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IMPROVING THE INTERACTION BETWEEN NET-ZEB AND THE GRID USING ADVANCED CONTROL OF HEAT PUMPS

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ABSTRACT

Design principles in Net-ZEB consider the local energy infrastructure as the virtual storage. Thus a large amount of energy exchange occurs with the grid and these buildings rely heavily on the grid to reach annual zero balance. Wide-spread application of such buildings could soon saturate the grid hosting capacity and limits their effectiveness on larger scale. In order to design buildings that effectively interact with the grid, well-designed energy solutions are paramount. As the recent market trends show strong growth in heat pumps and the photovoltaic applications, this study investigates the flexibility of such all-electric Net-ZEB (using electric heat pump with photovoltaic) that it could offer to the grid. Four different strategies of heat pump with thermal energy storage (TES) are compared to a directly coupled heat pump (reference) case. The flexibility of these cases to self-consume the onsite electrical production and reduce their interaction/impact on the grid is analyzed. Results shows that using the TES with proper control can lead to 10% increase in the self-consumption, 35% reduction in the peak-exchange hours and 5% reduction in import bills. The results show that major part of the improvement in the self-consumption and exchange hours can already be realized using standard-sized TES with application of proper control. However, the reduction in import bills has more strong dependency on TES capacity. In overall, results shows that with proper application of control strategy, significant maneuvering space in demand-supply matching could be achieved at the level of an individual building.

INTRODUCTION

Background

Building stock accounts for nearly 40% of the European Union final energy consumption and nearly 36% of its CO_2 emissions leading to huge environmental and economic challenges. According to a McKinsey assessment on average cost of end use energy savings, building sector is the most economical and carries the highest potential towards energy efficiency (McKinsey and Company, 2009). Recognizing this potential, European commission in its recast directive (EU Parliament, 2010) has obliged that all new buildings should be nearly zero energy buildings by 2020.

Net-Zero Energy Building Concept

Although, no clear definition exists on 'nearly zero energy building' from the EU directive, several definition could be found in literature (Marszal et al., 2011). In its simple concept, net-zero energy building is a building that produces as much energy as it consumes over the year leading to net-zero energy on annual basis. The concept, in practice, is realized using a combination of energy efficiency measures on the building side along with local renewable energy production. Current approaches to energy efficient buildings (Lautsen, 2008) has led to strong growth in heat pump applications (EHPA, 2012). Along with sustained growth in photovoltaic markets (EPIA, 2009), a combination of heat pump and photovoltaic appears to become a standard solution in Net-ZEB buildings. As heat pumps are available in several different types, air-to-water and ground-source water-to-water heat pumps due to their higher efficiencies have the highest potential for low energy houses (Alonso and Stene, 2010). Although, water-to-water heat pumps has better efficiencies compared to air-to-water heat pump, the additional investment cost of source-side collectors for water-to-water heat pumps favors does not provide favorable economy. Consequently, application of energy supply solution based on air-to-water heat pumps in heating systems and photovoltaic in onsite energy supply systems in residential sector has got increased focus in Net-ZEB context.

Application of such solutions leads to finally a building that consumes electricity as the single fuel for both the heating and the non-heating purposes. Whereas, strong seasonal and diurnal variations in solar irradiance at higher latitudes like Norway does not coincide with the building loads resulting into strong exchange of electricity between the Net-ZEB concept and the grid (Dar et al., 2012b). Although, such exchange at level of individual building has little significance, wide-spread penetration of Net-ZEB with such disparity would meet the grid capacity limitations. In a worst case scenario, poorly-designed Net-ZEB could require further expansion of grid transmission capacities and increased number of balancing powers. As the core objective of Net-ZEB concept is to improve the performance of overall energy system, large scale integration of such all-electric Net-ZEB requires solutions where both the amount, as well as temporal distribution of this energy exchange is well adapted to the grid. As such, a particularly intriguing question lies in the potential demand-side management (DSM) of heat pump by introduction of thermal energy storage (TES) systems leading to two potential scenarios: i) where heat pump is driven by onsite photovoltaic production to minimize the grid export ii) where heat pump is controlled to level-off the grid exchange profile. The first scenario could be seen as promoting building energy supply security whereas the second scenario can study the active role of Net-ZEB towards Smart Grid implementation. Thereby, the gap between the two scenarios could be seen as the flexibility that an all-electric Net-ZEB could offer to the grid.

