

Economic and Energy Performance of Heating and Ventilation Systems in Energy Retrofitted Norwegian Detached Houses

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Abstract. The aim of this study is to compare the life cycle costs (LCC) and energy performance of different heating and ventilation systems (HVAC) in deep-energy renovation of Norwegian detached houses. More specifically, the relative performance of nine different HVAC combinations based on heat pumps is compared using two case buildings with four different insulation levels for the building envelope. The case buildings are small wooden dwellings without hydronic heating system, which is representative for existing Norwegian detached houses. The energy performance was simulated using the dynamic software IDA-ICE, in compliance with Norwegian Standards. The standard NS-EN 15459 (2017) was mainly used for the cost performance assessment. HVAC combinations with low investment costs (e.g., EAHP, balanced ventilation and air-to-air heat pump) showed lowest global costs, but the highest delivered energy. Low energy consumption can be achieved with different balances between investments on energy measures for the building envelope versus HVAC systems. Heat pumps can contribute significantly to the reduction of the energy use. In many cases, the cost uncertainty within one HVAC combination is larger than the difference between the combinations. The global cost and delivered energy diagram show a Pareto front relatively flat over a long range of energy use, so that some HVAC combinations can significantly decrease the energy use for a small increase in global costs. The compact heat pump and ground source heat pump fall into this category. For the investigated cases, the current governmental subsidies in Norway do not seem large enough to make investments in deep energy renovation profitable. Finally, results show that the prebound effect should be taken into account to make a realistic analysis of the cost performance of energy retrofit.

Keywords. Deep-energy retrofit, life cycle costs, energy performance, heat pumps.

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1. Introduction

The Norwegian residential sector is characterised by a large share of detached wooden houses, privately owned. They are responsible for more than half of the total energy use in the Norwegian building stock. A great number of these houses were built between 1950 and 1990, and are now ready for major renovation. If these houses undergo deep energy renovation, it would contribute significantly to the national target of 10 TWh/year energy saving for existing buildings by 2030. A large share of these houses have direct electric heating, some supplemented with wood stoves. Heat pumps have been installed in recent years, the majority being air-to-air. Unlike many other countries, few detached houses from this period have a hydronic heat

distribution system installed (1). A history of low electricity prices, and high investments costs in buildings, heating and ventilation systems (HVAC), have contributed to this situation. The additional cost to install a hydronic system can strongly affect the cost-effectiveness of heat pumps with hydronic space-heating distribution.

The aim of this study is to evaluate the performance of different HVAC solutions used in energy renovation of Norwegian wooden detached houses. Both life cycle costs (LCC) and energy performance are considered. The goal is to understand pros, cons and trade-offs between different HVAC combinations, according to different insulation levels and building sizes. The research questions are:

- What is the balance between LCC and energy performance and for different HVAC solutions?
- How is this affected by insulation level?
- How do preboud effects affect this?

This work is based on an architecture competition in the OPPTRE project (2). Energy renovations were proposed for six existing dwellings built between 1950 and 1990. More information about OPPTRE can be found in Moschetti et al (3). Two of the OPPTRE houses are used as case buildings in our study.

The number of existing studies on HVAC systems in energy renovation of detached houses in a cold climate are limited. The Norwegian context is different from most other countries due to renewable electricity at low prices and little use of hydronic distribution. Several studies investigated different technologies, but few have assessed both the costs and energy performance. Dermentzis et al. (4) investigated the use of a compact (exhaust air) heat pump in a renovated multi-family house in Germany, and found the system to be cost efficient due to prefabrication. Gustafsson et al. (5) compared energy performance of three HVAC systems for a renovated semi-detached house, and found that balanced ventilation combined with a micro heat pump, and exhaust air heat pump (EAHP) had the lowest energy consumption in Stockholm climate. Ekstrøm et al (6). evaluated the renovation of detached houses to Passive House level in Sweden, and found EAHP, and also ground source heat pumps (GSHP) the most cost-effective. Langdal investigated cost-effectiveness of energy renovation of Norwegian detached houses and found air-to-air heat pumps to be cost-efficient. He also found governmental grants crucial for profitability of the general upgrading (7). Felius et al. studied the potential of different energy renovation measures on detached and multi-family case houses in Norway, and estimated that an air-to-air heat pump had greater energy-saving potential than reducing heat loss through the building envelope (8).

