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ABSTRACT

This paper deals with individual air-to-air heat pumps in Danish dwellings and summerhouses and the question of to what extent they actually deliver savings of energy consumption. Results show that 20% of the expected reduction of electricity consumption is converted into increased comfort in the homes, including extended heating areas, keeping a higher temperature and a longer heating season and using the heat pump for air conditioning. Data include electricity consumption in 185 households before and after installation of heat pumps together with survey results of 480 households. Furthermore, 12 households were selected for in-depth analysis including technical inspection and qualitative interviewing. Especially for summerhouses, results indicate that on average there is no reduction in electricity consumption, as energy efficiency is counter balanced by increased comfort and changed heating practices. These results have to be taken into account when making long-term energy planning for a sustainable energy system.

Key words: heating practices, household behaviour, rebound effect, thermal comfort, air-to air heat pump

1. INTRODUCTION

The sale of air-to-air heat pumps has been quite high, notably in Norway where some hundred thousand have been sold [1], but also in Sweden and France growing sales figures for heat pumps are reported. In Sweden, the domestic sale of heat pumps rose from approx. 20 000 to 80 000 per year between 2006 and 2007 and in France from approx. 50 000 to 70 000 per year [2]. Studies from several different European countries have pointed out that there are good economic reasons for consumers to install air-to-air heat pumps [3, 4, 5]. The question of what role air-to-air heat pumps play in a future sustainable energy system has to be discussed together with other technical changes of the whole energy system including to what extent electricity is produced by renewable energy [6, 7] and to what extent the building stock is energy renovated [8]. Replacing direct electric heating with air-to-air heat pumps are, however, always more energy efficient, because heat pumps can provide 2-5 times more heat than the electricity they use as driving force [3]. Thus, in a scenario for future 100% renewable energy systems in Denmark, individual heat pumps are included for areas not covered by district heating [9]. From a socio-technical point of view it can, however, be expected that the full technical potential for energy efficiency will not be met due to changes in user practices towards still higher expectations and norms of comfort [1], as is also known from studies of other types of household technologies [10]. Within a techno-economic perspective the corresponding phenomenon is known as the rebound effect, which focuses on how the economic gains that households get from implementing more efficient technologies are used to increase consumption in other areas or within the same area resulting in higher standards and thus increased energy consumption. There has been a debate about the size of the rebound effect within the household sector, and a recent review suggests a rebound effect of 20%, meaning that 20% of the energy savings gained from efficient technologies within the household sector are transformed into increased energy consumption and thus not realised as energy savings

[11, 12]. The purpose of the study presented in this paper was to analyse to what extent the potential reduction from the installation of air-to-air heat pumps are realised or converted into increased consumption. Furthermore, it was the aim to go more into detail with the explanation of precisely in which areas the increases in comfort are seen and to understand in more sociological terms why and how these changes occur.

By 2009, 8% of houses in Denmark [13] and 84% of summerhouses were heated by direct electric heating [14]. Summerhouses in Denmark are small detached houses or cabins often located in coastal areas. There are about 215 000 summerhouses in Denmark and approx. 7% of Danish households own a summerhouse. One fourth of these summerhouses are old and without modern facilities, whereas the majority of summerhouses built today are equipped with modern facilities and technologies, including some kind of heating technologies [15]. Danish summerhouses have traditionally primarily been used during the summertime, however, with a higher building and installation standard of the summerhouses, it is becoming more normal to use them also during some weekends and holidays throughout the year. The majority of the summerhouses and permanently occupied dwellings that are heated by direct electric heating are not situated near city centres and thus reachable by district heating; the most relevant future heating supply for these homes is therefore individual heat pumps [9]. As these houses have not installed central heating based on water-borne systems, the economically most attractive choice most often is to install air-to-air heat pumps. Another argument for looking at air-to-air heat pumps in relation to changes in comfort norms is that they can easily be used for air conditioning as well. Air conditioning has until now not been the norm in Danish households; however, having available technologies installed in the home might contribute to changing this.

In the following, we first describe the methods of the study and then, in the main part of the paper, present findings and analysis for permanently occupied dwellings and summerhouses. In the conclusion, results are discussed in relation to the implications for interaction between heating technologies and renewable energy systems.

2. METHODS

Data presented in this paper were based on a survey from 2010 of house owners in two Danish regions that have installed air-to-air heat pumps. The survey population of 2793 households was drawn from the customer lists of two Danish regional energy companies, which participated in this study. All customers with a heat pump installed in either their permanently occupied dwelling or their summerhouse received an invitation to participate in the survey. A sample of 681 house owners or 24.4% of the population completed the online questionnaire with questions on heating technology, heating practices, other electric appliances and characteristics of the household before and after the purchase of an air-to-air heat pump. The questions concerning summerhouses differed slightly from those concerning ordinary dwellings (permanently occupied houses). People were asked to indicate the type and brand of their heat pump and only households that were certain to have an air-to-air heat pump are kept in the analysis. This included 481 houses, 76 of which were summerhouses and this was the final sample that was used in the analysis of this article. In order to detect changes in energy consumption following the installation of a heat pump, the questionnaires were combined with available electricity metering data from the years 1990 to 2009 supplied by the energy companies. Some questionnaires were removed from this part of the survey if the year of installation of the heat pump was unknown, or if the installation year was too recent or too old to have metering data for at least one year before and after installation. This resulted in a data set of 138 questionnaires, 42 of which were for summerhouses. Finally, a follow-up survey was carried out among the summerhouse owners asking questions on how they kept their summerhouse heated in wintertime, as this turned out to be an important question (however, it was only possible to get in contact with 35 of the 76 summerhouse owners). These data sets are summarised in Table 1.

Table 1. Number of households in dataset

	Total	Permanently occupied dwellings	Summer houses	Follow-up on summerhouses
Questionnaire survey	481	405	76	35
Survey incl. electricity data	180	138	42	
In depth analysis	12	8	4	

Regarding the question of representativeness, the population of 2793 households included all customers of the two regional energy companies, who had a registered air-to-air heat pump according to the customer lists. However, missing from this list were customers who had installed heat pumps on their own (and not by accepting an offer from the energy companies). As some of these customers might have installed inexpensive models bought in DIY centres etc., which in some cases might even have been installed by unauthorised professionals, it might be expected that the survey population of this study had a general bias towards air-to-air heat pumps of a higher quality and working with a higher energy efficiency compared with the total population of air-to-air heat pumps in Denmark. With regard to age, there was an overrepresentation of older people in the sample with only 5.4% of the survey respondents with a heat pump in their dwelling being younger than 41 years (compared with 32.1% of the population in the regions) and 91% of the respondents with a heat pump in their summerhouse being older than 50 years (compared with 78% of all summerhouse owners). Furthermore, there was an overrepresentation of low-income households among the respondents with a heat pump in their dwelling; 45% have an annual income of less than DKK 400,000 (approx. EUR 53,000) compared with 34% of the house owners in the two regions (see also [16]). It was not possible to conclude whether the overrepresentation of older persons and low-income households reflected the actual socio-demographic characteristics of air-to-air heat pump owners or a methodological bias as no national statistics existed on heat pump owners. Still, when interpreting the results it should be kept in mind that the respondents were in general older and less affluent than the rest of the population.