Objectives of the paper

The aim of this paper is therefore, to quantify active role of heat pump concepts in an all-electric Net-ZEB. Specific objectives of this paper are thus to investigate:

i. the maximum self-consumption that could be realized by an onsite-production driven heat pump

ii. the availability of Net-ZEB to respond to external signal

iii. the flexibility offered by an-electric Net-ZEB to the grid

The remainder of this paper is structured as follows. Next section introduces the methodology and investigated cases whereas the results and the main conclusions are presented subsequently.

METHODOLOGY

Numerical Setup

A simulation methodology is used to investigate different configurations of energy system. Increased focus is placed on the system side while building-side is simplified. The simulation model is set up to reduce computational effort while keeping integrity of the results. This is done by providing same level of accuracy among different simulation. For this purpose, the building model is implemented after the five-resistance single capacitance model presented in (ISO13790, 2008) whereas the performance of heat distribution and emission systems in the building are modeled according to (EN15316-2-1, 2007). The model for heat pump is implemented after the quasi-steady state approach (EN15316-4-2, 2008). However the models for stratified storage (Newton, 1995), and photovoltaic systems (Duffie and Beckman, 2006) are implemented using a dynamic approach. All the model are implemented in Matlab using Object-Oriented Programing (Mathworks, 2012). Further details on the methodology could be found in (Dar et al., 2012a). The models are adapted to enable simulation at any discrete time steps. Here a time-step of 10-minutes is used for the analysis.

Detached single family house

A typical Norwegian two-storey detached single-family house with a total heated area of 178 m^2 is considered. The building thermal properties are adjusted to fulfill Norwegian passive house requirement (NS3700, 2010). Drastic reduction in envelop losses is achieved by application of thermal insulation with overall heat transfer coefficient of 0.15 $W/(m^2.K)$, 0.11 $W/(m^2.K)$, 0.12 $W/(m^2.K)$, 0.72 $W/(m^2.K)$ for external walls, floor, roof and windows, respectively. The building is assumed to be tightly constructed such that infiltration losses does not exceed 0.60 h^{-1} at 50 Pa. A mechanically balanced ventilation unit with a ventilation rate of 1.2 $m^3/(h.m^2)$ and a heat recovery unit with exchange effectiveness of 85% are assumed. The house is simulated for the Oslo climate having an outdoor design temperature of -25^{o}C and an annual mean temperature of 6.3 ^oC. The house is modeled using a single zone. Finally, the heating needs of the house are evaluated to fulfill the normative criteria for passive house. This is done by using internal gains, temperature set-points and occupancies schedules as set by the Norwegian passive house standard (NS3700, 2010). The annual space heating needs result into 18 $kWh/m^2/y$ and thus meets the Norwegian passive house requirement. For rest of the paper, representative profiles for the internal gains, appliances, light and domestic hot water extracted from a modified Richardsons load model are used (Dar et al., 2012a).

Energy supply system

Two different hydraulic configurations for the heating system are analyzed in this study. In both configurations, heating system consists of an inverter-controlled air-to-water heat pump and a stratified storage tank. The reference characteristics for the heat pump are derived from a 16 kW nominal Mitsubishi's Zubadan model having a COP of 3.84 (7 ^oC/ 35^oC) (Mitsubishi Electric). The heat pump has a frequency-controlled compressor and could modulate down to 30%. The supply temperature of the heat pump depends on outdoor air temperature and could deliver maximum supply temperature up to 57 ^oC at -10 ^oC. Variation in heat pump characteristic as function of different disturbances such as temperatures on source and sink side is defined by manufacturer data according to standard reference conditions (EN14511-4, 2007). For remainder of the paper, the heat pump characteristics are kept constant although nominal power of the heat pump is sometimes changed. The storage tank in the heating system is modeled as a 20-stratification layers tank having a 15 cm thick uniform PUR insulation (with thermal conductivity of 0.049 $W/[m^2.^oC]$). The thermal bridges due to valves are taken into account by increasing the overall-thermal heat transfer coefficient using a multiplier. The multiplier is a function of storage tank size and in varies between 1.3 (0.1 m^3) to

2 (10.0 m^3). Losses from the storage tank are modeled inside the conditioned zone. The heating in the house is supplied using low-temperature radiators with design-supply/return temperatures of 40/30 ^oC.

