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Review of HVAC strategies for energy renovation of detached houses towards nZEB in cold climates

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Abstract. This paper provides a review of heat and ventilation measures that can be applied to ambitious energy renovation of detached houses in Nordic countries. In this review, requirements for solutions are defined. Key technologies are described and analysed in the context of renovation. The review focuses on strategies that are simple, cost-effective and robust, and can be transposed to the Norwegian context. The review revealed that a wider range of concepts and strategies than commonly used in Norway seem to be relevant. No solution or system appears to be an obvious and universal choice. A number of very different system solutions, with their pros and cons, are relevant, depending on the individual house and situation. Some combined heat and ventilation systems include hydronic space heating. This is however not common in Norwegian houses, and installing this is a major cost and intervention. Wood stoves, on the other hand, are regular, and can be used for peak heating. These factors seem to be crucial for the choice of system. Improved airtightness after renovation makes systematic ventilation measures necessary. Assumptions for occupant preferences and behaviour also seem to be important for choice of system. There are also differences in the commonly used HVAC concepts and strategies for renovation between the Nordic countries. These differences do not seem to be explained by climate only, and differences in building code may be part of the reason. A number of demonstration projects on ambitious energy upgrading are completed, but few of them have been systematically monitored and evaluated.

1. Background

30% of Norwegian residential buildings are detached houses built between 1950 and 1990. This building stock is reaching a stage where major renovations are needed. Some of these houses are renovated step by step and some in one large operation. Unfortunately, only half of the renovations taking place in Norway include energy renovation. A recent study found that 60% of the Norwegian detached households made no changes to the ventilation system when performing an energy renovation, while only 9% installed balanced mechanical ventilation. Renovation usually includes a substantial improvement in air tightness. This reduces the air change due to infiltration, demanding systematic ventilation measures to provide sufficient indoor air quality (IAQ). The challenge is to develop ventilation concepts that provide good indoor environment and energy performance, and still are simple and affordable enough to actually be implemented.

Renovation requires solutions to a very complex situation. A wide range of heat, ventilation and air-conditioning (HVAC) strategies can be considered, not only the most common ones. Although heating and ventilation systems are interconnected, the main focus in this review is on the ventilation. Strategies such as balanced, exhaust, decentralized and hybrid ventilation are key technologies considered in the review.

2. Method

In the review, research publications have been investigated according to several aspects: the systems overall complexity and robustness, its integration in the existing building structure, energy performance, indoor environment and the possibility to create significant thermal zoning, lifecycle costs, among others. The review focuses on measures that can be transposed to the Norwegian context. Several demonstration projects on ambitious energy upgrading are completed. Nevertheless, few of them have been systematically monitored and evaluated, and the number of studies on HVAC-systems in energy renovation of detached houses in a cold climate, are limited. Therefore, some studies on apartment buildings or milder climates are included. Not all technologies and strategies relevant for energy renovation are thoroughly investigated in a renovation context. Studies on the actual technologies or components themselves, even used in new buildings, can give useful insight. Therefore, some studies about new buildings are included. The reviews primary focus is deep energy renovation, or renovation towards nearly zero-energy buildings (nZEB). However, some less ambitious projects were included when relevant.

3. Requirements

3.1. Existing buildings and HVAC

Due to low electricity prices, very few of the Norwegian detached houses from 1950 – 1990 have hydronic heating [1]. The additional cost to install a hydronic system can strongly impact their cost-effectiveness compared to cheap direct electric heating. Strategies like ventilation radiators also need hydronic heating. Finding space for technical units, including ventilation channels, can be an issue in the small houses. In Norway, most houses have a wood stove that can provide useful peak heating on cold days, reducing the needed power output from the base heating system [1].

3.2. Indoor air quality (IAQ)

There have been some concerns about IAQ after deep energy renovation, due to reduced air change rates from infiltration with more airtight houses. Several studies report good IAQ and good user satisfaction when balanced ventilation is installed. Leivo [2] found slightly better IAQ and better occupant satisfaction after installing heat recovery into exhaust ventilation system in Finnish apartment buildings. Some studies also report good IAQ with exhaust ventilation. Wells [3] found no differences in IAQ between exhaust and balanced ventilation. However, occupants with exhaust ventilation reported their homes as more comfortable. Efficient filtering is an advantage for handling allergy and for polluted outdoor air. If filters are not changed regularly, they can degrade the IAQ.