Twelve respondents were selected for in-depth analysis including face-to-face qualitative interviews and technical inspections of their heat pumps. The aim of the technical inspection was to detect to what extent technical issues could explain the lacking reductions of electricity consumption. The technical inspections focused on visible conditions that might affect the efficiency of the heat pump: the condition of the evaporator/condenser (physical damage or dirt obstructing the airflow) and risks of “thermal short-circuit” due to the placing of the evaporator/condenser. The aim of the interviews was to provide detailed descriptions of the use of the heat pumps and how they had been integrated into the heating practices of the households. Respondents were chosen in order to ensure variety in the sample with regard to heating system, development in electricity consumption and household composition. The interviews lasted about one hour each and were carried out as semi-structured interviews [17]. They were recorded and afterwards thematically transcribed and analysed.

Results from this project were presented previously in two conference papers, one focusing on qualitative material [16], and another focusing on quantitative material [18], whereas this paper includes both approaches. In the following, the analysis of the results is divided into two sections dealing with permanently occupied dwellings and summerhouses respectively

3. ANALYSIS OF PERMANENTLY OCCUPIED DWELLINGS

3.1 Theoretical energy savings achieved from installing air-to-air heat pump

First it is relevant to estimate the reductions that could be expected in the electricity consumption of dwellings after the purchase of a heat pump. From technical specifications and tests of the performance of heat pumps at different outdoor temperatures, it is known that the Coefficient of Performance (COP) is highly dependent on the outdoor temperature. Tests have shown that COP varies between 2 and 4 when outdoor temperatures vary between -15^{0}C and +7^{0}C. The COP of the heat pumps included in this study was estimated to be approx. 3 based on assumptions of typical outdoor winter temperatures in Denmark [19].Thus, a reduction of two thirds of the electricity used for heating would be expected when substituting direct electric heating with heat pumps. Standard calculations based on household size and floor space suggest that on average 64% of the participating households' total electricity consumption is used for heating, while the remaining 36% is used for appliances/lighting [19]. However, in practice the heat pump does not deliver all the needed heating in all dwellings. On the basis of the survey, respondents' answers regarding the total floor space of their dwellings and the size of the floor space heated by their heating pumps, the average heat pump coverage was estimated to be approx. 75% of the total floor space (this only included households with direct electric heating as primary heating source before heat pump installation and the heat pump as primary heating source after the installation). The remaining 25% of the floor space was expected to continue to be heated by direct electric heating. On the basis of this, the expected (theoretical) reduction from substituting direct electric heating with heat pumps can be calculated as: 100% - 64%*0,75/3 – 64%*0,25 – 36% = 32%. Thus, the installation of heat pumps should result in a reduction of the total electricity consumption by approximately one third. It should be noted that there are quite some assumptions and uncertainties involved in this estimate, if e.g. COP varies from 2.5 to 3.5, the expected reduction would vary between 29 and 32%. The rebound effect is the difference between the calculated 32% reduction and the actual measured reduction.

3.2 Comparing energy consumption before and after installation of a heat pump

To estimate the actual reduction, electricity consumption has to be corrected for degree days. Degree-day correction is a method used for comparing the heat consumption of different years with each other independently of the specific weather of each of the years. This means that the actual weather conditions of each year are used for converting the actual heat consumption into a corresponding heat consumption for a standard year. In this study, electricity was used for other purposes than just heating, the share of electricity used for other purposes was estimated for each household on the basis of information about the number of people in the household and the size of the building and the rest of the electricity consumption is then corrected for degree day. In Figure 1, electricity consumption before and after installation of the heat pump is compared. The figure shows the slope to be below one, indicating that for the majority of the households electricity consumption after installation of a heat pump was lower than before, as would be assumed. However, especially households with prior low levels of electricity consumption, did not in general realise a lower level of consumption after installation.

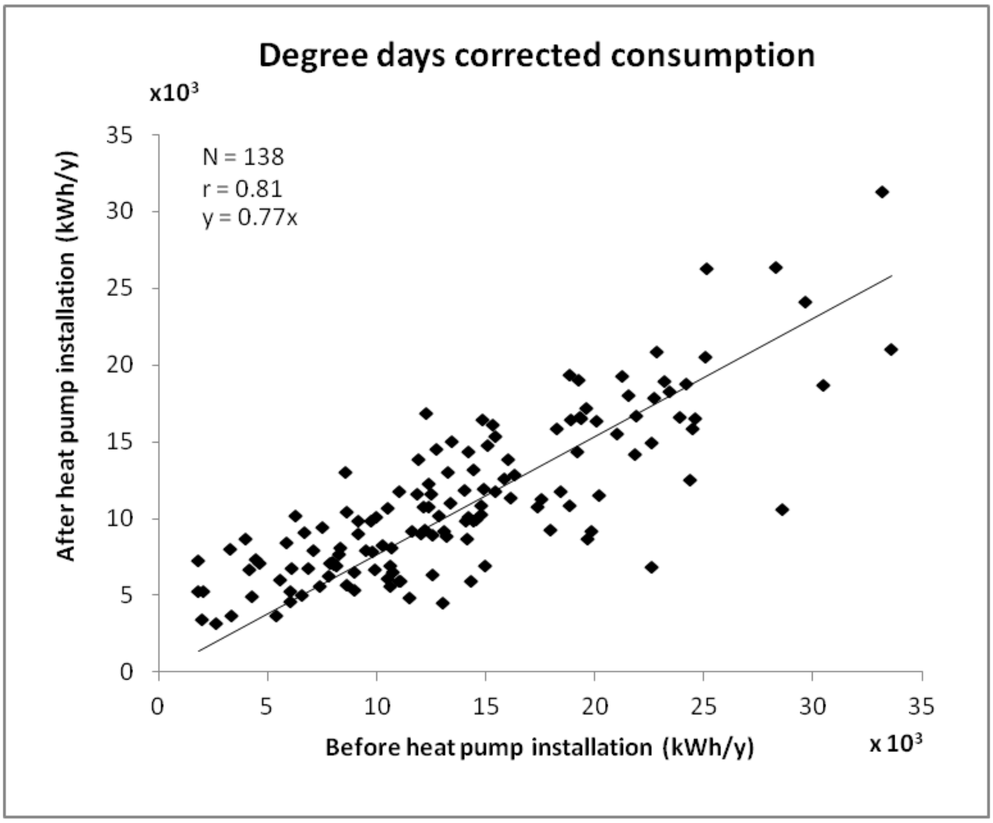
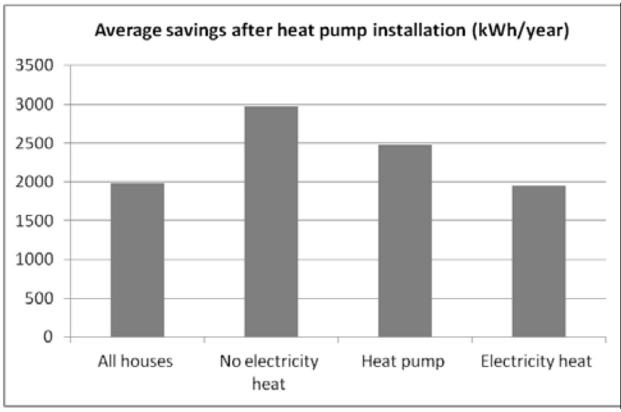