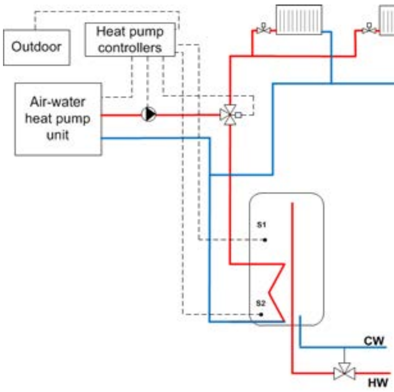

Figure 1: Schematic diagram of directly coupled (reference) heating system configuration

For the reference case, the heat pump is directly coupled to both the space heating distribution system and a 300*l* domestic hot water storage tank (through a heat exchanger) as shown in Figure 1. The heat pump works in alternative duty mode between space heating or domestic hot water (storage) heating modes. The selection of the heating duty is decided by a controller that diverts the three-way valve to the selected mode. The controller prioritizes the domestic hot water heating in case of simultaneous need. The house is heated with a temperature set-point of 20.5 ^oC having a deadband of 1 ^oC, whereas loading of storage tank is controlled using a sensor located in the top and the bottom part of the tank. In the space-heating mode, the supply set-point (SSP) temperature of the heat pump is adapted according to outdoor temperature: this is done by defining a temperature curve as a function of outdoor temperature taking the emitters design characteristics into account (EN15316-4-2, 2008).

Table 1: Reference system control strategy

Space heating mode
$if\ T_z < (20.5 - 1) \vee (T_z <= 20.5 \wedge hp_m = sh)$
$then\ hp_m = sh$
$elseif\ T_{op} >= 20.5 \quad then\ hp\ off$
Domestic hot water mode
$if\ (T_{s1} < T_{dhw}) \vee (T_{s2} <= (T_{dhw} + 5) \wedge hp_m = dhw)$
$then\ hp_m = dhw$
$elseif\ T_{s2} > (T_{sp,dhw} + 5)\ \ then\ hp\ off$
$\wedge$: *and* , $\vee$: *or* , $<$: $lessthan$, $>$: $greaterthan$

The second configuration of the heating system is shown in Figure 2. Here the heat pump is coupled to a TES that supplies both the DHW and the space heating needs to the house. As the heat pump's COP drops as a function of supply temperature, the storage tank is divided into two temperature zones that enable to load the storage tank at different temperature. This is done by installing a heat exchanger both in the upper and the lower zone. The selection of loading temperature as well as loading zone is decided by the applied control strategy.

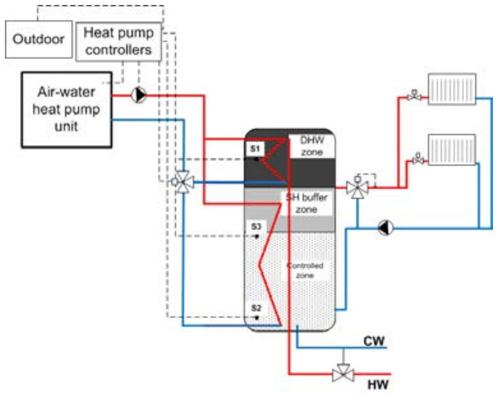

Figure 2: Schematic diagram of heating system configuration using TES

Control strategies

TES decouples the demand and supply interaction and enable to investigate different control strategies. Several different investigations on such combinations could be found in literature. While the main focus of most of these studies has been on improving heat pump performance, investigation in Net-ZEB context has been very limited. Whereas the model predictive controls (MPC) have been widely studied and has showed advantages over other types of controls, challenges in dynamics identification for non-linear systems (like building and thermal energy storage) and expensive computation involved in MPC implementation is considered restrictive in their wide-spread application. Therefore, simple control algorithms that are based on the combination of short-term prediction and real-time measurements are presented in this study. Accordingly, three different control strategies are studied.

i. Firstly, a standard control scheme with TES is simulated. Similar to the reference system, the heat pump provides both the space heating and the DHW heating and is prioritized to ensure the DHW comfort. Control of temperature in upper and lower zone is controlled using two sensors (S1 and S2): one in each zone. The set-point temperature in the upper zone is decided by maximum supply temperature of heat pump while the set-point temperature of lower zone is adjusted as similar to the reference system using the outdoor compensation curve.

ii. The second strategy enhances the self-consumption of onsite electricity production in Net-ZEB. While the domestic hot water comfort is ensured in similar way, operation of heat pump outside the onsite production hours is minimized by reducing the comfort buffer for space heating. This is done by placing additional sensors (S3) below the supply line of the space heating circuit in the storage tank. The space-heating comfort is still maintained by tighter control over S3 however, reduction in space-heating comfort buffer could result into frequent cycling of heat pump in cases with smaller storage sizes. The zone between S2 and S3 is thus utilized to consume the excess onsite electricity that would otherwise have to be delivered to the grid. Matching between the transitory heat pump electrical consumption and excess electrical exchange is achieved by controlling the compressor power. It is well known that the heating capacity and coefficient of performance (COP) of an air-to-water heat pump are strongly dependent on the supply temperature on the condenser side and the outdoor temperature on evaporator side as given in Equation 1.- 3.. Nevertheless, actual work done by the compressor depends on the load applied on the condenser side (Equation 4.), control of condenser supply temperature offers the largest flexibility.

