamics. Usually, an exergoeconomic analysis is conducted assuming steady state processes. Sayadi et al. [18] conducted a dynamic exergy and exergoeconomic analysis for a building envelope. Sangi et al. [19] presented an approach, to conduct a quasi-dynamic exergoeconomic analysis by analyzing the result of each time step for a dynamic simulation of a building heating system.

In this paper, we used a dynamic exergoeconomic analysis to assess the system performance. The method is extended by the definition of exergy fuel and exergy product for the stratified storage tank and an approach to allocate the cost to both products of the system – heat and demand flexibility. In section 2 we describe the method, including a description of the case study, the mathematical model, exergy and exergoeconomic analysis. Section 3 presents the results found for the case study and section 4 discusses the results and the method that was used. Finally, in section 5 the conclusions are presented.

2 Method

The paper presents an approach to use dynamic exergoeconomic analysis to assess the performance of a conversion unit in an integrated energy system. Further, we propose a way to allocate the cost between heat and demand flexibility. The method is applied to a case presented in the following.

2.1 Case study

The case studied was a district heating island system that was designed for the Ocean Quay cruise ship terminal in Copenhagen. The system was designed to supply three terminal buildings and a large warehouse with heat for space heating and domestic hot water. The heat pump replaced the formerly implemented oil burners and has a nominal capacity of 800 kW. Figure 1 shows a sketch of the described system and all water and electricity flows in the system. The heat source for the heat pump was groundwater delivered by the groundwater (GW) pump. Further, the system comprised a stratified storage tank of 120 m^3, a district heating (DH) pump and two electric boilers of 100 kW each. The heat demand, including distribution losses, was lumped into a heat demand model and it was assumed that the heat pump system should supply a constant temperature of 70 °C into the DH grid (Stream 8 in Figure 1). Table 1 summarizes the capacity of the components used in the assessed case.

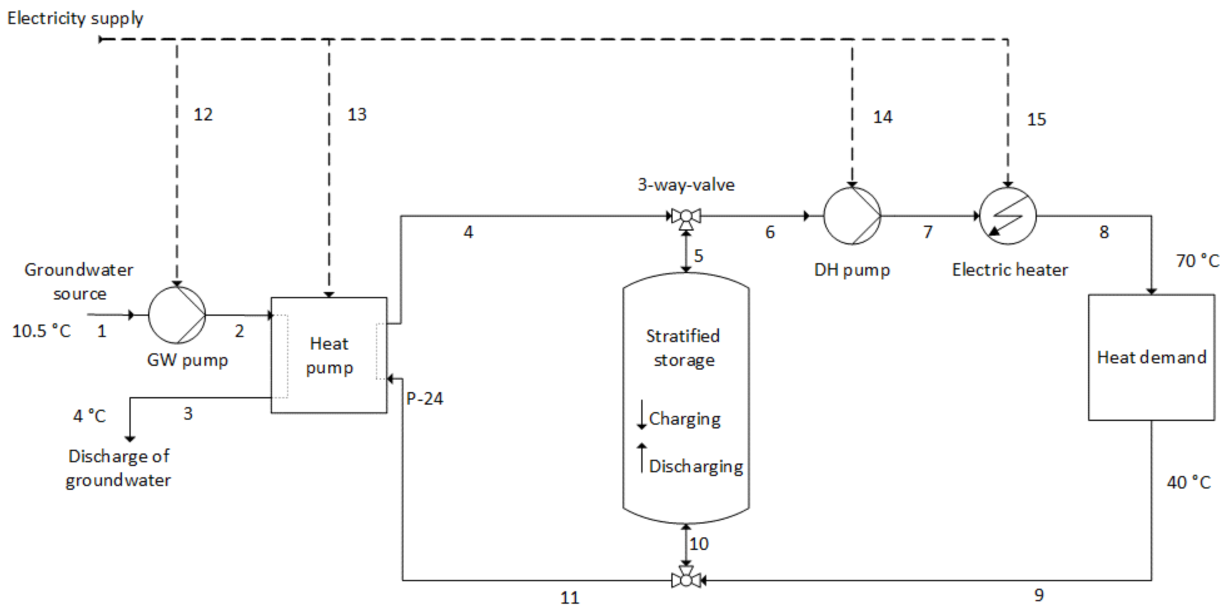

Figure 1 Sketch of the considered heat pump system in, Copenhagen, solid lines – water, dashed lines – electricity

Table 1 Specification of units in the considered system

Unit	Capacity
Heat pump minimum heating capacity	150 kW
Heat pump nominal heating capacity	800 kW
Electric boiler capacity	$2 \cdot 100$ kW
District heating pump design flow	$2 \cdot 16.7 \frac{kg}{s}$
Groundwater pump design flow	$2 \cdot 44.3 \frac{kg}{s}$
Stratified Storage tank	$120\ m^3$

To compare the results on an energy basis we defined the seasonal heat pump COP and the seasonal system coefficient of performance (SCOP) as

$$\mathrm{COP}_{\mathrm{season}} = \frac{Q_{\mathrm{heat}}}{W_{\mathrm{HP}}} \tag{1}$$

$$\mathrm{SCOP}_{\mathrm{season}} = \frac{Q_{\mathrm{heat}}}{\sum_{k} W_{\mathrm{k}}} \tag{2}$$

where Q_{heat} denotes the annual amount of heat delivered into the DH network, W_k is the annual amount of electric energy supplied to component *k and accordingly* W_{HP} *is the annual amount of electric energy supplied to the heat pump.*. In the sum all electrical components, i.e. the heat pump, the electric heater, the groundwater pump and the DH pump were considered.

2.2 Model

The model was formulated in Modelica [20] and implemented in Dymola [21]. It contained seven main component models representing a heat pump, an electric boiler, a stratified storage tank, two pumps, a lumped heat demand model, two three-way-valves and a central control unit. Models for the heat demand, the heat pump, the control unit and stratified storage tank are further described below. All models were based on energy, mass and impulse balance equations. When not indicated differently, pressure losses were neglected. The pump model was adapted from an existing model from the TIL library [22]. The pump efficiency was implemented as a quadratic function, obtained from manufacturer's data [23,24].

Heat demand model

The heat demand model was a simplified model of the demand side of the system. It included the accumulated demand of all buildings and the heat losses in the distribution system. The demand was measured demand data of the system on hourly basis for the year 2012 [25]. In practice, the heat demand would be forecasted and the operation schedule of the day ahead would be optimized. However, for the current study a simplified approach was chosen. Based on the demand data, the required mass flow for each time step was calculated which was used to control the district heating pump supplying the network. It was assumed that the building substations are designed to cool the district heating water to a constant return temperature of 40 °C (Stream 9 Figure 1). The actually supplied heat was calculated from an energy balance in the model. The system pressure loss was estimated to be at 3 bar, independently of the flow.

Heat pump model

The heat pump was a two stage ammonia heat pump with open intercooler. It was equipped with a piston compressor, which was controlled via a variable frequency drive. Brackish groundwater at 10.5 °C was the heat source. It was assumed that the groundwater can be cooled to 4 °C before being discharged into the sea.

A dynamic energy balance for the heat pump was used to describe the model.

$$\frac{dQ_{HP}}{dt} = \dot{Q}_{eva} + \dot{W}_{HP} + \dot{Q}_{con} \quad (1)$$

The term $\mathrm{dQ_{HP}/dt}$ represents the changed heat flow due to inertia in the heat pump. $\dot{Q}_{\mathrm{eva}}$ is the heat flow in the evaporator, $\dot{W}_{\mathrm{HP}}$ is the power uptake of the compressor and $\dot{Q}_{\mathrm{con}}$ represent the condenser heat load.