Figure 1. Comparing annual household electricity consumption before and after a heat pump was installed. Electricity consumption for heating is corrected for degree days.

A major explanatory variable was expected to be the question of what the primary heating source was before and after installation of the heat pump. In Figure 2 the average savings in all households are shown together with combinations of what the primary heating source was before and after installation of a heat pump. Besides a correction for degree days, these average saving values were also corrected for a yearly decrease of consumption of 5%. This 5% reduction was calculated by comparing one year with the following one, except for the year when the surveyed households installed the heat pump.



1. All houses: All houses degree day corrected and corrected for a yearly 5% general decrease (N=138)
2. No electricity heat: Houses using direct electricity heating before heat pump installation and no direct electricity heating after (N=16);
3. Heat pump: Houses using direct electricity heating before heat pump installation and using heat pump as primary heating source after (N=70);
4. Electricity heat: Houses using direct electricity heating before heat pump installation and after still using direct electricity as primary heating source. (N=32)

Figure 2. Average savings in annual household electricity consumption (kWh) before and after heat a pump was installed, for different combinations of heat supply before and after installation of a heat pump. For all four cases, the savings differ significantly from zero.

In all four cases shown in Figure 2, a paired-samples test shows that the savings were significantly different from zero (not shown here), though there were big variations for the savings especially in the second case, which was also where we saw the biggest average savings and where we had a low number of households. Thus, the biggest average savings (and the biggest variation) were not surprisingly seen in households where they used direct electric heating before they installed the heat pump, and where they did not use any direct electric heating after the heat pump was installed.

The group of households that used direct electric heating before the installation of a heat pump and primarily heated by means of the heat pump after its installation was the group that could be compared with the expected theoretical reduction of 32%. The slope of the red line in Figure 3 indicates that on average the reduction in electricity consumption for these households was 26%. Comparing this with the expected 32% reduction suggests that about 19% of the expected savings were used for increasing other consuming practices as (32-26)/32 = 19%. In the following part of the analysis, we explain in detail this lacking reduction or rebound effect.

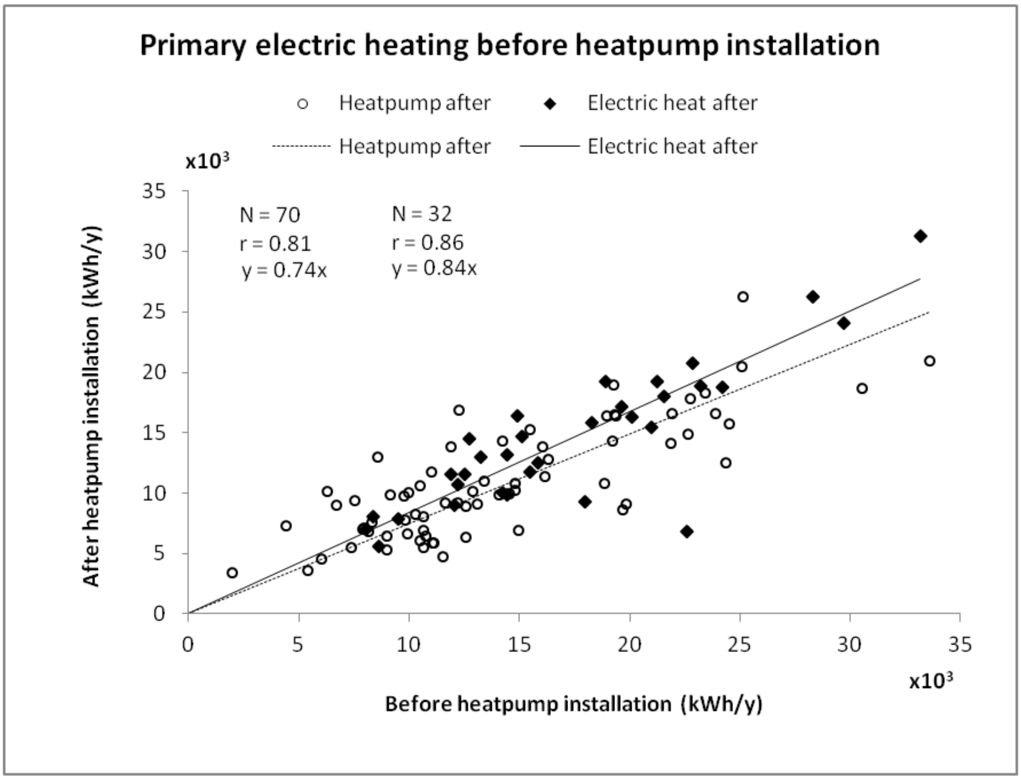


Figure 3. Comparing annual household electricity consumption before and after a heat pump was installed for households that used direct electric heating before and distributed on what type of heating they used afterwards. Electricity consumption for heating is corrected for degree days.