3.3. Indoor thermal environment

In addition to comfortable operative temperature and moderate temperature stratification, the absence of cold draft is important.

3.4. Temperature zoning.

High insulation levels tend to reduce temperature differences inside the building. This enable to simplify the space-heating distribution using a fewer number of heat emitters [4, 5]. In highly insulated buildings however, many occupants report the bedrooms as too warm even though not equipped with heat emitters. One main reason seems to be that one-zone balanced cascade ventilation with efficient heat recovery moves heat from the warmest to the coldest rooms. High temperatures in bathrooms and living rooms are partly transferred to bedrooms. Many occupants open the windows in bedrooms to reduce the temperatures during winter time, thus increasing energy use for heating. This has been investigated for new buildings by Berge, Georges and Thomsen [4-6]. The same problems could occur in deep-renovated houses, with good insulation and balanced ventilation. Although this finding requires additional confirmation, Klinski [7]reported open bedroom windows in a renovated house where balanced ventilation has been installed. The desire for cool bedrooms is also reported in Denmark, typically 16°C in apartment bedroom [8]. Bjørneboe [9] reported that the occupants preferred a lower temperature in bedrooms also after renovation.

With increasing internal gains from appliances [10], more insulation and a warmer climate, overheating during summer needs to be addressed. Several studies also report floor heating in bathrooms working during summer, increasing the internal heat load [6, 7]. In some cases, better roof insulation can improve the thermal comfort. In one study [9], the house owners reported the house to be cooler in summer and warmer in winter after the renovation. In a Scandinavian climate, solar shading and window cross ventilation is an important strategy. The selected systems should be burglar-proof. Psomas et al [11] investigated automated roof windows to address the risk of overheating in energy renovated dwellings. They found that an automated window system with integrated heuristic passive cooling control strategies significantly decreases the thermal discomfort and overheating risk without any significant compromise on the indoor air quality.

3.5. Occupant sensitivity
Some strategies may fulfil the preference of specific occupants but not for the others. For instance, window ventilation is positive if cooler bedrooms are desired while balanced cascade ventilation favours warmer bedrooms [4, 5]. Some people are very sensitive to the fan sound in bedrooms but not everyone [12, 13]. Systems that can accommodate a very wide range of user preferences are less occupant sensitive. Some systems may also require specific knowledge or skills from the occupants.

3.6. Energy and environmental performance
In addition to a low energy consumption, strategies to minimize the peak power consumption, and adaption to variations in energy prices and supply, is interesting. The ability to store heat is a key factor. The ability to use low temperature heat sources can also be useful.

4. Ventilation

4.1. Mechanical ventilation with heat recovery (MVHR)
Balanced ventilation with heat recovery is one main ventilation strategy for energy efficient buildings. Efficient heat recovery ensures a low energy consumption, preheating of supply air gives good thermal comfort. Controlled ventilation rates and efficient filtering provide good IAQ. The challenges are the limitation for temperature zoning, the requirement to install ducts and the overall investment costs. Some solutions for integrating ducts are shown in Lien et al. [14]. Some other studies [15, 16] investigated a system with the heat exchanger and part of the ducts integrated into the façade. Installing MVHR in some rooms and leaving some rooms (typically bedrooms) outside the MVHR system, is also a way to reduce the duct work, although this is not described in field studies. In renovation projects, it is difficult to ensure low infiltration and this reduces the heat recovered by the heat exchanger compared to new buildings. Measured infiltration values before renovation are typically between 4 and 10 ach and are reduced to between 1.0 and 2.5 ach after renovation [9, 14, 17]. These studies refer to only one case each.