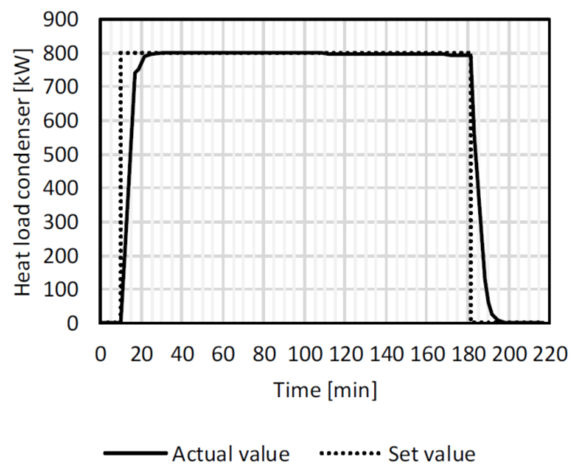

Figure 2 Steady state set value and actual value of condenser heat load for start-up and shut-down

The heat pump is implemented as a black box. Thus, a function for the actual heat output from the condenser during load changes was implemented to represent the dynamic start-up and load changing characteristics of the heat pump. Full heat production is not available during start-up compared to an theoretic instantaneous start-up, and heat will still still be rejected after shut-off of the compressor (Figure 2). It was assumed that the dynamic heat load at the condenser follows a first order characteristic, which was included as function for the actual heat load $\dot{Q}_{\text{con}}$ into the model.

$$\frac{d\dot{Q}_{\text{con}}}{dt} = \begin{cases} k_1 \cdot \left(\dot{Q}_{\text{con,ss}} - \dot{Q}_{\text{con}}\right) & \text{for } \left(\dot{Q}_{\text{con,ss}} - \dot{Q}_{\text{con}}\right) > 0 \text{ (ramp – up)} \\ k_2 \cdot \left(\dot{Q}_{\text{con,ss}} - \dot{Q}_{\text{con}}\right) & \text{for } \left(\dot{Q}_{\text{con,ss}} - \dot{Q}_{\text{con}}\right) \leq 0 \text{ (ramp – down)} \end{cases} \tag{2}$$

The parameters $k_1 = 0.0016$ and $k_2 = 0.0018$ were chosen to represent a start-up time of 15 minutes and a shut-down time of 20 minutes. The term $\dot{Q}_{\text{con,ss}}$ represents the condenser heat load in steady state, which was calculated from the coefficient of performance (COP) in steady state. It was assumed that COP in steady-state depends solely on the sink and source temperatures and a given exergy efficiency ϵ_{ss} [26].

$$\text{COP}_{\text{ss}} = \left(1 - \frac{T_{m,\text{source}}}{T_0} * \left(\frac{1}{\epsilon_{\text{ss}}} * \left(\frac{T_0}{T_{m,\text{sink}}} - 1\right) + 1\right)\right)^{-1} \tag{3}$$

$$T_{m,i} = \frac{T_{\text{out},i} - T_{\text{in},i}}{\ln\left(\frac{T_{\text{out},i}}{T_{\text{in},i}}\right)} \tag{4}$$

$$\dot{W}_{\text{el,HP}} = \frac{\dot{Q}_{\text{con,ss}}}{\text{COP}_{ss}} \tag{5}$$

$T_{m,i}$ is the logarithmic mean temperature and T_0 is the reference state temperature. ϵ_{ss} represents the steady-state exergy efficiency of the heat pump. It was assumed to have a constant value of 0.5. The part-load COP of a frequency controlled heat pump would typically increase for decreasing load, reaching a maximum at approx. 50 %[27]. However, we assumed constant part load efficiency.

The resulting actual COP was calculated from the condenser heat load and the power uptake.

$$\text{COP} = \frac{\dot{Q}_{\text{con}}}{\dot{W}_{\text{HP}}} \tag{6}$$

The model further included energy, mass and impulse balance (no pressure loss) equations for the evaporator and the condenser. The heat pump was controlled according to the desired heat output at the condenser using an external control unit.

Control unit

The described system was controlled using a central control unit, which contained the algorithm according to which the heat pump, the three-way-valve, the pumps and the electric heater were controlled. Via the three-way-valve at the top of the stratified storage tank the charging and discharging of the tank was controlled, by setting a value for the ratio between the flow into the storage and the flow from the HP. The pumps were controlled to deliver the necessary mass flow to the heat demand model and the heat pump, respectively. The electric heater heated the DH supply flow to 70 °C if the temperature supplied was lower.

The operation of the heat pump was based on a simple, heuristic approach, which does not utilize variations in the electricity price, but is only based on the heat demand, the state of the storage and a regulation signal. This approach was chosen to focus on the effect of the provision of ancillary services for the electricity system. The algorithm changed the mode of operation of the system according to up- and down regulation signals, which were taken from data of hourly realized up- and down-regulation from the Transmission System Operator Energinet.dk's market data from 2012 [28]. The model does not include the prices for regulating power, but aims at quantifying the true cost of providing this. The results may be compared to the actual prices in the regulating market.

The up- and down regulation signals from Energinet are based on the generation side, i.e. an up-regulation signal means that the current demand is too high. The heat pump would react to this by reducing the power uptake. Accordingly, a down regulation signal would cause the heat pump to switch to full load.When the storage level and the current heat demand allowed for variation of the heat pump load, the heat pump was ramped up to full load in case of a down-regulation signal and shut-off for an up-regulation. This was done using a PI-controller ($k = 0.08$, $\tau = 50\ s$) where the desired heat output was the set value, the actual heat load was the input and the power uptake of the compressor was the output signal. In practice, the load of the heat pump could be increased or reduced to another value than full load or no production. However, the considered heat pump is small in terms of its electricity regulation ability and would have to be aggregated to actually act on the regulation market. Therefore, we chose to only consider the maximum provision of regulation power. Figure 3 shows a flow diagram of the control algorithm for flexible operation. If no regulation signals were considered, the algorithm would follow only the left branch (regulating signal: none). The different paths of the algorithm ended up in 4 different operation modes for the heat pump:

- HP part load = heat demand: The heat pump is operated in part load according to the heat demand.

- HP off: The heat pump is shut-off or remains off.
- HP minimum load: The heat pump is operated at lowest part load (150 kW).
- HP maximum load: The heat pump is operated at full load.

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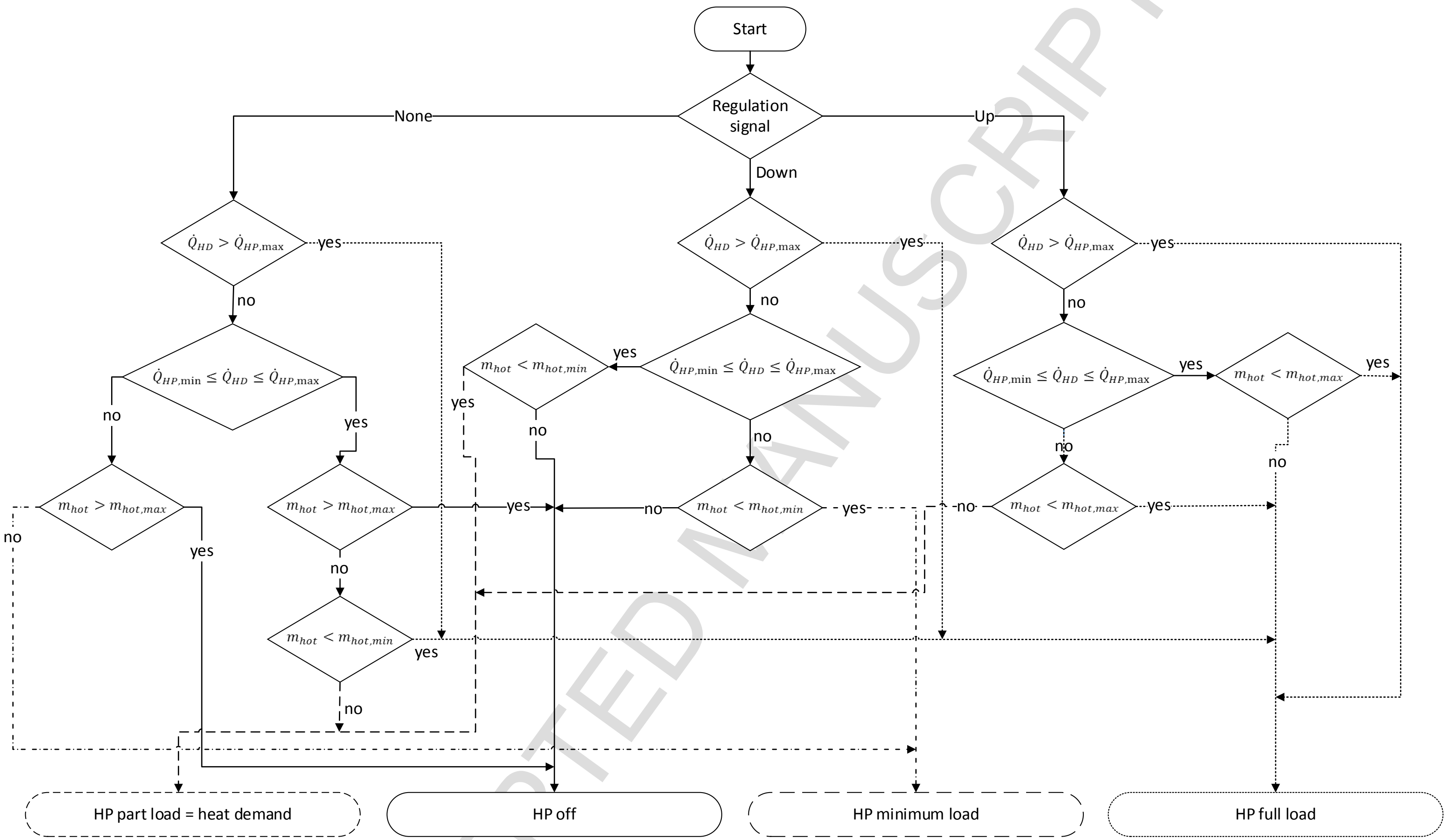

Figure 3 Structure of control algorithm for flexible operation. HD- Heat demand, HP_min/max – Heat pump minimum load/ full load, m_hot – mass of hot water in the storage, m_hot_min/max – minimum/maximum mass of hot water in the storage, HD – Heat demand.