3.3 Regression analysis of variables explaining changes in energy consumption

As there are numerous variables which might cause a change in electricity consumption other than the installation of a heat pump, the results of regression analysis with all available and relevant variables from the survey are shown in the following. These variables include a change of the primary heat supply, number of household members, number of rooms, heating period, heating temperature, cooling days, electrical appliances, thermal insulation, consumption of firewood and installation of a wood-burning stove. Furthermore, there were some descriptive variables on the household members such as the number of children and adults and household income as well as descriptions of the house such as size and age and heated area. These variables are further presented in Appendix C. The regression analysis can be described by the equation:

$$X_{after_i} = a + b \cdot X_{before_i} + \sum_{j=1}^{N} c_j \cdot X_{\mathrm{cov}_{i,j}} + \varepsilon_i \qquad (1)$$

Where X_{after} is the electricity consumption after heat pump installation, X_{before} is the consumption before, and X_{cov} are the different other variables. In the regression analysis a constant a has been included in the test, however, as seen in the results of the regression, this constant is not tested different from zero. Results of this first full regression analysis are shown in Appendices A and B. Appendix A includes the regression analysis for the households primarily using direct electricity for heating before they purchased the heat pump and primarily use the heat pump after. Appendix B shows the regression analysis for all households in the survey. The *b* coefficient to X_{before} is a measure for the heat pump effect and possible other effects from variables not included in X_{cov}. T-test is used to determine the significance of variables different from zero, with a significance level of 0.05. In Appendices A and B, it is seen that no variables from the X_{cov} matrix were found to be significant in Scenario A and only two variables in Scenario B in these first regressions which include all variables. Using forward selection and stepwise regression, noisy variables are removed from the regression thus revealing that three variables become significant in each of the two regressions, which are respectively household income, cooling days and change of appliances for the first regression and household income, extra TV and heating period for the second. This is not shown in the appendix, as the appendices show only the starting situation for the stepwise regressions.

For analysis of the households primarily using direct electricity before they purchased the heat pump and primarily use the heat pump after, the regression is:

$$X_{after} = 0.60 * X_{before} + 2.7 * Income\_household + 199 * Cooling\_days + 616 * Appliances\_chng \qquad (2)$$

For all households in the survey the regression is:

$$X_{after} = 0.6 * X_{before} + 2593 * TV\_extra + 4.4 * Income\_household - 923 * HeatPeriod\_chng \quad (3)$$

It is seen that in both cases the intercept remains insignificant. The coefficient for change in appliances, white goods in the first case and for an extra TV in the second case, is rather high and this may be interpreted as these variables cover for a more general increase in wealth and not only for the white goods or TV. These prediction models also turn out to offer an improved explanation of the electricity consumption as the correlation coefficient r is respectively 0.86 and 0.92 as compared with Figure 2 where we had r = 0.81. However, the number of observations decreased to 67 and 83 because some answers to the significant explaining variables were lacking.

Thus, it is interesting that what seemed to explain the change of electricity consumption, other than the installation of the heat pump, were variables related to general wealth and to a change of heating practices represented by the cooling days variable or by the heat period variable. The combination of these three variables was the best explainable combination we could obtain from the available data. This does not mean that the excluded variables did not have any influence on some of the specific cases. However, the amount of independent variables of the study compared with the amount of households included was a limitation on this analysis.

Still, the main effect arising from X_{before} was greatly significant and the corresponding coefficient was estimated to 0.6 as seen from the equation in both regressions. This meant that the effect of the heat pump together with the 5% general annual decrease gave a reduction of 40% of the electricity consumption. Thus, the heat pump alone gave a 35% reduction of the electricity consumption, which was also quite close to the previous calculation of the assumed reduction if the heat pumps substituted 75% of electricity used for heating purposes.

3.4 Yearly development of electricity consumption after installing a heat pump

In the previous analysis, electricity before and after installation had been summarised for several years from 1990 to 2009 depending on when the heat pump was purchased. Another approach to studying the impact on electricity consumption after installing a heat pump was to analyse how electricity consumption developed in the years after the purchase. Figure 4 shows how the average annual consumption developed year by year after installation, distributed on which year the household purchased the heat pump. In this figure, all households were included without regard to their primary heating type before and after installation. We found that electricity consumption was rather low the first year after installation, and that it rose during the following years. This was interesting as it might indicate that people saved the most the first year after installation, but when they had got used to the lower electricity consumption, they started to use more. Furthermore, it was seen that year 2003 was a year when all lines (except the black representing those who had just installed the heat pump) had a peak. When looking for characteristics of this year, it should be remembered that data were already corrected for degree days, so extreme winters were taken into account. Instead, the peak in 2003 might be explained by the fact that it was actually an extraordinarily hot summer and many people might have used the heat pump for air conditioning. If we exclude the 2003 point in Figure 4, the tendency seems to be significant energy savings within the first year after the installation, which is followed by a small increase, then a stable period and finally a new reduction of consumption. In general it was found that there were several increases and decreases which were not related to the purchase of the heat pump.

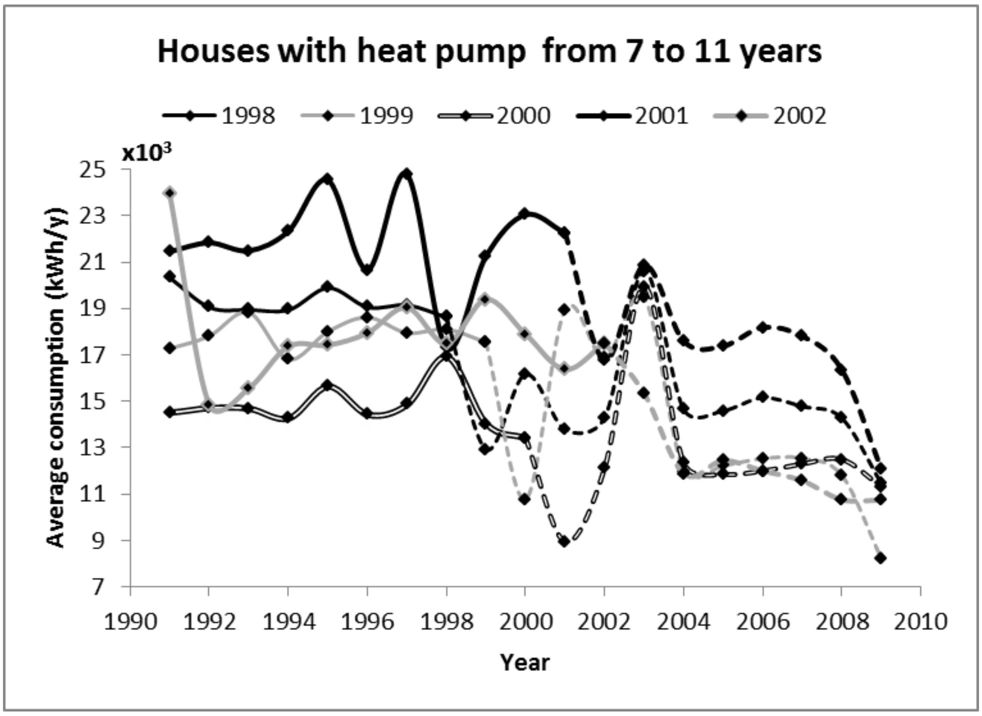


Figure 4. The average household electricity consumption, distributed on the year of heat pump purchase. Dotted lines indicate electricity consumption after the heat pump purchase.