$$Q_{hp} = f(T_{sup}, T_{outdoor}) \tag{1}$$

$$COP_{hp} = f(T_{sup}, T_{outdoor}) \tag{2}$$

$$E_{hp} = \frac{Q_{hp}}{COP_{hp}} \tag{3}$$

$$Q_{load} = f(V, SOC, T_{sup}, T_{ret}) \tag{4}$$

As a result, the control strategy is defined to adapt the supply temperature according to predicted excess onsite production. This is done by predicting next 10 minutes excess electricity and conform the load on the condenser side to match the onsite excess electricity. This is done by iteratively guessing the supply temperature (based on a real-time temperature measurement at S2 and state of charge (SOC) of controlled zone) and hence solving the load on condenser side and the SPF of heat pump. In this way, supply temperature set point for the next time step is defined to scale the momentary compressor power as close as possible to excess onsite energy.

iii. The third control strategy is defined to improve the relation of the Net-ZEB with the grid. Here, the optimizing problem is defined to analyses the potential of Net-ZEB to actively response to the grid. As such, thermal energy storages (TES) are considered active element in Smart-Grid applications. In such applications, a signal to identify energy contents of TES is needed. For this purpose, a state of charge that represents the average energy contents at S2 and S3 is defined. As the storage tank serves for both domestic hot water and space heating needs, S3 is used to define DHW energy contents while S2 is used to identify space heating energy contents. This enables to define the control strategies that operate the heat pump while keeping track of the energy contents of the store. While the Smart-Grid could offer extensive communication among different appliances as well as energy markets, here control of power exchange by only active control of heat pump is studied. To study the impact of such control on exchange profile, two control variants with a local and global variable are identified. In the local control variant, the control scheme is implemented at building scale to limit the exchange of the building within a certain threshold limits. This is done by switching on the heat pump if the excess onsite production exceeds the threshold limit and switching off the heat pump if electricity delivered by grid exceeds the threshold limit and additionally implementing a minimal cycle length of heat pump. In the global control variant, control scheme is implemented to operate the heat pump to maximize its operation during low-tariff hours. The hourly point tariff is considered to represent the stress on grid and control is considered equivalent to shift the demand from high-stress to low-stress periods. The control is implemented using day-ahead prices obtained from the Nordic power market. The prices are published for the next day before 12:00 AM at Nord Pool website NordPool (2012).

Table 2: TES with different control strategies

TES with Standard control
<u>*Space heating mode*</u>
$if\ (T_{s2} < (T_{ssp} - 2)) \vee (T_{s2} <= T_{ssp} \wedge hp_m = sh)$
then $hp_m = sh$
$elseif\ (T_{s2} > T_{ssp})$ *then hp off*
<u>*Domestic hot water mode*</u>
$if\ (T_{s1} < T_{dhw}) \vee (T_{s1} <= (T_{dhw} + 5) \wedge hp_m = dhw)$
then $hp_m = dhw$
$elseif\ (T_{s1} > (T_{s,dhw} + 5))$ *then hp off*
TES with self-consumption control
comfort constraints on s1 and s3
$if\ (P_{ex} > 0) \wedge (T_{s2} < T_{ssp})$
then solve predictive set-point algorithm
$elseif\ (P_{ex} <= 0) \vee (T_{s2} >= T_{ssp})$
then hp off
TES with power-exchange limit control
comfort constraints on s1 and s3
$if\ ((T_{s2} < T_{ssp}) \wedge (P_{ex} > P_{lim,d})) \vee ((SOC < 0.5)$
$\wedge (P_{ex,a} - E_{hp}) > -2500)$
then hp on
$elseif\ (t_{hp,op} >= 20 \wedge (SOC > 0.8 \wedge ((P_{ex,a} - E_{hp})$
$< P_{lim,d}) \vee (P_{ex,a} < -2500) \vee (T_{s2} > T_{ssp}))$
then hp off
TES with load-shift control
comfort constraints on s1 and s3
$if\ (T_{s2} < T_{sp} \wedge TR < TR_{lim})$
then hp on
$elseif\ (t_{hp,op} >= 20 \wedge (SOC > 0.8 \vee TR > TR_{lim}))$
then hp off