Stratified storage tank

The stratified storage tank was modelled using a one dimensional discretization [29] (Figure 4). The tank was divided into 100 layers from top to bottom. For each layer dynamic mass and energy balances were solved. It was assumed that the fluid inside each layer was ideally mixed and thus had constant properties. Heat losses to the environment and between layers were considered. Pressure differences across the tank were neglected as well as increased mixing between the layers during charging and discharging. The minimum and maximum amount of hot water is limited by the inlet design and was assumed to be 1/12 and 11/12 of the total stored mass, respectively.

2.3 Exergy analysis

As reference state the groundwater temperature $(T_0 = 10.5\ °\mathrm{C})$ at atmospheric pressure ($p_0 = 1.013\ \mathrm{bar}$) was chosen. The groundwater temperature was assumed to be constant throughout the year. All material streams were assumed to be water and no reactions occur at any place in the system. So, the chemical exergy would be equal for all streams and can be neglected [17].

To conduct the exergy analysis of the system, balance equations were formulated for all components. The balance equation for a general control volume can be formulated as

$$\frac{dE}{dt} = \sum_i \dot{m}_i \cdot e_i + \sum_j \dot{E}_{Q,j} + \sum_l \dot{W}_l - \dot{E}_L - \dot{E}_D \quad (7)$$

where *E* is the exergy content of the control volume, the first sum denotes the exergy content of the material streams entering and exiting the control volume which is calculated as the product of mass flow $\dot{m}$ and specific exergy e. The second sum is the sum of all exergy flows related to heat flows $\dot{E}_{Q,j}$ and the third sum considers power flows $\dot{W}_l$. $\dot{E}_L$ is the exergy loss to the environment and $\dot{E}_D$ denotes the exergy destruction within the control volume. All entering flows are accounted as positive by sign convention.

For the exergy analysis, exergy fuel and product were defined for all components (Table 2). The exergy efficiency of every component can be calculated according to:

$$\epsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \tag{8}$$

Table 2 Exergy fuel and -product and specific cost per unit of exergy fuel and product for the components used in the case study. Charging and discharging refer to charging/discharging of the storage tank. When there is no flow in or out of the tank, the equations for discharging are valid.

	Exergy fuel $\boldsymbol{\dot{E}_{F,i}}$/ Specific cost per unit of exergy fuel $\boldsymbol{c_F}$	Exergy product $\boldsymbol{\dot{E}_{P,i}}$/ Specific cost per unit of exergy product $\boldsymbol{c_P}$	Auxiliary equations
Heat pump	$\dot{E}_F = \begin{cases} \dot{W}_{13} + \frac{dE_{HP}}{dt} & :\text{if } \frac{dE_{HP}}{dt} < 0 \\ \dot{W}_{13} & :\text{else} \end{cases}$ $c_F = c_{\text{el}}$	$\dot{E}_P = \begin{cases} \dot{E}_4 - \dot{E}_{11} + \frac{dE_{HP}}{dt} & :\text{if } \frac{dE_{HP}}{dt} > 0 \\ \dot{E}_4 - \dot{E}_{11} & :\text{else} \end{cases}$ $c_P = \frac{\dot{C}_4 - \dot{C}_{11}}{\dot{E}_4 - \dot{E}_{11}}$	$c_3 = c_F$
3-way-valve	$\dot{E}_F = \begin{cases} \dot{E}_4 & :\text{charging} \\ \dot{E}_4 + \dot{E}_5 & :\text{discharging} \end{cases}$ $c_F = \begin{cases} \frac{\dot{C}_4}{\dot{E}_4} & :\text{charging} \\ \frac{\dot{C}_4 + \dot{C}_5}{\dot{E}_4 + \dot{E}_5} & :\text{discharging} \end{cases}$	$\dot{E}_P = \begin{cases} \dot{E}_5 + \dot{E}_6 & :\text{charging} \\ \dot{E}_6 & :\text{discharging} \end{cases}$ $c_P = \begin{cases} \frac{\dot{C}_5 + \dot{C}_6}{\dot{E}_5 + \dot{E}_6} & :\text{charging} \\ \frac{\dot{C}_6}{\dot{E}_6} & :\text{discharging} \end{cases}$	$c_5 = c_6$ (for charging)
DH Pump	$\dot{E}_F = \dot{W}_{14}$ $c_F = c_{\text{el}}$	$\dot{E}_P = \dot{E}_7 - \dot{E}_6$ $c_P = \frac{\dot{C}_7 - \dot{C}_6}{\dot{E}_7 - \dot{E}_6}$	
GW Pump	$\dot{E}_F = \dot{W}_{12}$ $c_F = c_{\text{el}}$	$\dot{E}_P = \dot{E}_2 - \dot{E}_1$ $c_P = \frac{\dot{C}_2 - \dot{C}_1}{\dot{E}_2 - \dot{E}_1}$	
Electric heater	$\dot{E}_F = \dot{W}_{15}$ $c_F = c_{\text{el}}$	$\dot{E}_P = \dot{E}_8 - \dot{E}_7$ $c_P = \frac{\dot{C}_8 - \dot{C}_7}{\dot{E}_8 - \dot{E}_7}$	
Stratified storage tank	$\dot{E}_F = \begin{cases} \dot{E}_5 & :\text{charging} \\ \frac{dE_{\text{hot}}}{dt} & :\text{discharging} \end{cases}$	$\dot{E}_P = \begin{cases} \frac{dE_{\text{hot}}}{dt} & :\text{charging} \\ \dot{E}_5 & :\text{discharging} \end{cases}$	$c_{10} = \frac{C_{\text{cold}}}{E_{\text{cold}}}$ (for charging)

$$c_F = \begin{cases} \dot{C}_5 & \text{:charging} \\ \frac{dC_{\text{hot}}}{dt} & \text{:discharging} \end{cases} \qquad c_P = \begin{cases} \frac{dC_{\text{hot}}}{dt} & \text{:charging} \\ \dot{C}_5 & \text{:discharging} \end{cases}$$

Heat pump

The exergy efficiency of the heat pump was defined as the increase of exergy of the DH water in the condenser over the power input into the compressor. As the groundwater was cooled down from the reference state temperature in the evaporator, it's exergy content increased. However, the cold stream was not a useful product in this case as it was discharged into the environment and represented an exergy loss of the system. A cost can be assigned to the exergy loss by assuming that the exergy loss is covered through the supply of a corresponding amount of fuel (auxiliary equation) [30].

Three-way-valve

The three-way-valve controlled the mass flow to and from the stratified storage tank. The exergy fuel and product were different during charging or discharging of the tank. The purpose of mixing in the three-way-valve was to vary between two different heat sources (the heat pump and the storage) and not to heat up the stream from the storage using the stream from the heat pump. Thus the above definition of exergy fuel and product is chosen [17].

Stratified storage tank

To define the exergy fuel and product of the stratified storage tank, the tank was divided into a hot and a cold control volume (Figure 4). We assumed that the purpose of the tank is to store hot water, and that the cold water is only used to fill up the tank volume that is not used by the hot water. Both control volumes were thus variable in size and additional mass balances for the control volumes are needed.

$$m_{hot} + m_{cold} = \bar{\rho} \cdot V_{storage} \tag{9}$$

$$m_{hot} = \frac{N_{hot}}{N} \cdot \bar{\rho} \cdot V_{storage} \tag{10}$$

m_{hot}, m_{cold} denote the mass of the hot and cold control volumes, respectively. N_{hot} is the number of layers with hot fluid which are defined as all layers with a temperature above 60 °C, $\overline{\rho}$ is the mean water density in the storage and $V_{storage}$ is the overall volume of the storage tank. Calculating m_{hot} in the presented way, has the advantage that the mass flow from the hot to the cold volume due to decrease in temperature can be easily accounted for.