3.5 Describing and explaining changes of heating practices

In the following, the results from the survey and the qualitative interviews are analysed in order to provide a more detailed understanding of changes in heating practices. As described in the methods section, there were more households in the survey than in the data set with electricity metering data, and it was therefore interesting to analyse the survey in more detail.

Respondents were asked why they had purchased the heat pump. As seen in Table 2, the majority had done this to save money and energy, and to a lower degree to improve their comfort. More than two thirds of the respondents indicated that they were very satisfied with their heat pump and only one per cent that they were very dissatisfied with it (not shown in any of the tables).

Table 2. Reasons to purchase the heat pump

	Number	Per cent (%)
To save money on heat consumption	290	72
To save energy	257	63
To improve comfort	152	38
Contributing to reduced pollution	92	23
Heating system needed renewing	14	3
Not applicable, Heat pump installed before we moved in	39	10
Other reasons	27	7

The qualitative in-depth interviews provided a more detailed picture of how the use of heat pumps was experienced. Seven out of eight interviewees in permanently occupied dwellings explained that the indoor air quality and comfort had improved since the installation of the heat pump. The interviewees typically mentioned benefits like less moisture, "cleaner air" and better "air circulation". For instance, a couple in their seventies experienced that they did not need to air their living room as often as before. The interviewees in general emphasised the non-economic advantages of the heat pump, while the energy-saving aspect was put more in the background. This indicated that even though the economic aspects seemed to play an important role for the decision to purchase a heat pump (cf. Table 2), other aspects like better indoor comfort played a more central role for the interviewees' later experience of the heat pump.

The survey results showed that the majority (86%) of the respondents used direct electric heating before they bought the heat pump and about half of them (44%) used the heat pump as the primary heat source now, though only 19% indicated that the heat pump was their only source of heating. Approx. 50% of all households in the survey combined heat pumps with a wood-burning stove and of these the majority reported that electric heating was their primary heating source at the time of the survey (36% direct electric heating and 43% heat pump). A wood-burning stove was owned by 164 respondents before they got the heat pump and among those 39% indicated that they used less wood after they got the heat pump, another 39% indicated that it had not influenced their firewood consumption, 31% did not know and only 3% indicated that they used more wood after they got the heat pump. Thus, it seemed that heat pumps in some households had partly substituted wood with electricity as a heating source.

Table 3. Changing heating practices related to heating season after purchase of a heat pump

	Number of households	Per cent (%)
No change	206	50.9
Shorter heating period of the year than previous	93	23.0
Longer heating period of the year than previous	69	17.0
Not applicable, Heat pump installed before we moved in	37	9.1
Total	405	100

Table 4. Changing heating practices related to temperature after purchase of a heat pump

	Number of households	Per cent (%)
Same temperature as previously	223	55.1
Temperatures are generally kept higher than previously	123	30.4
Temperatures are generally kept lower than previously	19	4.7
Not applicable, Heat pump installed before we moved in	40	9.9
Total	405	100

The question whether people change their heating practices and norms of comfort after purchasing a heat pump was a main research question in this paper. In Table 3, it is seen that 50% of the respondents did not believe that they had changed habits in relation to how much of the year they heated their house, and more people (23%) believed that they heated their house for a shorter period after they had got the heat pump than the percentage (17%) who believed they now heated for a longer period than before. Thus, there was no reason to believe that the heat pump in general entailed a longer heating season in permanently occupied dwellings. If we look at Table 4, there is however an indication that approximately one third of the households established a higher temperature setting after they had purchased the heat pump, while only 5% thought they kept a lower temperature. We did not ask for exact thermostat data before and after installation of the heat pump, as it was our impression that it would not be realistic to assume that most people could actually remember or know this. However, we did ask whether they thought that they generally kept a higher, a lower, or the same temperature before and after acquiring the heat pump, which we found to be a more realistic question to answer. The in-depth interviews indicated that this temperature increase might be closely related to the understanding that heat pumps are a less expensive form of heating compared with direct electric heating, which most of the interviewees regarded as very expensive. This was illustrated by one of the interviewed families (a couple aged 49 and 55 years respectively with two children) whose heat pump replaced direct electric heating in their kitchen and living room. However, their electricity consumption had only been reduced moderately by 10%, which might partly be explained by higher indoor temperatures. As the couple explained:

> Husband: We have probably got a higher temperature in here.
>
> Wife: Yeah, previously we were satisfied with 20 degrees (...)
>
> Husband: (...) now it's 21.5, so we have actually raised the indoor (...) temperature since we have got the heat pump. In a way, we have allowed ourselves a bit of luxury.

This quote illustrates how the users' understanding of economic characteristics of different heating forms influenced their heating practices and norms of comfort.

Another way of heightening the comfort was to enlarge the heated area, e.g. start to heat rooms which had not previously been heated. According to 13% of the respondents more rooms were heated after the purchase of the heat pump, and these rooms were typically 10-30 m^2. Two of the interviewed families had installed their heat pump in connection with building a new extension to their house. One of them had built a 30-m^2 extension (conservatory) to their house. They chose a heat pump as this was cheaper than radiators (due to costly piping work) and more simple than a wood-burning stove which needs a chimney. Also, they liked that the heat pump could be used for air conditioning in the summer as the conservatory could be very hot on sunny days. This household's electricity consumption had increased by 60% since the installation (the rest of the house was still heated by district heating).

Following this example, a last issue to be raised relates to the question of to what extent people use their heat pump for air conditioning. The first question was whether people know about the option that their heat pump can be used for air conditioning. According to 76% of the respondents, their heat pump could be used for air conditioning, 22% stated that it could not (which was probably wrong) and only 3% said that they did not know. Among the 306 respondents who knew that their heat pump could be used for air conditioning, 21% of households had actually used it and those 64 households had furthermore estimated how much they used it for air conditioning. In Table 5, it is seen that one third used it only a few days and that 17% used it more than 15 days during a normal summer.

Table 5. Number of days the heat pump is used for air conditioning during ordinary summer

Number of days	Number of households	Per cent (%)
1-4 days	24	38
5-9 days	17	27
10-14 days	12	19
15 days or more	11	17
Total	64	100

4. ANALYSIS OF SUMMERHOUSES

When we combined survey results on summerhouses with data on electricity consumption, we had 42 cases. Unfortunately, this number was too small for proper regression analysis including all available variables. Therefore we just made a comparison of electricity before and after purchase of the heat pump for these 42 summerhouses (see Figure5). It was seen that the slope of the line was below 1 thus showing an overall reduction of electricity consumption after installing the heat pump. Even though we detected a slope by regression, a pair-wise test showed that the mean difference was not significantly different from zero. The slope thus arose from high consumption cases having high leverage. Among summerhouses with low electricity consumption there seemed to be a tendency that they had increased electricity consumption after purchasing a heat pump. Regression analysis including supplementary variables confirmed that it was a significant relation that summerhouses with low levels of electricity consumption experienced an increase of the electricity consumption, an increase which could not be explained by any of the supplementary variables. It is reasonable to assume that some summerhouses with electricity consumption below 3000 kWh only to a limited degree heated their house with electricity during the winter before installing the heat pump, and that the increase of the electricity consumption was partly a result of the increase of the heating season and the indoor temperature in wintertime.