4.2. Real heat exchanger efficiency.
Several field studies show a lower heat recovery efficiency than the nominal value. Regarding rotating exchangers, Lassen [18] found 10 to 20% lower efficiency than the nominal value. Petersen et al. [19] measured 5 to 37% below nominal for five schools. Kamendere et al. [16] found a heat exchanger efficiency of 80% at an outdoor temperature of +15°C and 75% at -5°C. The efficiency of the whole ventilation system was lower due to temperature drop in ducts. Merzkirch et al. [20] found an average

IOP Conf. Series: Earth and Environmental Science **352** (2019) 012048 doi:10.1088/1755-1315/352/1/012048

efficiency of 65% for 20 centralized systems, and 70% for 80 decentralized systems. Østin [21] found an efficiency from 72 to 76 % when nominal value was 80% in a new single family house. In a renovated apartment La Fleur [22] reported on a measured recovery efficiency of 57.4% while the estimated value was 70% (based on the nominal value). This could indicate that the real energy performance of MVHR is slightly overrated, having consequences when comparing different strategies.

The possibility of temperature zoning is limited with regular balanced ventilation. However, some possible ways to achieve cool bedrooms without increasing energy consumption have been proposed, but not thoroughly investigated: reducing the efficiency of the heat exchanger [23], balanced supply and extract airflow rates also in bedrooms (meaning removing the cascade flow) [24], automatic stop (or reduction) of the air supply to bedroom when the window is open, or keeping naturally ventilated bedrooms outside the MVHR-system [25].

4.3. Single room ventilation with heat recovery (SRVHR)

Several different systems and sizes of decentralized ventilation with heat recovery can be found, from tiny regenerative units to larger counter-flow boxes. These can be completely integrated into the facade or mounted as a box inside the building envelope. Usually no internal ductwork is needed, resulting in lower pressure losses, lower fan consumption and easier installation. For renovation purpose this is a significant advantage, also affecting costs. Natural ventilation in bedrooms, combined with SRVHR in other room has also been used, but no study on this is found. In addition, SRVHR supports temperature zoning as they operate separately for the different rooms.

Single room units often have higher noise levels [20]. To achieve acceptable noise levels, users might reduce the airflow rate, resulting in unsatisfactory IAQ. Some devices have very simple filters, less efficient for pollen [26]. Due to smaller fans with low pressure increase, these systems are more sensitive to the dynamic pressure from the wind and the stack effect. This can cause unbalanced flows and thus lower heat recovery or increased frost risk. Dual units with axial fans are more affected [27, 28]. Nominal heat recovery efficiencies are in the same range as centralized heat exchangers (or only slightly below). Coydon [29] points out that the common methods to evaluate the energy performance of ventilation devices do not take into account all the important aspects, especially for façade integrated ventilation systems. He has developed a calorimetric evaluation method which seems to be more accurate for regenerative heat exchangers. Using this method on façade integrated heat exchangers, one regenerative with alternating flows gets an efficiency of 73,3%, and a counter flow 79,3%.

4.4. Natural ventilation

A number of detached houses are renovated without installing balanced ventilation. Keeping the original natural ventilation system is simple and cheap, without intervention. However, if the air change was based on general infiltration, this strategy collapses completely when the house gets airtight. Lack of ventilation strategy is not comparable to implementation of a natural ventilation strategy. Using natural ventilation requires a systematic approach, with careful design of air vents and stacks, to utilize and control wind- and buoyancy forces. The main challenge with natural ventilation is the lack of heat recovery, leading to colder supply air and a higher space-heating demand. Another issue is to control the ventilation airflow rate. With a purely manual control, the system is dependent on the occupant skills and behaviour. However, automatic window and vent control systems are possible. Sensor-assisted manual control (based on CO_2 or relative humidity) is so far not much investigated

Another issue is the pollution and sound levels outdoors. Some studies have shown low IAQ in naturally ventilated buildings, although this is not always the case. Kamendere [16] measured IAQ in two identical renovated apartment buildings, one with new MVHR and one with the original natural ventilation system. The building had CO_2-concentrations above 1000 ppm 68% of the time for MVHR and 40% using natural ventilation**.** The naturally ventilated building also had slightly higher temperatures and lower RH. From the CO_2-level measurements, it was concluded that the residents regularly ventilated by opening windows (partly compensating for variation in air change rates due to variable outdoor temperature and wind). There are also some reports of occupants blocking ventilation supply terminals in natural ventilated houses. This is usually explained as aiming to prevent draft (due to low temperature of the supply air and poor air mixing, resulting in downward movement of cold air), and a lack of understanding of the real need for sufficient air change. Partial blocking of supply air terminals is also reported in some cases with new MVHR [8]. This seems to depend on design of the inlet and localization of the draft, exposing people or not.