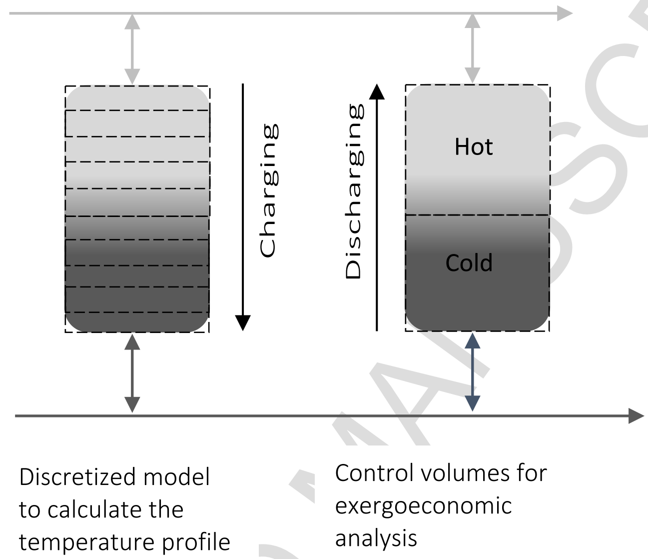

Figure 4 One-dimensional discretization of storage tank and division into hot and cold control volume

The exergy fuel during charging was defined as the exergy of the hot water coming in at the top of the tank (stream 5) and the product was the increase in stored exergy inside the hot control volume of the tank. The amount of stored exergy was calculated for both control volumes as

$$\frac{d\left(E_{hot} + E_{cold}\right)}{dt} = \dot{m}_5 \cdot e_5 - \dot{m}_{10} \cdot e_{10} - \dot{E}_D \tag{11}$$

$$E_{\text{hot}} = \sum_{n=1}^{N_{\text{hot}}} \left(m_n \cdot e_n\right) \tag{12}$$

where E_{hot}, E_{cold} denote the exergy stored in the hot and cold volume respectively. m_n is the mass and e_n the specific exergy of layer n. The volume work due to variation of the control volume size was found to be small compared to the exergy of stored heat and was neglected. The heat loss from the storage is accounted for as exergy destruction $\dot{E}_D$. Assuming that the water in the tank behaves as an ideal liquid, the specific exergy e_n for every discretization layer can be calculated from temperatures obtained from the energy balances for every control volume [31].

$$e_n = c_{p,H_2O} \cdot (T_n - T_0) - T_0 \cdot c_{p,H_2O} \cdot \ln\left(\frac{T_n}{T_0}\right) \tag{13}$$

An overall exergy efficiency for the storage was calculated as the ratio of the integrals of the output from - and the input into the hot control volume.

$$\epsilon_{storage,tot} = \frac{\int \dot{E}_{5,out}\, dt}{\int \dot{E}_{5,in}\, dt} \tag{14}$$

System exergy efficiency

The exergy efficiency of the overall system for every time step had to take the storage of exergy in the storage tank into consideration. During charging the exergy stream into the storage represented a product of the system, whereas during discharging the exergy stream out of the tank was a fuel to the overall system:

$$\epsilon_{\text{system}} = \begin{cases} \dfrac{\dot{E}_{\text{heat}} + \dfrac{d(E_{\text{hot}} + dE_{cold})}{dt}}{\sum_k \dot{W}_k} & \text{if charging} \\[2ex] \dfrac{\dot{E}_{\text{heat}}}{\sum_k \dot{W}_k + \left|\dfrac{dE_{\text{hot}} + dE_{cold}}{dt}\right|} & \text{if discharging} \end{cases} \tag{15}$$

The annual mean exergy efficiency was calculated according to the following equation.

$$\epsilon_{\text{system,tot}} = \frac{E_{\text{heat}}}{\sum_k W_k} \tag{16}$$

E_{heat} denotes the overall amount of exergy of heat supplied per year and W_k is the overall amount of electric energy of component *k* per year.

2.4 Exergoeconomic analysis

Within an exergoeconomic analysis a cost is assigned to all exergy streams. This allows to determine the cost of exergy destruction in every component, which can give useful information about the sources of costs throughout the system and how they can be lowered [17].

In order to assign a cost to every exergy stream a dynamic cost balance for every component was set up,

$$\frac{dC}{dt} = \sum_i \dot{C}_i + \sum_k c_{\text{el}} \cdot \dot{W}_k + \dot{Z} \tag{17}$$

C denotes the cost that accumulates within the component, $\dot{C}_i$ is the cost streams associated with material streams, c_{el} is the electricity cost in the respective time step and $\dot{Z}$ denotes the levelized cost stream of the component. The cost stream of the component includes investment cost, capital cost, and operation and maintenance costs for the estimated lifetime of the respective component. It was calculated as described in [17]. However, the cost was not levelized to the full load hours per year but to the actual operation hours per year and $\dot{Z}$ was only considered when the respective component was in operation. The DH network was existent and we assumed that the operation and maintenance costs are the same for any kind of heat supplying system. Thus, the costs of the DH network were neglected in the present work.

The economic data used to calculate $\dot{Z}$ is summarized in Table 3. An average annual discount rate of 4 % and a nominal escalation rate of 2 % for operation and maintenance cost was assumed [32].

The cost of electricity used in this study is historic spot market prices for Eastern Denmark 2012 from NordPool [33]. 59 DKK/MWh transmission net tariff and 24 DKK/MWh system tariff were included [33]. Administration, and trading and unbalance cost were assumed to be 3 DKK/MWh and 2 DKK/MWh, respectively.

Table 3 Economic data case study

Unit	Capacity	Total capital investment [DKK]	Plant economic life [a]	Operation hours per year [h/a]		Fixed O&M cost 1st year [DKK]	Source
				Non-flex.	flexible		
Heat pump	800 kW	560.000	25	7527	6917	3000	[34]
El. heater	200 kW	150.000	20	1233	3000	220	[34]
DH pump	2×16.7 kg/s	30.000	10	8760	8760	440	[23]
GW pump	2×44.3 kg/s	40.000	10	7527	6917	440	[23]
Storage tank	120 m^3	31.200	40	8760	8760	700	[34]
Drilling		900.000	40	7527	6917	18000	[35]

2.5 Allocation of cost

The allocation of cost to both products of the heat pump system, i.e. heat supply and provision of demand flexibility, is a central question when operating energy conversion units in an integrated energy system. The characteristics of both products are different. Heat is an output from the system and so is the related heating service. Electricity is an input into the system, but the corresponding flexibility is a service provided by the system, see Figure 5. The cost of providing flexibility is not directly connected to the electricity stream and all extra cost will be reflected in the heat generation cost. However, as the source of cost difference was not the supply of heat but the additional exergy destruction due to the provision of flexibility, the cost should be allocated accordingly. The exergy destruction related to flexible operation does not only occur at the same time as the provision of regulation power. Thus, we chose an integral approach to determine the cost related to flexible operation.

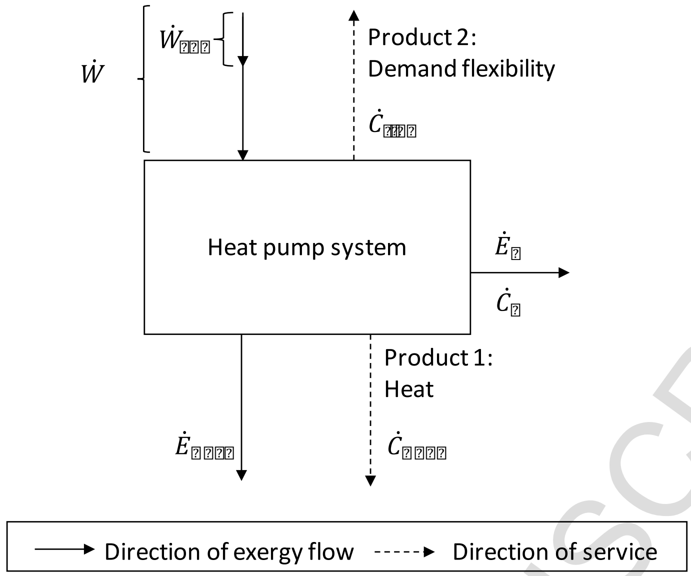

Figure 5 Direction of energy flow and product delivery for a conversion unit in an integrated energy system

As the flexibility provided to the electricity sector was not directly connected to an exergy product stream, the cost was allocated according to the increased exergy destruction due to flexible operation, which was given as the difference between the overall exergy destruction in the flexible and the non-flexible case. The specific cost per unit of exergy was calculated as:

$$c_{\mathrm{ex}} = \frac{\left(C_{\mathrm{heat}} + C_L\right)}{E_{\mathrm{heat}} + \left(E_{D,\mathrm{flex}} - E_{D,\mathrm{nonflex}}\right)} \tag{18}$$

The overall cost exiting the system is the sum of the integrated cost of heat C_{heat} and of the exergy loss C_L. E_{heat} is the integrated amount of exergy supplied as heat to the DH grid and $E_{D,\mathrm{flex}}$, $E_{D,\mathrm{nonflex}}$ is the overall exergy destruction caused during flexible operation and non-flexible operation, respectively. All values were calculated by integrating the respective cost and exergy flow rates over one year.