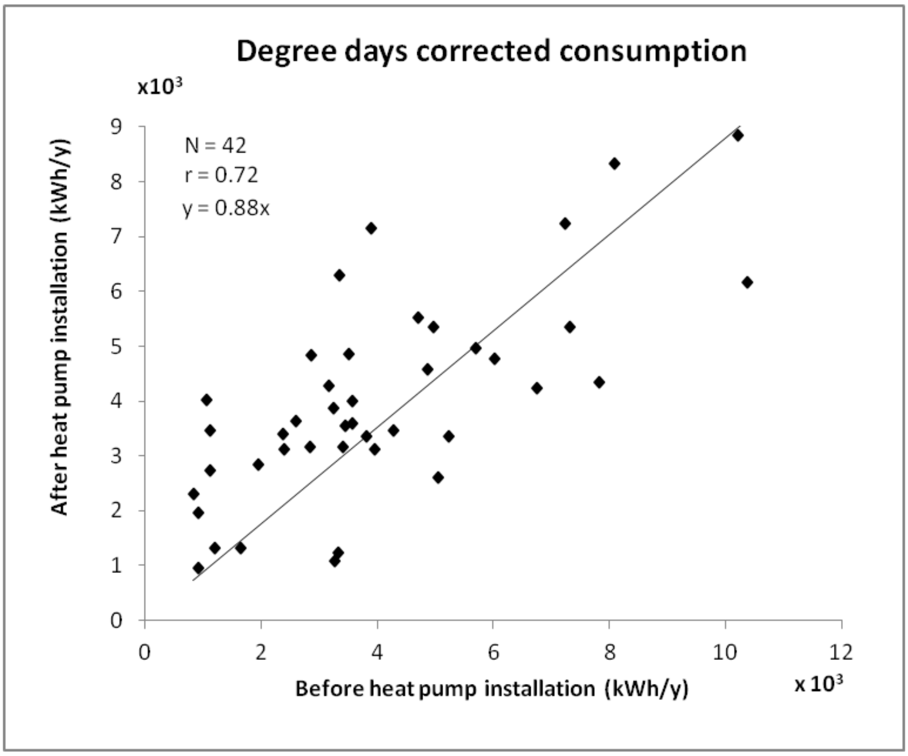


Figure 5. Comparing annual household electricity consumption before and after a heat pump was installed in summerhouse. Electricity consumption for heating is corrected for degree days.

Table 6. Reasons to purchase the heat pump in summerhouses

	Number of households	Per cent (%)
To save energy	46	61
To improve comfort	40	53
In order to frost-proof the house in the winter	39	51
To save money on heat consumption	38	50
Contributing to reduced pollution	16	21
Heating system needed renewing	0	0
Not applicable, Heat pump installed before we moved in	2	3
Other reasons	6	8

The answers to the question of why people purchased their heat pump for the summerhouse are listed in Table 6. A majority of 61% gave as a reason to save energy, and the second and third most often reported reasons were to increase comfort and to frost-proof the summerhouse in wintertime. Half of the respondents indicated saving money on heat consumption, which was considerable lower than the 72% of the owners of permanently occupied dwellings (Table 2). It thus seemed that there were different reasons involved in purchasing a heat pump for the summerhouse and for the permanently occupied dwelling, which also appeared from the qualitative answers that the respondents filled in under "Other reasons". These included: "Having a nice temperature when we arrive at the summerhouse"; "Better use of the summerhouse in wintertime"; "Higher temperatures in wintertime with lower consumption". The qualitative interviews with owners of four summerhouses showed that in all four cases, the owners used the heat pump to keep the house heated during the winter, and this had actually played an important role for the informants' original decision to purchase a heat pump. Before the installation of the heat pump, the interviewees had either "shut down" their summerhouse during the winter or kept it heated up to 5 ^{o}C by means of direct electric heating. The interviewees explained that the low temperatures in the winter had resulted in problems with moisture and mould growth. Now, their houses were heated to the lowest technical set-point of the heat pumps (which differs for different heat pumps, but in these cases it was16 ^{o}C) the entire winter, which made it more comfortable to use the house also in the wintertime. As a consequence, most interviewees used their house more often during the winter.

The survey showed that in more than two thirds (72%) of the summerhouses the heat pump was the primary heat supply and more than half of the respondents indicated that they used direct electric heating as their primary heat supply before installation of the heat pump. Furthermore, 80% indicated that they also used firewood for heating, and half of those (47%) who had firewood-burning stoves both before and after installation of the heat pump indicated that they used less firewood after the installation of the heat pump. The respondents were asked about changes in their heating practices and norms of comfort following the purchase of the heat pump. Tables 7 and 8 summarise these answers. Here it is seen that more than half of the respondents indicated that they heated for a longer period and kept a higher temperature after the purchase of the heat pump.

Table 7. Changing heating practices related to heating season after purchase of a heat pump

	Number of households	Per cent (%)
No change	25	33
Heat is turned on for a shorter period of the year than previous	5	7
Heat is turned on for a longer period of the year than previous	42	55
Not applicable, Heat pump installed before we moved in	4	5
Total	76	100

Table 8. Changing heating practices related to temperature after purchase of a heat pump

	Number of households	Per cent(%)
Same temperature as previously	32	42
Temperatures are generally kept higher than previously	40	53
Temperatures are generally kept lower than previously	1	1
Not applicable, Heat pump installed before we moved in	3	4
Total	76	100

The follow-up survey showed that 23 of 27 respondents heated their summerhouse to more than 10 ^{o}C after purchasing the heat pump; all of them, except one, closed the house completely or kept it heated at a lower temperature during the winter before the installation of the heat pump. This supports the previously mentioned findings from the qualitative interviews. It is interesting to note that for the majority of the types of heat pumps, which these people had installed, it was not technically possible to have a set-point temperature lower than 16 ^{o}C, meaning that many of the summerhouses were now heated to 16 ^{o}C during the entire winter. Other air-to-air heat pumps could have the lowest set point at 10 ^{o}C or 18^{o}C and this might thus be crucial for the actual electricity consumption with this kind of use.

The respondents were also asked whether they were aware that their heat pump could be used for air conditioning. Only about half of the respondents among the summerhouse owners were aware of this, and among these, less than half (41%) had actually used it for air conditioning. Table 9 shows that only 6 of these households had used their heat pump for air conditioning more than 5 days a year.