$\wedge$: and , $\vee$: or , $<$: $lessthan$, $>$: $greaterthan$

Evaluation criteria

The effectiveness of different strategies is analyzed using the energy exchange between the building and the grid as well as the energetic performance of the overall system. The energy exchange between the building and the grid is computed for each time-step at building boundary and is distinguished between energy import and energy export as given in Equation 5 -7 . The non-simultaneity between building loads and the onsite-production and the quality of exchange are analyzed using self-sustenance factor (SSF) (Born, 2001) and extent of exchange (Salom et al., 2011) defined using Equation 8 and 9 . An additional factor to account for load shifting from high tariff to low tariff period is defined using relative import bill (RIB) given by the Equation 10. Further, the energy performance analysis of both systems is presented using annual seasonal performance (SPF) factors given in Equations 11 and 12 .

$$nex(t) = e_{pv}(t) - e_{bdg}(t) \tag{5}$$

$$d(t) = max(0, (e_{pv}(t) - e_{bdg}(t))) \tag{6}$$

$$i(t) = min(0, (e_{pv}(t) - e_{bdg}(t))) \tag{7}$$

$$SSF = \frac{\sum i(t)}{\sum e_{bdg}(t)} \tag{8}$$

$$E_{>xlim} = \sum(nex(t) > xlim) \tag{9}$$

$$RIB = \frac{\sum(i(t).TR_{actual}) - \sum(i(t).TR_{min})}{\sum(i(t).TR_{max}) - \sum(i(t).TR_{min})} \tag{10}$$

$$SPF_{hp} = \frac{\sum(Q_{hp})}{\sum(E_{hp}) + \sum(E_{par})} \tag{11}$$

$$SPF_{sys} = \frac{\sum(Q_{shn}) + \sum(Q_{dhw})}{\sum(E_{hp}) + \sum(E_{par}) + \sum(E_{aux})} \tag{12}$$

In all simulation cases, the photovoltaic sizing is done to ensure an ideal zero balance such that:

$$\sum_{0}^{\tau} e(t) + \sum_{0}^{\tau} d(t) = 0 \tag{13}$$

RESULTS AND ANALYSIS

Table 3 shows the energetic performance along with exchange indicators for all simulated cases. Starting with the cases where heat pump is strongly coupled to building, electrical load of heat pump along with onsite excess electricity is analyzed. Figure 3. and Figure 4. shows the heat pump and onsite excess electricity profiles for an example week of winter and summer respectively. Looking at winter week profile for reference system and system with buffer tank it could be seen that in both concepts, the heat pump either working at minimum power or switches-off during high onsite production hours. This could be attributed to increased solar gains during hours of high onsite production as well as increased internal gains during day-time leading to reduced heating needs and thus heat pump is only able to consume a very small fraction of onsite-excess electricity. On the other hand, during summer period, the heat pumps are only used to load the DHW storage. To avoid frequent cycling of heat pump and elongate the operating time, heat pumps in such conditions are configured to wait until storage tank is empty. As a result, they operate during night or early morning-hours. As a consequence, most of the excess electricity is exported to the grid and only 20% of onsite excess production is consumed by the building loads. Looking at quality of exchange for the two reference cases, Table 3 reports the number of hours of energy exchanges above lower and upper thresholds. As expected, the number of hours when exchange exceeds certain threshold level reduces in case of export hours from 426 h to 372 h and in case of import hours from 480 h to 407 simply by introduction of TES. Although, no particular control on exchange limitation has been implemented, the improvement could attributed to the smaller nominal power of heat pump required in case of TES. Moreover, introduction of TES also flattens the load on heat pump compared to directly coupled system.

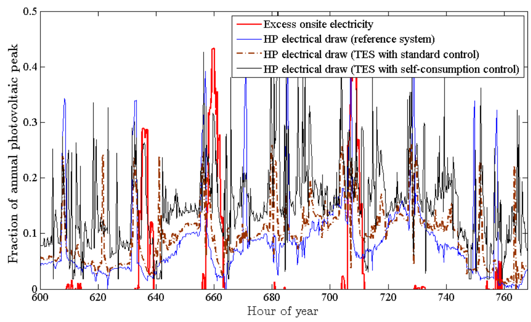

Figure 3: Profile of excess onsite production and heat pump electrical consumption for an example winter week