Knowing the overall cost related to flexible operation per year, the specific cost per unit of regulating energy W_{reg} provided can be determined.

$$c_{\text{flex}} = \frac{c_{\text{ex}} \cdot \left(E_{D,\text{flex}} - E_{D,\text{nonflex}}\right)}{W_{\text{reg}}} \tag{19}$$

In order to be able to compare different units, we also calculate the annual specific cost of flexible operation per kW installed electric capacity $\dot{W}_{\text{installed}}$.

$$c_{\text{flex, capacity}} = \frac{c_{\text{ex}} \cdot \left(E_{D,\text{flex}} - E_{D,\text{nonflex}}\right)}{\dot{W}_{\text{installed}} \cdot 8760 \cdot 3600\ \text{s/a}} \tag{20}$$

The heat generation cost is calculated from the overall cost delivered into the DH grid over the overall amount of heat.

$$c_{\text{heat}} = \frac{c_{\text{ex}} \cdot E_{\text{heat}}}{Q_{\text{heat}}} \tag{21}$$

3 Results

To calculate the performance of the system when operated flexibly the system was simulated and the exergoeconomic analysis was carried out for two different cases:

A. Non-flexible operation– the heat pump is not operated according to regulation requests from the grid, but only according to heat demand. This means the heat pump is mostly operating in part load.
B. Flexible operation according to regulatory signal – the heat pump is controlled according to the heat demand, the state of storage and a regulatory signal to provide flexibility. This control strategy was presented previously in chapter 2.2, Figure 3.

Figure 6 shows the heat load at the heat pump condenser for the non-flexible and flexible operation. The non-flexible operation followed the heat demand apart from the periods, where the heat demand was lower than the lowest allowable part load of the heat pump (150 kW). In that case, the heat pump was operated at minimum part-load until the storage was filled to the maximum, then the heat demand was supplied from the storage and the heat pump was switched off until the storage was emptied.

In the case of flexible operation the heat pump load changed frequently. When down- or up-regulation was requested, the system ramped up to full load or shut down, if possible. When there was no regulation signal, the heat load at the condenser followed the heat demand.

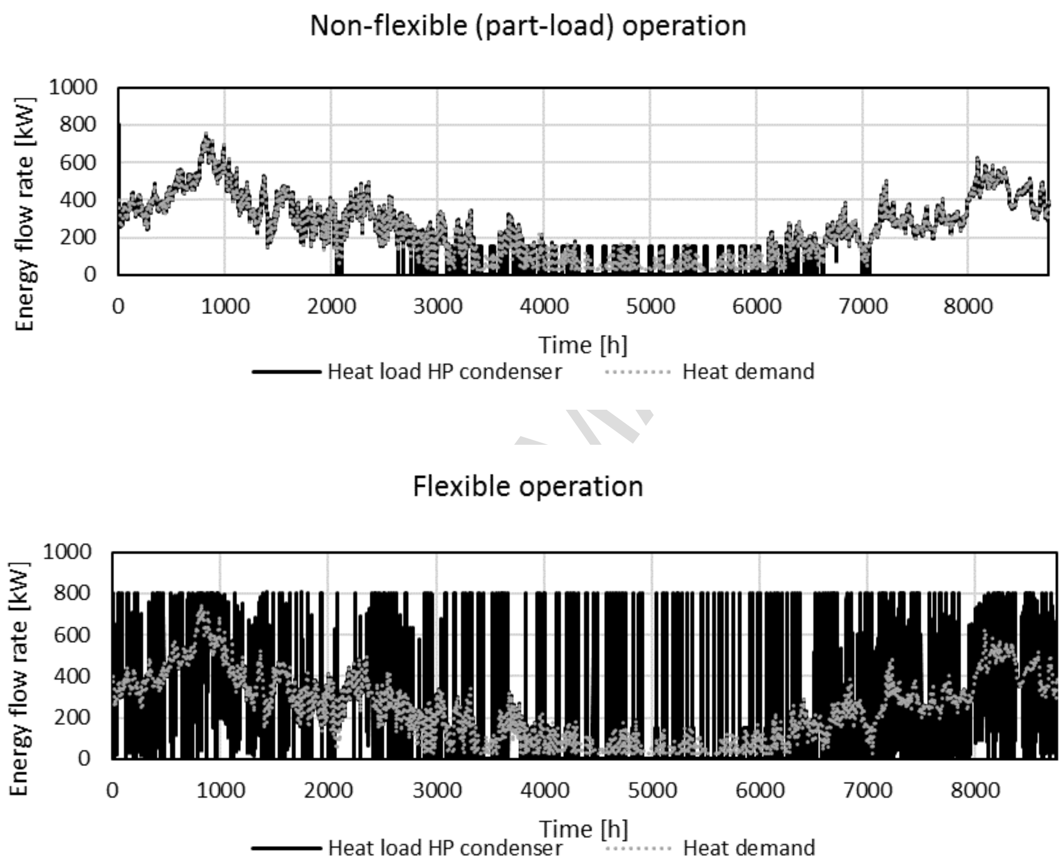

Figure 6 Heat load at heat pump condenser and heat demand for non-flexible operation and flexible operation for one year (2012)

The overall power uptake was higher for flexible operation (Table 4). This was mainly due to reheating the water from the storage in the electric heater. The electric heater consumption increased from 37 MWh/year to 85 MWh/year. The power uptake of the heat pump was slightly lower during flexible operation. The seasonal heat pump COP was the same for both operation modes, whereas the seasonal SCOP was lower for the flexible case.

The overall exergy input into the system is given as the sum of all electric energy inputs into the system. The exergy provided to the heat pump accounts for 84.5 % and 79.4 % of the overall exergy input in the non-flexible and flexible case, respectively.

Table 4 Energetic performance indicators

		Non-Flexible operation	Flexible operation
Heat pump electric energy consumption	[MWh/a]	582	577
Electric heater electric energy consumption	[MWh/a]	37	85
GW pump electric energy consumption	[MWh/a]	40	35
DH pump electric energy consumption	[MWh/a]	30	30
Total electric energy consumption	[MWh/a]	689	728
Heat supplied to DH system	[MWh/a]	2125	2125
Overall heat loss within the conversion system	[MWh/a]	5.9	41.2
Seasonal heat pump COP	[-]	3.60	3.60
Seasonal system COP (SCOP)	[-]	3.09	2.92
Exergy of heat	[MWh/a]	293	293
Total exergy destruction	[MWh/a]	360	399
Overall exergy loss	[MWh/a]	43.6	43.4
Overall exergy efficiency	[%]	42.6%	40.3%

3.1 Exergy analysis

Error! Reference source not found. shows the exergy destruction within the major components for a week in February. When the heat pump turned on, the exergy destruction in the heat pump increased rapidly and leveled out to a steady state value. The exergy destruction of the heat pump increased with the overall power input. When the heat pump turned off, the exergy destruction in the heat pump decreased to zero. The exergy efficiency peaked at these times because the heat supplied from the upper layers of the storage had a high enough temperature to supply the DH grid directly. When the temperature from the storage dropped, the electric heater was turned on to heat the supply flow to the desired temperature. The exergy efficiency decreased accordingly.

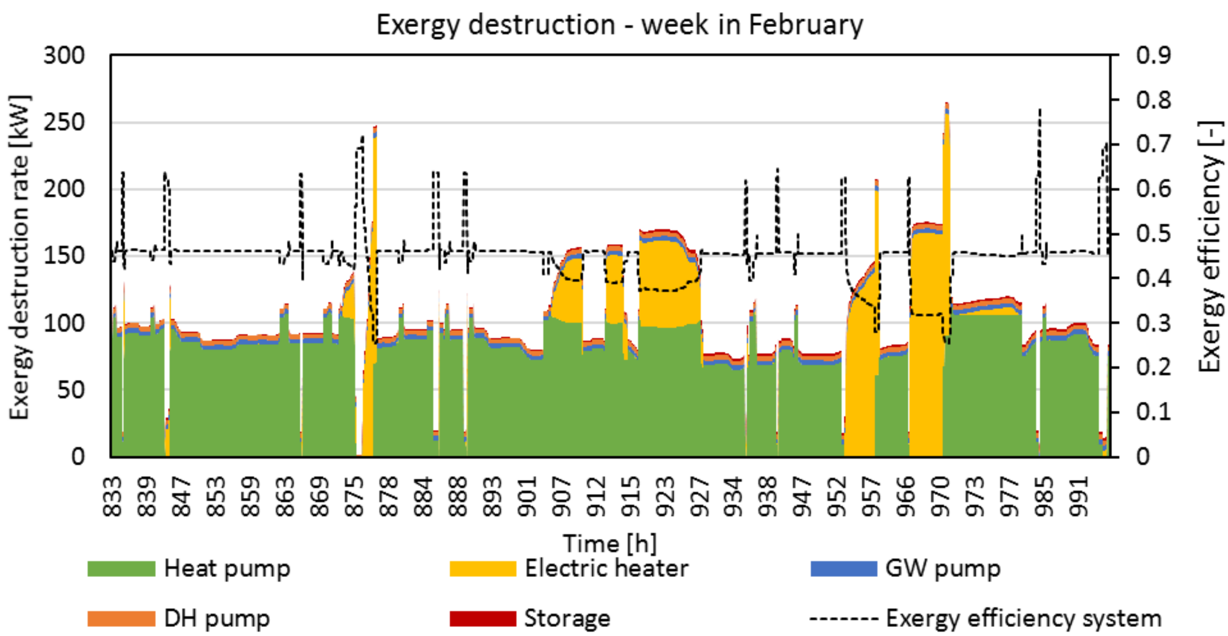

Figure 7 Exergy destruction (ED) rates during flexible operation for major components