Table 9. Number of days the heat pump has been used for air conditioning in summerhouses

Number of days	Number of households	Percent (%)
1-4 days	10	63
5-9 days	4	25
10-14 days	2	13
Total	16	100

5. TECHNICAL INSPECTIONS

Technical inspections of the heat pumps were carried out in connection with the qualitative interviews. This revealed some examples of technical problems that might have influenced the effectiveness of the heat pumps: In two cases there was a risk of thermal air short-circuits in relation to the condenser and evaporator, which could potentially result in an estimated 10-20% increase in electricity consumption. In a third case, dirt on the evaporator could potentially increase energy consumption by approx. 10%. No visual problems were observed in the other 9 cases. Also, almost 60% of the survey respondents reported that they had regular servicing for their heat pump (buyers of heat pumps from the energy companies are normally offered a yearly servicing scheme). Therefore, it could be expected that the heat pumps covered by this study in general had a high maintenance standard. Among the surveyed heat pumps, this indicated that approx. 25% of the heat pumps might have technical problems which could result in extra 10-20% electricity consumption for these specific heat pumps. The study thus indicates that technical defects were part of the explanation of the lacking energy savings but not the main important factor.

6. CONCLUSION

The study showed that the expected reductions in electricity consumption by substituting direct electric heating with air-to-air heat pumps in individual households were only to some extent achieved in real life settings. It was found that in many cases households increased their comfort through changed heating practices or by expanding other energy-consuming practices rather than by realizing the potential energy savings. On one hand, this confirmed the general learning from socio-technical studies that new technological solutions were in most cases accompanied by new norms and practices. In a techno-economic perspective this had been discussed within the frame of the rebound effect. Previous research indicated a direct rebound effect of 20% in households [12]. Based on the results presented in this paper, the rebound effect for air-to-air heat pumps installed in summerhouses could be estimated to 100%, as on average there was no realised reduction, whereas in permanently occupied dwellings there was on average a 26% reduction, which indicated an overall rebound effect of about 20%. In future energy planning, it is important to be aware of these socio-economic processes, which considerably reduce the actual energy savings that can be obtained from introducing new and more efficient technologies like heat pumps. There are basically two different approaches in dealing with this. One way would be to include the rebound effect and the increased consumption following from new norms in energy modelling and energy planning. Another more preferable way would be to develop measures that have proven successful in real life on how to introduce new efficient technologies to users without resulting in practices changed to achieve higher norms and expectations and thus growing energy consumption. One way of doing this could be by introducing progressive energy tariffs together with the more efficient technologies [19].

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Appendix A: Full regression analysis of the households primarily using direct electricity before they purchased a heat pump and primarily used the heat pump after: including t-test to determine which variables are significant. No variables are significant.

Coefficients[a]

Model		Not standardised Coefficients		Standardised Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	19814.026	31685.786		.625	.537
	Xbefore	.502	.085	.649	5.915	.000
	Adults	-70.960	810.033	-.010	-.088	.931
	Children	-422.075	677.919	-.081	-.623	.538
	House_size	15.712	19.902	.097	.789	.436
	House_age	-10.594	15.900	-.064	-.666	.510
	Person_changes	-738.384	1702.737	-.038	-.434	.668
	HeatPump_only	-1852.963	1117.192	-.159	-1.659	.108
	HeatedArea	15.238	18.933	.084	.805	.427
	NewRooms	.426	23.776	.002	.018	.986
	Fireplace	-477.153	1027.360	-.050	-.464	.646
	HeatPeriod_chng	-1024.791	823.045	-.122	-1.245	.223
	HeatTemp_increase	-428.353	893.299	-.056	-.480	.635
	Cooling_days	191.214	128.039	.156	1.493	.146
	Appliances_chng	399.078	337.810	.133	1.181	.247
	CFL	-731.567	818.226	-.077	-.894	.379
	Appliances_new	430.671	418.707	.101	1.029	.312
	Settopbox_new	392.997	710.540	.051	.553	.584
	TV_exstra	951.408	1290.617	.087	.737	.467
	PC_extra	433.857	900.332	.048	.482	.634
	InsolateHouse	486.183	911.352	.047	.533	.598
	Income_household	2.919	2.316	.136	1.260	.218
	Firewood_save	64.071	1193.305	.006	.054	.958

a. Dependent Variable: Xafter

Appendix B: Full regression analysis of all households in the survey including t-test to determine which variables are significant. TV_extra and Income_Household are significant.

Coefficients[a]

Model		Not standardised Coefficients		Standardised Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7767.307	23158.526		.335	.739
	Xbefore	.559	.068	.730	8.205	.000
	PrimaryAfter_not_elheat	-2012.748	1222.823	-.172	-1.646	.105
	PrimaryAfter_elheat	1066.528	925.510	.081	1.152	.254
	PrimaryBefore_not_elheat	3563.225	3899.641	.252	.914	.365
	PrimaryBefore_elheat	2417.948	3905.136	.175	.619	.538
	Adults	-461.929	603.701	-.048	-.765	.447
	Children	-59.842	441.250	-.010	-.136	.893
	House_size	16.239	10.657	.115	1.524	.133
	House_age	-4.933	12.102	-.025	-.408	.685
	Person_changes	1800.260	1365.837	.098	1.318	.193
	HeatedArea	-7.107	12.656	-.038	-.562	.577
	NewRooms	-3.142	21.338	-.010	-.147	.883
	Fireplace	-1022.652	887.956	-.096	-1.152	.254
	HeatPeriod_chng	-1016.633	533.758	-.119	-1.905	.062
	HeatTemp_increase	281.046	650.248	.028	.432	.667
	Cooling_days	85.050	80.368	.070	1.058	.294
	Appliances_chng	106.592	253.996	.031	.420	.676
	CFL	-1048.031	683.312	-.091	-1.534	.131
	Appliances_new	-216.478	686.176	-.022	-.315	.754
	Settopbox_new	36.928	633.955	.004	.058	.954
	TV_exstra	2297.504	812.431	.196	2.828	.006
	PC_extra	302.535	678.122	.029	.446	.657
	InsolateHouse	-544.083	795.562	-.045	-.684	.497
	Income_household	4.357	1.847	.180	2.359	.022
	Fireplace_instal	194.599	1946.206	.008	.100	.921
	Firewood_save	1119.234	875.294	.091	1.279	.206