4.5. Ventilated windows (VW)

With exhaust- or natural ventilation, it is still possible to preheat the supply air to some extent by letting it pass through a culvert, or between the glass panes in a ventilated window (VW). The motivation is improving thermal comfort and reducing energy use. The air brings most of the heat loss through the window back in, and typical efficient U-values of 0,4 -0,5 W/m2*K [30]. A cooling effect can also be achieved by letting the air flow between the panes returns to the outside. Liu [31] has investigated the optimal configuration of the panes, for comfort and energy use. Simulations by Carlos et al [32] for Oslo-climate find a preheating of 2-5 degrees without sun, at typical airflow rates, most at the lowest outdoor temperatures. VW might result in more frosted windows on cold days, due to colder outer glass surface.

5. Combined systems (heat and ventilation)

Only technologies that need a specific discussion in the context of renovation are included in this section. Other technologies (like pellet boilers) needing no specific treatment in this context are therefore not discussed here.

5.1. Exhaust (extract) air heat pump (EAHP)

Mechanical exhaust ventilation has some advantages. It requires only one fan, a less complicated duct system and low pressure in the building minimizing the risk of condensation in the construction. The disadvantage is the lack of heat recovery and the risk of poor thermal comfort when cold air is brought directly through the building wall. Heat pumps using the extract air as the heat source can recover more energy than air-to-air heat exchangers. In addition, they can provide both space-heating and heating of domestic hot water (DHW). The maximum heat output is limited by the ventilation air flow, and this used to be limited to around 2 kW for a detached house [33]. However, 7-8 years ago, a new inverter-controlled heat pump that can cool the air to a lower temperature was introduced in the market, leading to 4-6 kW heating capacity. With laboratory testing, they found a typical seasonal coefficient of performance (SCOP) of 2.2 to 3.0 for these new heat pump types and 1.5 to 2.0 for the older type. This reported SCOP combined both space-heating and DHW.

Mikola [34] made field studies on EAHP into refurbished apartment buildings with exhaust ventilation in Estonia. He described several measures important for success: reducing thermal losses through the envelope and using the heat for both space heating and DHW. Also recommends using a low temperature heating graph, with a supply temperature from 55-60 to 40°C according to the outdoor temperature. However, lower radiator temperature reduces the ability to counteract down-draft from ventilation air, and he reported people reducing air change rates due to cold unheated supply air. This could indicate that the combination of exhaust ventilation and reduced temperatures in the existing radiators is not an optimal combination [22]. With floor heating (FH) or ventilation radiator (VR), the thermal comfort is reported to be better. With a ventilation radiator, outdoor air flows in through a duct in the wall and is heated by the radiator panels before entering the room (Figure 1). The higher air velocity and temperature difference increases the heat transfer and allows a lower water temperature. Several studies [35-37] show that VR provide a slightly better thermal comfort, although FH and conventional high-temperature radiators also proved to be satisfactory. When supplied by a heat pump, FH allowed a lower supply temperature and electricity use than VR and conventional radiators [35]. If used in highly-insulated houses, VR could cause problems with cold draft when the outdoor temperature is near the balance temperature of the house. As the radiators are not heating, supply air will not be preheated [37]. Gustafsson also made an energy performance comparison of three HVAC systems for a renovated semi-detached detached house. With the insulation level of the EnerPHit-standard (renovation standard from Passivhaus Institute), in Stockholm climate, balanced ventilation with heat recovery and EAHP had the lowest energy consumption. Second best was exhaust ventilation with EAHP and VR. With slightly higher infiltrations (e.g. 1.5), or smaller ventilation rates (e.g. 0.35), the situation would change.

Despite similar climates, EAHP are frequent in Sweden and Finland but not in Norway. For many years EAHP were installed in 90% of all new built detached houses in Sweden[33]. Part of the reason could be the building code that favored EAHP. The Swedish code counts *delivered energy* and thus rewards the heat captured by the EAHP. In Norway, the requirements are only set for the *net energy demand (i.e. neglecting the heating system efficiency)*, so only part of the captured energy is accounted for. Another important aspect is probably the ventilation air flow requirements more strictly specified for different rooms in Norway.