The component exergy efficiencies are presented in Figure 8 for the same week. The heat pump exergy efficiency was constant during operation (Figure 8 (a)). Peaks only occurred during ramping and shut-off. This is due to the heat stored in the heat pump components, which is still available during shut-down.. The exergy efficiency of the electric heater is lower than the HP efficiency with approx. 17 %.

The exergy efficiency of the groundwater pump was highest when the heat pump was operated at full load, i.e. at nominal conditions. Accordingly, the exergy efficiency decreased with decreasing mass flow.

The exergy efficiency of the storage was above 90 % when the storage was charged or discharged (Figure 8 (c)). Losses from the storage also occurred when the storage was not operated. Thus, the mean exergy efficiency of the storage was calculated as approx. 86.3 %.

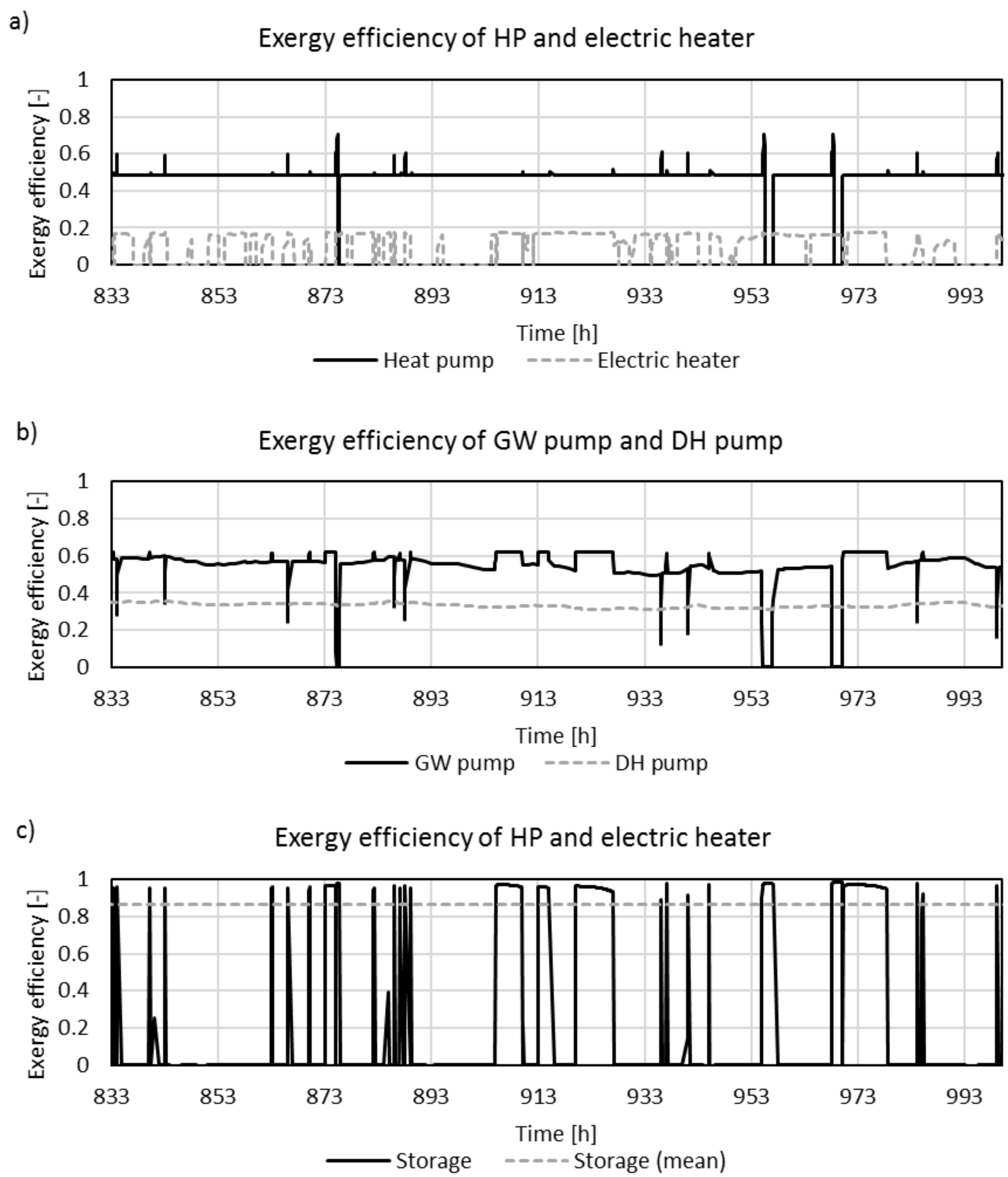

Figure 8 Exergy efficiency of major components for flexible operation

Figure 9 shows the exergy content of the storage for the first thousand hours of the year for flexible operation. The amount of exergy stored as hot water increased during charging and the exergy content of the cold water decreased accordingly. When the storage was not charged or discharged over a longer period, the exergy content decreased slowly due to heat losses.

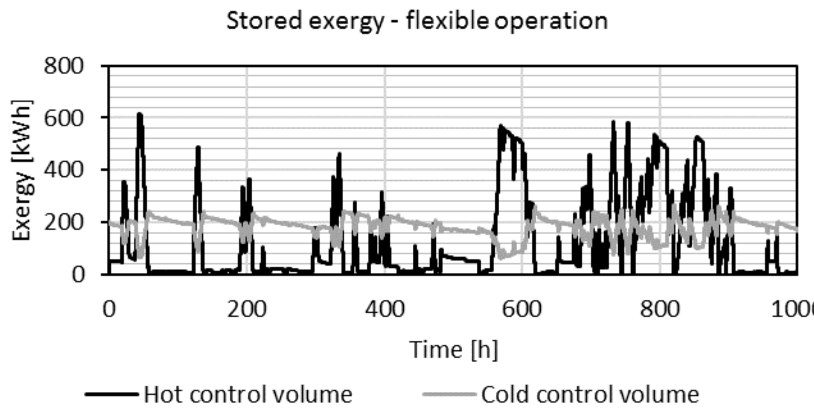

Figure 9 Exergy content of hot and cold control volume of the stratified storage tank for the first 1000 hours of the year 2012

3.2 Exergoeconomic analysis

Figure 10 shows the condenser load of the heat pump and the overall specific cost per unit of exergy that was delivered into the DH system. Further, the cost of electricity is shown. The yearly average for eastern Denmark for the year 2012 was 0.3757 DKK/kWh including the tariffs given in section 2.4.

The specific cost per unit exergy of the non-flexible operation followed the development of the electricity cost (Figure 10). In the flexible operation case, the specific cost increased when the heat pump was turned off, as the heat had to be delivered from the storage tank and reheated in the electric boiler. The flow taken from the storage tank had a higher specific cost than that fed into it due to the cost of exergy destruction in the tank and the levelized cost of the tank. The cost was accounted to the exergy stored in the warm control volume of the tank. The exergy destruction and levelized cost of the electric boiler further increased the specific cost. The specific cost did not differ significantly between the flexible and non-flexible operation while the heat pump is running. The mean specific fuel cost (spot market prices) during regulation was found to be slightly higher than the yearly average.