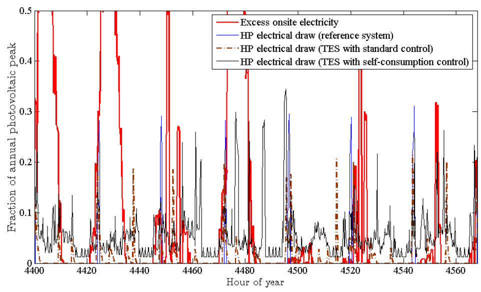

Figure 4: Profile of excess onsite production and heat pump electrical consumption for an example summer week

Improving self-consumption

Although in theory, heat pump could be operated during onsite-excess production hours to store heat in TES, standard controls to merely enforce heat pump switching during excess production has shown limitation in reaching improving self-consumption. In such controls, a contrast in profiles of the two entities exists. On one side, the heat pump in such control works independent of onsite production and operates at full loads to meet the loads that are set by comfort control whereas on the other side, the onsite production has a strong variability in profile and increasing along the day with highest peak somewhere at mid-day. As a result of standard controls, under favorable outdoor

Table 3: Results of different heat pump control strategies for an all-electric Net-ZEB

System Type	Control scheme	Storage size	SPF HP	SPF SYS	Self-sustenance factor	Relative import bill	Extent of export	Extent of import
–	–	l	–	–	%	%	h	h
Reference	Standard control	300	2.86	2.41	20.4	43.3	426	480
System with thermal energy storage	Standard control	500	2.88	2.19	21.5	43.2	372	407
	Self-consumption control	500	2.66	2.12	26.2	41.6	360	339
		1000	2.74	2.15	30.2	42.2	303	285
		1500	2.72	2.11	30.7	42.4	306	288
		2000	2.70	2.07	31.0	42.3	305	305
	Power exchange limit control	500	2.88	2.31	21.7	42.8	413	334
		1000	2.88	2.29	21.7	42.5	400	330
		1500	2.87	2.27	21.7	42.3	392	327
		2000	2.86	2.46	21.9	42.3	387	322
	Load-shift control	500	2.79	2.25	21.2	40.1	435	290
		1000	2.81	2.24	20.9	39.5	440	305
		1500	2.81	2.22	20.9	38.9	440	304
		2000	2.80	2.20	20.8	38.2	451	311

would apparently offer an improvement in self-consumption, a large exchange between Net-ZEB and grid at higher resolution would exist as the heat pump electrical consumption does not eventually occur at right moments. Additionally, large part of building electrical consumption is caused by non-heating loads and a part of onsite-production is consumed by these loads. As such, coincident operation of heat pump during periods with onsite consumption by non-heating loads would eventually not improve the overall self-consumption. As no electrical storage or demand-side management on non-heating loads is considered in this investigation, therefore, all the excess onsite-production is considered solely available for heat storage or exported to the grid. Therefore, the proposed self-consumption control is connected to exchange meter and acts on 10-minute smoothed exchange. The choice of the resolution on one hand would result in smoothing the disturbances in onsite production whereas on the other hand would even-out the effects of load-spikes due to short-lived peak loads such as microwave. An additional challenge also lies in matching the heat pump electrical consumption to onsite excess production lies in diurnal characteristic of solar production. As the heat pump could not operate below a certain temperature difference on condenser side, enforcing the match between very small production quantities during early and later hours of day would result into unnecessary cycling of the heat pump. Therefore, a minimum temperature different on condenser side is always enforced to avoid such cycling. Looking at results of such control strategy in comparison to reference cases in Figure 3 and 4, it could be seen that profile of electrical energy consumption of heat pump using such control strategy follow the onsite-consumption quite closer as compared to both reference cases.

Further, the results for the control strategy on overall improvement on self-consumption are presented in Table 3. It is found that use of self-consumption control with even same storage size as in standard case could immediately lead to almost 4.8% increase in self-consumption compared to TES with standard control and 5.8% improvement compared to the reference system. It is further found that through reasonable increase storage size; these improvements can be doubled to 10%. Nevertheless, it is found that there is excess electricity and some energy demand for heating, capacity of heat becomes a limiting factor to meet the high ends of excess electricity. As a result, increasing the storage tank beyond certain capacity could not automatically guarantee the increase in self-consumption. Thus, a value of around 30% self-consumption using a storage size of 1000l is found above which only minor improvement in self consumption are noticed by increasing storage size. In order to analyzing the performance of control itself and to identify if the optimum found by control is a global optimum, an ideal heat pump (having a resistance heater like characteristic with a COP of 2.35) with storage tank to enable daily heat consumption is simulated. This results into a theoretical optimum of 33.3 % self-consumption. A first-order comparison of both the results shows that the proposed control strategy has shown quite good performance.