a. Dependent Variable: Xafter

Appendix C: Explanations of variables used in regression analysis

Variable	Explanation	Code
Adults	Number of adults in the household	Number
Children	Number of children in the household	Number
House_size	Area of the house in square meters of the house	m^2
House_age	Year of construction of the house	Year
Person_changes	Changed number of people in household before and after HP installation	More people=1 Same=0 Fewer people=-1
HeatedArea	Square meters heated by the HP	m^2
NewRooms	Are more rooms heated after installation of HP, (in square meters)	m^2
Fireplace	Is there a fireplace in the house	yes=1 no=0
HeatPeriod_chng	Do you heat for a longer period after installation of HP	longer=1 same=0 shorter=-1
HeatTemp_increase	Do you keep a higher temperature after installation of HP	higher=1 same=0 lower=-1
Cooling_days	How many days in an average summer is HP used for cooling?	number
Appliances_chng	Number of white goods changed after installation of HP	number
CFL	Changed a majority of the lighting to CFL	yes=1 no=0
Appliances_new	Number of new appliances (not substituting previous of the kind)	number
Settopbox_new	Have settopbox been installed since installation of HP	yes=1 no=0
TV_exstra	Have the number of TVs in use been changed since installation of HP	higher=1 same=0 lower=-1
PC_extra	Have the number of PCs in used been changed since installation of HP	higher=1 same=0 lower=-1
InsolateHouse	Is the house insulated since installation of HP	yes=1 no=0
Income_household	Household income	1000 DKK
Fireplace_instal	When was fireplace installed	After HP=1 Before HP=0
Firewood_save	Changes in amount of firewood used	higher=1 same=0 lower=-1

REFERENCES

1. S.I. Heimdal, Reliability of air to air heat pumps and their contribution to energy savings in Norway, in: Energy efficiency first: The foundation of a low-carbon society. Proceedings of the ECEEE summer study 2011, Presqu'île de Giens, France, 2011, pp. 1807-1813.

2. H. Singh, A. Muetze, P.C. Eames, Factors influencing the uptake of heat pump technology by the UK domestic sector, Renewable Energy 35 (2010) 873-878.
3. M.S. Torekov, N. Bahnsen, B. Quale, The relative competitive positions of the alternative means for domestic heating, Energy 32 (2007) 627-633.
4. F. Suerkemper, S. Thomas, D. Osso, P. Baudry, Switching from fossil fuel boilers to heat pumps: A multi-perspective benefit-cost analysis including an uncertainty assessment, in: Energy efficiency first: The foundation of a low-carbon society. Proceedings of the ECEEE summer study 2011, Presqu'île de Giens, France, 2011, pp. 1685-1695.
5. T. Terlizzese, E. Zanchini, Economic and exergy analysis of alternative plants for a zero carbon building complex, Energy and Buildings 43 (2011) 787-795.
6. P. Johansson, A. Nylander, F. Johnsson, Electricity dependency and CO_2 emissions from heating in the Swedish building sector: Current trends in conflict with governmental policy?, Energy Policy 34 (2006) 3049-3064.
7. M. Bojic, N. Nikolic, D. Nikolic, J. Skerlic, I. Miletic, A simulation appraisal of performance of different HVAC systems in an office building, Energy and Buildings 43 (2011) 1207-1215.
8. I. Sartori, B.J. Wachenfeldt, A.G. Hestnes, Energy Demand in the Norwegian building stock: Scenarios on potential reductions, Energy Policy 37 (2009) 1614-1627.
9. B.V. Mathiesen, H. Lund, K. Karlsson, 100% Renewable energy systems, climate mitigation and economic growth, Applied Energy 88 (2011) 488-501.
10. E. Shove, Comfort, cleanliness and convenience: The social organization of normality, Berg, Oxford, 2003.
11. L.A. Greening, D.L. Greene, C. Difglio, Energy efficiency and consumption: The rebound effect – a survey, Energy Policy 28 (2000) 389-401.

12. S. Sorrell, J. Dimitropoulos and M. Sommerville, Empirical estimates of the direct rebound effect: A review, Energy Policy 37 (2009) 1356-1371.

13. Dansk Energi, Dansk Elforsyning Statistik 2009, Dansk Energi, Copenhagen, 2010.

14. N. Kofoed, E.R. Rasmussen, P. Weldingh, J. Worm, L.A. Rasmussen, M. Reuss, K. Ellehauge, C. Kjærgaard, O.M. Jensen, Elbesparelser i sommerhuse her og nu, Danish Building Research Institute, Aalborg University, Hørsholm, Denmark, 2010.

15. H. S Andersen Sommerhuse og sommerhusejere i Danmark. Center for Bolig og velfærd 2008

16. T.H. Christensen, K. Gram-Hanssen, P.E. Petersen, T.F. Larsen, E. Gudbjerg, L.S Rasmussen, P. Munter, Air-to-air heat pumps: A wolf in sheep's clothing, in: Energy efficiency first: The foundation of a low-carbon society. Proceedings of the ECEEE summer study 2011, Presqu'île de Giens, France, 2011, pp. 1963-1974.

17. S. Kvale, Interviews: An Introduction to Qualitative Research Interviewing, Sage, Thousand Oaks, CA, 1996.

18. K. Gram-Hanssen, T.H. Christensen, P.E Petersen, T.F. Larsen, E. Gudbjerg, L.S Rasmussen, P. Munter, Energy Savings with Air-to-Air Heat Pumps: True or False? Findings and Policy Implications from a Danish Study, paper presented at the 6th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL), 24-26 May 2011, Copenhagen.

19. T.H. Christensen, K. Gram-Hanssen, P.E. Petersen, P. Munter, R. Marsh, T.F Larsen, E. Gudbjerg, L.S. Rasmussen, Varmepumper og elforbrug : Betydningen af ændrede komfortpraksisser, Danish Building Research Institute, Aalborg University, Hørsholm, Denmark, 2011.

20. B. Allibea, M-H. Laurenta, D. Osso, Bound the rebound! How the combination of progressive energy tariffs and adapted soft loans can curb rebound effect and promote

energy sufficiency, in: Energy efficiency first: The foundation of a low-carbon society. Proceedings of the ECEEE summer study 2011, Presqu'île de Giens, France, 2011, pp. 89-96.

Figure captions

Figure 1. Comparing annual household electricity consumption before and after a heat pump was installed. Electricity consumption for heating is corrected for degree days.

Figure 2. Average savings in annual household electricity consumption (kWh) before and after a heat pump was installed, for different combinations of heat supply before and after installation of a heat pump. For all four cases, the savings differ significantly from zero.

Figure 3. Comparing annual household electricity consumption before and after a heat pump was installed for households that used direct electric heating before and distributed on what type of heating they used afterwards. Electricity consumption for heating is corrected for degree days.

Figure 4. The average household electricity consumption, distributed on the year of heat pump purchase. Dotted lines indicate electricity consumption after the heat pump purchase.

Figure 5. Comparing annual household electricity consumption before and after a heat pump was installed in summerhouse. Electricity consumption for heating is corrected for degree days.