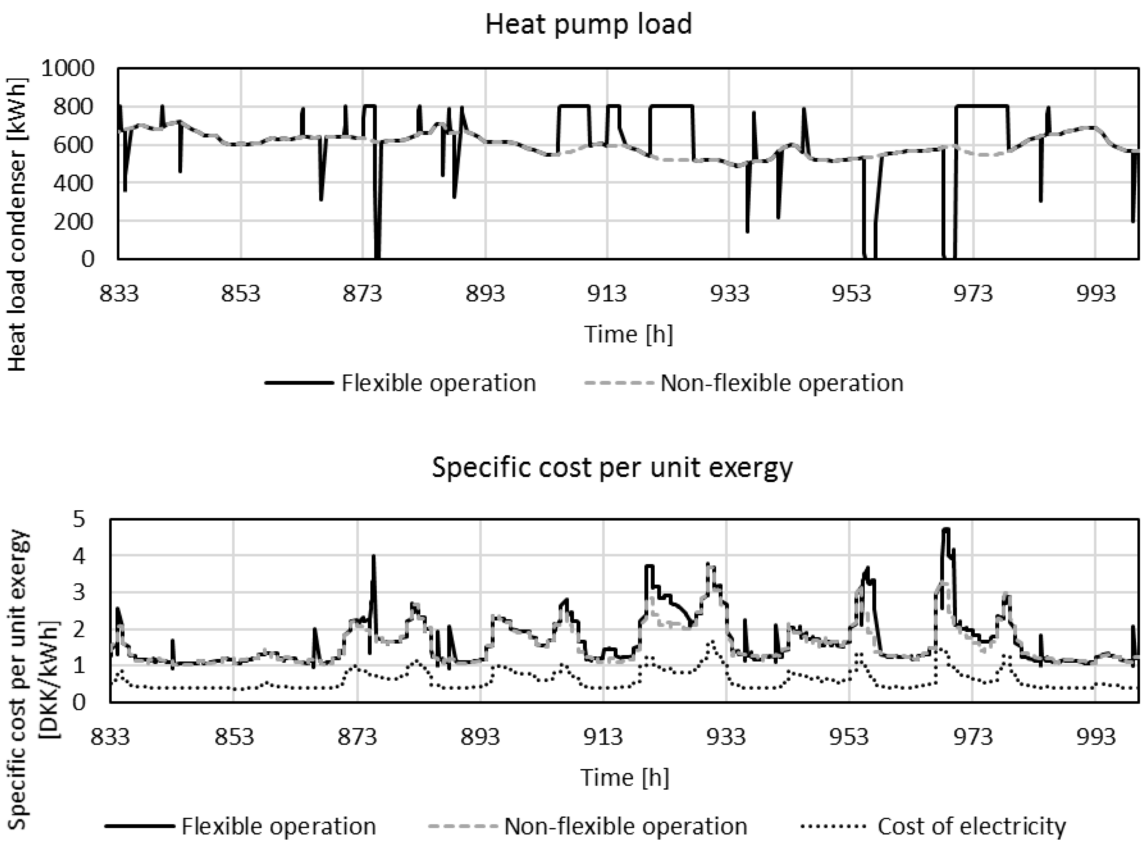

Figure 10 Heat load condenser, overall product cost for non-flexible and flexible operation and cost of electricity for a week in February 2012

The regulation energy that was available from the heat pump system is shown in Table 5. The response rate given here is the ratio between the time where the system reacted to a regulation signal and the time where the system received a regulation signal. The response rate was lower for down-regulation, while the overall regulation energy was approx. six times larger than for up-regulation.

The specific cost of heat was lower for the flexible operation compared to the non-flexible operation, as 12 % of the overall product cost were assigned to the provision of flexibility and the overall cost were reduced. The specific cost per kWh of regulation energy was 0.660 DKK/kWh. This corresponds to an annual cost of flexible operation per kW installed capacity (only heating units) of 65 DKK/kW/a. The average difference between the balancing price and the electricity spot price, i.e. the possible benefit by providing balancing services, was 0.133 DKK/kWh for down-regulation and 0.208 DKK/kWh for up-regulation for 2012 [28]. The corresponding values for 2017 were found to be even lower with 0.093 DKK/kWh for down-regulation and 0.153 for up-regulation. During individual hours the benefit of performing the service could be higher. For 2012 it was found that in 180 h out of 3101 h where balancing power was needed the benefit provided was larger than 0.660 DKK/kWh, this corresponds to 5.8 % of the hours where balancing services where provided.

Table 5 Amount of regulation energy and heat and specific cost of both products

	Non-flexible operation	Flexible operation	Flexible operation - Winter	Flexible operation - Spring	Flexible operation - Summer	Flexible operation - Autumn
Heat [MWh/a]	2125	2125	965	540	155	464
Up-regulation [MWh/a]	0	67.8	18.5	14.2	15.6	19.5
Down-regulation [MWh/a]	0	11	0.99	0.72	5.49	4.02
Response rate Down-regulation [%]	0	37%	33%	48%	34%	39%
Response rate Up-regulation [%]	0	67%	27%	69%	100%	76%
Specific heat cost [DKK/kWh]	0.219	0.184	0.168	0.181	0.303	0.186
Cost of flexibility [DKK/kWh]	0	0.660	1.079	0.830	0.018	0.695
Overall cost [DKK]	465000	443000	183000	110000	47000	102000
Overall exergy of heat [MWh]	293	293	133	75	21	64
Overall exergy loss [MWh]	44	43	20	11	3	9
Overall exergy destruction [MWh]	360	399	160	103	44	93
Additional exergy destruction [MWh]		39	17	9	0	12

The overall cost input into the system is 443000 DKK/a for flexible operation and 464000 DKK/a for non-flexible operation. 37 % and 43 % of the overall cost of flexible and non-flexible operation, respectively, are the levelized cost of operation. The remaining part is the fuel cost of the system.

The exergy destruction and the related cost are presented in Figure 11 and Figure 12. The exergy destruction of the heat pump was very similar for both scenarios. This indicates that the increased exergy destruction during load changes did not have a significant influence on the overall exergy destruction of the heat pump. The exergy destruction in the groundwater pump was lower in the case of flexible operation, due to part-load operation.

The cumulated exergy destruction in the electric boiler was higher during flexible operation compared to non-flexible operation. This is due to an increased amount of heat, which was supplied from the storage and had to be heated up to fulfill the requirement of 70 °C supply temperature. The exergy destruction in the DH pump was similar for both cases, as the heat demand, and thus the mass flow rate were the same.

The exergy destruction in the storage occurs mainly due to heat losses and is low compared to the other components. The cost of exergy destruction in the storage was responsible for 16 % and 7 % of the overall cost of exergy destruction in flexible and non-flexible operation mode, respectively. The cost related to the exergy destruction in the storage was a larger share of the overall cost. This occurred as the fuel of the storage was the warm inlet, which had a high specific cost due to the cost of the upstream components assigned to it.

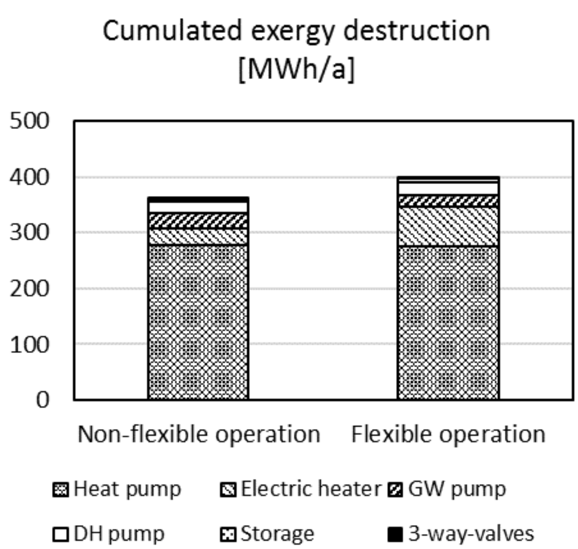

Figure 11 Overall exergy destruction of all components per year for flexible and non-flexible operation

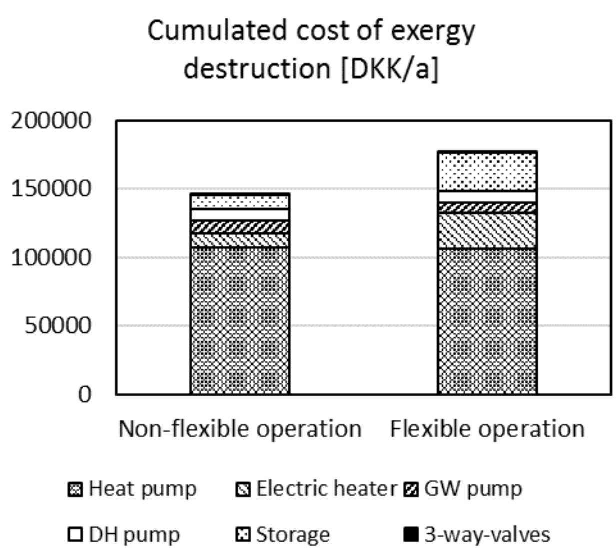

Figure 12 Overall cost of exergy destruction of all components per year for flexible and non-flexible operation

3.3 Influence of heat pump capacity

The system assessed here, was oversized for the given heat demand. This was done with the aim to be able to operate the system very flexibly. The simulation was repeated for an increase and decrease of the heat pump capacity of 100 kW each, keeping all other components and the heat demand the same. The results (Figure 13) indicated that the specific cost of heat is almost constant for all three cases and the overall cost per year increases slightly with increasing HP capacity. Whereas, the specific cost of flexibility decreases considerably with increasing HP capacity. This is caused by two effects. Firstly, an increase in the additional exergy destruction due to flexible operation for larger heat pump capacities leads to a decrease in the specific cost per unit exergy. Secondly and more importantly, the amount of regulation energy provided increases with increased heat pump capacity.