Strengthening the grid

Although, energy exchange of an individual building does not offer challenge to grid, large scale Net-ZEB penetration with large imports or exports powers could lead system overloads. There could be several solutions to such problem with one of the solution to move towards stronger grids with large flow capacities as well as introduction of more balancing powers or another to act on the renewable systems to curtail energy exports. Such solutions do not always improve the overall performance of the system and therefore, application of control strategies to improve the energy exchange at building level to minimize its impact on grid offers an interesting alternative. In identifying such control that curtail the peak power-exchange and have a net-effect of leveling-off the demand profile, performance of a power-exchange limit control and a load-shift control are investigated.

In the first case of peak-shaving control strategies, while the energy import threshold is placed at 2500 Wh, setting a fixed threshold for export does not offer a viable solution to peak-export shaving. This could be associated with diurnal and seasonal variation of onsite production whereas the daily peak enlarges towards the summer when both the heating needs as well as electrical consumption of heat pump is minimal. As the objective of this control strategy is to operate the heat pump during these peak export hours, fixed threshold limit would result into peak shaving of exchange in a local regions and reduction in peak exports hours when grid is facing major capacity limitation issues would not be properly addressed. Therefore, a dynamic threshold limit is selected as 80% of the daily peak in cases where surges above 2500 Wh. peak Although the choice of such peak might itself be a question of optimizing, here the limit is adopted by taking roughly into account the energy demands that could conveniently filled in areas between this threshold and the daily peaks. Eventually, the control strategy is simulated with different storage sizes and results for simulation are reported in Table 3. Comparing the results for extent of export and import with reference system, although reduction in both export and import peaks noticed, effectiveness of control on export threshold has been found limiting.

In the second case of load-shift control, control strategy is investigated to evaluate the flexibility of TES to shift the loads from high demand to the load demand periods. For this purpose, next day tariff is used to control the operation of the heat pump and shift its operation towards the low tariff periods. Simulating with different storage sizes and comparing the results with reference cases, it is found that flexibility in load shifting is directly coupled to the storage size and distribution of heat demand over the day. As increasing storage sizes shows linear improvement in load shift factor, almost 5% improvement in import bill is realized with a 2000 l of storage tank.

Energetic performance

Both the performance of energy distribution system as well as heat pump is strongly dependent on supply side temperature. Higher supply temperatures lower the COPs for the heat pump as well as increase losses related to the distribution circuit and the storage tank. Looking at SPF of the heat pump and the overall system in Table 3, almost 10% drop in SPF due to use of introduction of TES is observed. As in both cases, principally the supply set points are same, increased losses are attributed to the mixing as well as temperature lapse in supply temperature due to thermal mass. As in all the cases, the photovoltaic is designed to meet the zero annual balance, drop in SPF leads to increased requirement of the photovoltaic area.

The control strategies also influence the load profiles of the building. As the application of such control strategies is a subject of wide-spread application, resulting profile would become meaningful in terms of its impact on the grid. Looking at averaged profiles over the whole year as shown in Figure 5., it could be seen that a significant shift in loads profile by introduction of TES is possible. Obvious advantage of TES results in case compared to the reference system that reducing the morning peak. However, the largest influence is noticed by tariff based structure which moves most of the heat pump loads to the night time resulting in significant flattening of the heat pump loads. Nevertheless, the ability of such shift directly depends on the capacity of the TES and flexibility of heating demand of the building. Finally, the profile of TES with self-consumption control shows a rather elongated profile over the day-time and even reduced loads on the evening hours. Keeping in view that a large part of energy export occurs during these hours, this kind of profile in wide spread application would further encourage the self-consumption within the building cluster by inter-consuming the variations in excess consumption.