A more precise term would actually be *extract* air heat pump, as most of these use the heat in the extract air. However, some compact units (see next subsection) include a heat pump that use the heat in the *exhaust* air (meaning after part of the heat is exploited by an air-to-air heat recovery unit). Østergaard [38] made a theoretical investigation on typical Danish detached houses from the 1990's. The study found that these houses can be heated with low-temperature heating with supply and return temperatures below 55°C/35°C for large parts of the year, with the existing radiators. When gone through reasonable energy renovation, these houses can be heated with a supply temperature below 50°C for more than 97% of the year. MVHR was assumed, thus it was a limited need to counteract the draft from the supply air.

5.2. Compact unit with heat pump

The standard compact unit consists of an air-to-air heat exchanger, a small exhaust air-to-water heat pump, a DHW tank and a supply air post-heater. Some of the tanks are equipped with coils for receiving solar heat (fig 2). The total power available from the ventilation air is only enough to heat highly-insulated buildings. Heating demand might be too large in a renovated house, also causing uncomfortably high air heating temperatures. However, the possibility of assistance from a drain-water heat exchanger (also called grey-water heat recovery) or a wood stove for peak heating could be investigated. Compact heat pump units that add ambient air when more energy is needed, are recently developed. These can definitely supply sufficient heat for renovated houses. Some of these also provide hydronic space-heating [39].

6. Conclusion

Requirements for HVAC-solutions for renovation of detached houses are suggested. Key technologies are described and analysed in the context of renovation. A main part of the contribution is a decision-making table. Some knowledge gaps have been identified. Some key conclusions are listed below:

- A number of demonstration projects on ambitious energy upgrading are completed. Nevertheless, few of them have been systematically monitored and evaluated.
- Improved airtightness after renovation makes systematic ventilation measures necessary
- A wider range of concepts and strategies than commonly used in Norway seem to be relevant.
- Whether or not the house has a hydronic space heating seem to be crucial for the choice of system. Most Norwegian detached houses do not have hydronic space heating. Installing this would be a major cost and intervention.
- Assumptions for occupant preferences and behaviour also seem to be important for choice of system.
- Between the Nordic countries, there are differences in commonly used HVAC concepts and strategies for renovation. They cannot be explained by climate differences only. Differences in building code, energy pricing and tradition may be part of the explanation.

IOP Conf. Series: Earth and Environmental Science **352** (2019) 012048 doi:10.1088/1755-1315/352/1/012048

Decision table **Qualitative assessment for planning process**	Energy-efficiency	Investment	Need hydronic	Space for technical	Need ducts	Noise	Filtering	Air quality	Temperature-Zoning	Cold draft	Occupant sensitive
Balanced ventilation	+ +	÷ ÷		÷	÷ ÷	?	+		÷		
Decentralized balanced ventilation	+	÷				÷ ÷	?		+		
Balanced.ventilation + window ventilation bedroom	+	÷		÷	÷		?		+		÷
Decentral.bal.ventilation + window ventilated bedroom	+	+					?		+		÷
Extract air heat pump, to DHW + ventilated window	+	÷			÷				+	÷	
Hybrid ventilation: balanced winter, natural summer	+ +	÷ ÷		÷	÷		?		?		
Natural ventilation	÷ ÷	+ +		+	+	?	÷	?	+	÷	÷
Extract air heat pump + ventilation radiator	+	÷	÷	÷	?				+		
Compact HVAC-unit	+ +	÷	?	÷	÷	?	+				
Ground source heat pump	+ +	÷ ÷	÷	÷							
Hydronic woodstove			÷	?							?
Solar thermal		÷	÷	?							
Air-air heat pump	+					÷					
Wood stove (not only peak)	+	+									÷
Pellet stove		÷									
Electric resistance heating	?	+ +		+							

Table1. Decision making table for qualitative assessment of HVAC-solutions for energy renovation of detached houses. Listed pros and cons estimated for different criteria.

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