The results for the overall exergy destruction and the additional exergy destruction due to flexible operation increased slightly for increased HP capacity. This is due to the lower minimum part-load capacity of the smaller heat pump and thus a higher share of heat that is directly supplied from the heat pump, avoiding exergy destruction in the storage and the electric boiler.

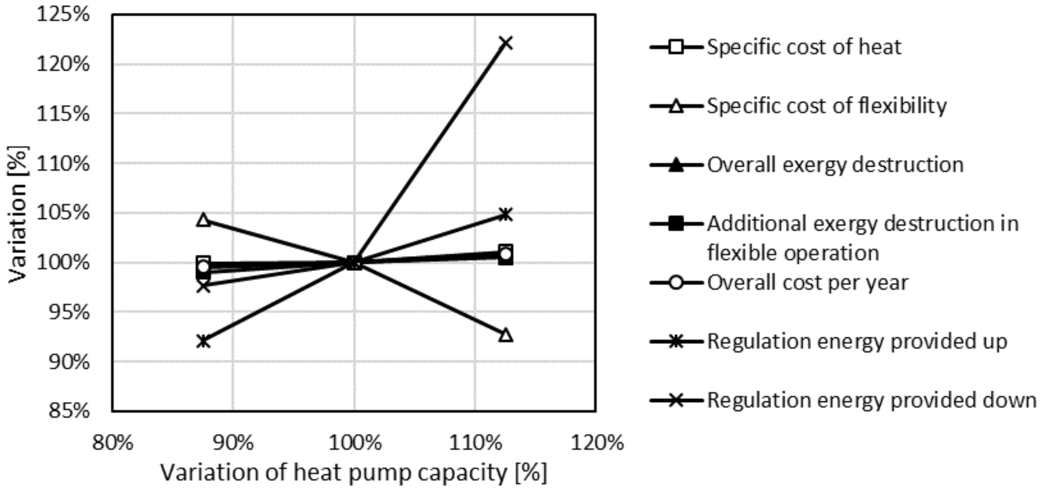

Figure 13 Variation of specific product cost, response rate and exergy destruction in % over the heat pump capacity in %

4 Discussion

A method was presented to value the two products of a heat pump system using a dynamic exergoeconomic analysis. The allocation of cost to the provision of ancillary services was based on the additional exergy destruction in the system. We found that this approach is well suited as it resembles the common exergy costing method closely, e.g. [30], and at the same time the problem of the different directions of exergy flow and service provision (Figure 5) can be handled. Allocating the cost in the presented way, a cost could also be assigned to the flexibility when the overall fuel cost is be lower than in the reference case. The applied approach is based on exergoeconomic theory. Other approaches based on economics or more heuristic assumptions would also be possible and may reach other costs of the flexibility.

For the case study of a heat pump island system the flexible operation of the system caused higher exergy destruction and thus fuel consumption. The overall fuel cost and the specific fuel cost were found to be higher during regulation. This is due to the difference between the trends of the electricity spot market price and the regulation requests found in the data for Eastern Denmark in 2012. Also, the control algorithm did not consider any kind of optimization, but the system would react to a regulation request whenever possible. In this case the difference between the overall cost for flexible and non-flexible operation was approx. 21000 DKK/a.

Further, using the sport market price for the calculation implicates that a perfect prediction of the heat demand can be made. This is of course not possible in reality. The spot market price is also used to calculate the cost during regulation, thereby the cost difference between the flexible and non-flexible case is indeed an opportunity cost of providing flexibility. The comparison showed that the obtainable price at the balancing price was in most cases lower than the additional cost due to losses in the storage and the electric boiler.

The additional exergy destruction was mainly caused by heat losses in the storage, which led to reheating of the DH forward flow and thus exergy destruction in the electric boiler. This result reconfirms findings of previous studies on individual HP systems [36,37]. Reducing heat losses in the storage and the need for reheating, will improve the systems efficiency.

No significant difference in the exergy destruction of the heat pump was found. This is related to the assumption that part load characteristics of the heat pump are not considered. The part load performance depends on the capacity control type of the compressor [27], as well as the design of the heat exchangers.

The assumption that a largely overdimensioned system can provide more flexibility made when designing the system correlates with the results of the parameter variation that showed that the amount of regulation energy provided increased with increased HP capacity. On the contrary, both the overall cost per year and the exergy destruction in the system increase for larger HPs. Thus, the examination of the optimal component sizes for systems that are designed to provide flexibility may be a topic for further analysis.

The presented work gave an insight into the effect of providing ancillary services on the conversion unit, in this case a heat pump system. The advantage of this approach is that the actual thermodynamic and economic effect of providing flexibility to another sector can be assessed. In this way it is possible to assess the additional amount of electricity used and the part of the conversion units cost that is caused by providing another product. This is valuable information for the heat pump operator and it adds a different perspective to the discussion about how flexibility should be valued. So far the overall system benefit was mostly discussed (e.g. [4], [15], [38]) and the actual effect on the conversion unit was not considered.

5 Conclusion

Energy conversion units are an essential part of integrated energy systems. They are able to connect different sectors and provide services to both of them. In the case of electricity and heating sector, the conversion units provide heat to the heating system while acting as flexible demand for the electricity sector. A method to assess the impact of flexible operation of a heat pump system was presented, where allocation of the cost of both the heating and the flexibility products was based on a dynamic exergoeconomic analysis.

The method was applied to a heat pump island system located in Copenhagen. We found that operation according to regulation request resulted in higher exergy destruction and higher overall cost of the system. The additional exergy destruction was mainly caused by heat losses in the storage and reheating of the forward stream. The cost allocated to the flexible operation was 12 % of the overall cost of the system.

Overall, the method gives important insights into the effect of integrating energy systems on the energy conversion units and can thus support the decision making process when considering how to design and operate a conversion unit.

Acknowledgements

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Nomenclature

Abbreviations

COP	Coefficient of performance
DH	District heating
El.	Electric
GW	Groundwater
SCOP	Seasonal system COP

Symbols

C	Cost	[DKK]
c	Specific cost per unit exergy	[DKK/J]
$\dot{C}$	Cost stream	[DKK/s]
$c_{p,\mathrm{H_2O}}$	Heat capacity water	[J/(kg*K)]
E	Exergy	[J]
e	Specific exergy per unit mass	[J/kg]
$\dot{E}$	Exergy stream	[W]
k_1, k_2	Parameters ramp-up function	[-]
$\dot{m}$	Mass flow	[kg/s]
m	Mass	[kg]
N	Number of discretization layers	[-]
p	Pressure	[bar]
Q	Heat	[J]
$\dot{Q}$	Heat flow rate	[W]
T	Temperature	[K]
t	Time	[s]
$T_{m,i}$	Logarithmic mean temperature for stream i	[K]
V	Volume	[m^3]
$\dot{W}$	Electric power	[W]
$\dot{Z}$	Levelized cost of capital investment, and operation and maintenance	[DKK/s]

Greek symbols

ϵ	Exergy efficiency	[-]
$\overline{\rho}$	Mean water density	[kg/m^3]

Subscripts

0	Reference state
capacity	Per installed capacity
cold	Related to cold control volume of the tank
con	Condenser
D	Destruction

el	Electricity
eva	Evaporator
ex	Per unit of exergy
F	Fuel
flex	Flexible operation
heat	Heat supply into DH grid
hot	Related to hot control volume of the tank
HP	Heat pump
i	Material stream indicator
in	Inlet
installed	Installed capacity
j	Heat flow indicator
k	Component indicator
L	Loss
l	Electricity flow index
max	Maximum capacity
min	Minimum capacity
n	Discretization layer indicator
nonflex	Non-flexible operation
out	Outlet
P	Product
reg	Regulation energy
season	Seasonal
ss	Steady state
storage	Stratified storage tank
system	Conversion system
tot	Yearly mean value

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Highlights - Dynamic exergoeconomic analysis of a heat pump system used for ancillary services in an integrated energy system

- Dynamic exergoeconomic analysis
- Cost allocation method for regulation power and heat provided by the heat pump
- Large scale heat pump providing manual reserve regulation
- Exergy destruction increase for flexible operation due to storage and reheating