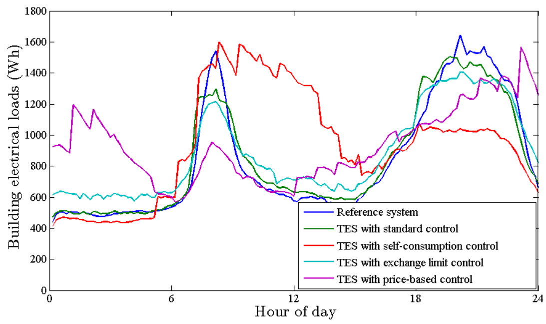

Figure 5: Mean daily load profile of different simulated cases

CONCLUSION AND FUTURE WORK

Improvement in self-consumption

A control strategy to operate the heat pump with energy exchange meter and a short-term load prediction is presented. Results have shown that significant amount of onsite loads could be consumed by the heat pump by such kind of control strategy. A net-reduction of 10.6% in momentarily (10-min) exchange is realized. Compared to ideal control, the proposed control has also shown quite good performance and actually reaches very close to maximum achievable self-consumption. Nevertheless, the control could have limits in term of prediction of onsite electricity and non-heating loads for next time step. As in this study, representative profiles along with exact onsite photovoltaic prediction is assumed, degradation in results could occur in real application.

Benefits to the grid

Investigation has revealed that flexibility offered by heat pump concept is clearly connected with size of thermal energy storage. Investigation of both type of control strategies have shown advantage on reducing the peak imports, potential in reducing the peak exports to the grid is found mainly limited. As the introduction of large TES is found to introduce flexibility in delaying the heat pump loads to feasible zones, large number of export peaks during summer time has shown limitation of concept to reduce these peaks. Nevertheless, it should be noted that this limitation mainly occurs due to only heating loads in the building. Thus, the concept could result in better performance in buildings with cooling load

NOMENCLATURE

The paper uses following variables and parameters in different equations.

Table 4: Parameters and variables used

Symbol	Description
T_{sx}	Temperature of the storage tank at sensor Sx (x = 1,2,3) (^{o}C)
T_z	Temperature of the building zone (^{o}C)
$e_{pv/blg}$	Electricity produced or consumed by PV/building respectively (Wh)
$P_{ex,a}$	Excess onsite production (production cum non-HVAC loads) (Wh)
$P_{lim,d}$	Exchange limit threshold for import and export (Wh)
nex	Net-electrical exchange from the building (Wh)
i/d	Energy impored/delivered by building (Wh)
TR	Hourly point tariff (NOK/kWh)
Q_{hp}	Heat delivered by the heat pump to storage tank (Wh)
E_{hp}	Electricity consumed by the heat pump (Wh)
E_{par}	Electricity consumed by the pumps (Wh)
E_{aux}	Electricity consumed by the back-up heaters (Wh)

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REFERENCES

Alonso, M. J. and Stene, J. 2010. Iea heat pump programme annex 32. umbrella report, system solutions, design guidelines, prototype system and field testing -norway. Technical report.

Born, F. J. 2001. Aiding renewable energy integration through complimentary demand supply matching.

Dar, U., Georges, L., Sartori, I., and Novakovic, V. 2012a. Influence of user-behavior on the energy supply system in net-zeb.

Dar, U., Sartori, I., Georges, L., and Novakovic, V. 2012b. Evaluation of load matching and grid interaction index of a norwegian all-electrical net-zeb under stochastic user loads.

Duffie, J. A. and Beckman, W. A. 2006. *Solar Energy Thermal Processes*.

EHPA 2012. European heat pump market and statistics. Technical report.

EN14511-4 2007. Air conditioning, liquire chilling packages and heat pump with electrically driven compressors for space heating and cooling.

EN15316-2-1 2007. Heating systems in buildings-space heating emission systems.

EN15316-4-2 2008. Heating systems in buildings-space heating generation systems,heat pump systems.

EPIA 2009. Solar generation v-2008: Solar electricity for over one billion people and two million jobs by 2020. Technical report.

EU Parliament 2010. Directive on the energy performance of buildings (recast).

ISO13790 2008. Energy performance of buildings - calculation of energy use for space heating and cooling.

Lautsen, J. 2008. Energy efficiency requirement in building codes, energy efficiency,policies for new buildings.

Marszal, A., Heiselberg, P., Bourrelle, J., Musall, E., Voss, K., Sartori, I., Napolitano, A., and eceee 2011. Zero energy building: A review of definitions and calculation methodologies.

Mathworks 2012. Object-oriencted programming in matlab.

McKinsey and Company 2009. Pathways to a low-carbon economy. Technical report.

Mitsubishi Electric. Ecodan next generation 16 zubadan.

Newton, B. J. 1995. Modeling of solar storage tanks.

NordPool 2012. Historical market data.

NS3700 2010. Kriterier for lavenergi- og passivhus-boligbygninger.

Salom, J., Widen, J., Candanedo, J., Sartori, I., Voss, K., and Marszal, A. 2011. Understanding net zero energy buildigns Evaluation of load matching and grid interation indicators. *Building Simulation and Optimization*.