2. Method

2.1 Evaluation of economic performance

The cost performance calculations were done on basis of the Norwegian and European standard NS-EN 15459-1:201 (9). The investment costs, the payback time and the total discounted costs were

used as indicators. The following assumptions and parameters have been considered:

- The calculation period is 20 years. If energy measures have a longer lifetime, the residual value of the system at the end of the calculation period is discounted to present value.
- The electricity price is assumed constant in this study at 1.5 NOK/kWh. Prices in Norway have historically been low. However, the increase seen the last years is expected to continue, due to several new international connection cables. An alternative analysis is also done, based on the average Norwegian price from 2012 to 2020, rounded up to 1.0 NOK/kWh (10).
- The reference scenario for the calculation of the payback time of different HVAC combinations is the building after the upgrade of the building envelope with all-electric heating and natural ventilation. Thus, costs for building envelope upgrade is not considered in the payback time.

Tab. 1 - Parameters for calculating the economic performance.

Parameter	Value
Calculation period (TC) [years]	20
Inflation rate [%]	2
Real discount rate [%]	3
Electricity price [NOK/kWh]	1.5

2.2 Two case houses

The two case houses were selected because they represent a certain diversity:

- Malvik house: built in 1957, 2 storeys, 184 m² heated area.
- Kristiansand house: built in 1972, 2 storeys, cold attic, 214 m² heated area, basement floor with a studio apartment.

The two houses had no hydronic distribution system.

2.3 Three building envelope upgrade levels

In addition to the pre-retrofitted state, three performance levels of the building envelope were analysed: TEK10, OPPTRE and PASSIV. TEK10 is mostly in accordance with Norwegian building regulations of 2010. OPPTRE is based on proposals from OPPTRE's architect competition (2). PASSIV is mainly in accordance with the Norwegian passive house standard NS3700 (11). Thermal properties of each performance level are summarized in Table 2.

Tab. 2 – Thermal properties for the two case houses for the different building envelope performance.

Parameter	Unit	Existing Kristians.	Existing Malvik	TEK10	OPPTRE	PASSIV
U-value external wall	W/(m ² .K)	0.45	0.44	0.22	0.18	0.11
U-value roof	W/(m ² .K)	0.5	0.3	0.18	0.14	0.08
U-value basement wall to ground	W/(m ² .K)	0.87	3.5	0.33	0.2	0.11
U-value external floor	W/(m ² .K)	0.54	4.3	0.3 (4.3*)	0.18 (4.3*)	0.11
U-value internal walls	W/(m ² .K)	0.47	0.6	0.47	0.47	0.47
U-value windows and doors	W/(m ² .K)	2.6	2.6	1.6	1.0	0.8
Normalized thermal bridge value	W/(m ² .K)	0.07	0.07	0.7	0.5	0.3
Infiltration	h ⁻¹	6.0	6.0	3.0	1.5	0.6

*U-value 4.3 in the Malvik house

2.4 Cost of envelope upgrade

Investment costs to upgrade the building envelope are included in the LCC analysis. Only measures to improve energy efficiency are included (i.e., other measures due to necessary maintenance or renovation was not included). A lifetime of 60 years was assumed for the envelope.

2.5 Nine HVAC combinations

Nine different HVAC combinations were analysed, see Table 3. These combinations are mainly named after the heat pump technology even though the combinations also include a ventilation measure. Eight have heat pumps and four of them have hydronic space-heating distribution. Six have balanced ventilation with heat recovery and two

have exhaust ventilation with EAHP. No systems are based on fossil fuel or biomass.

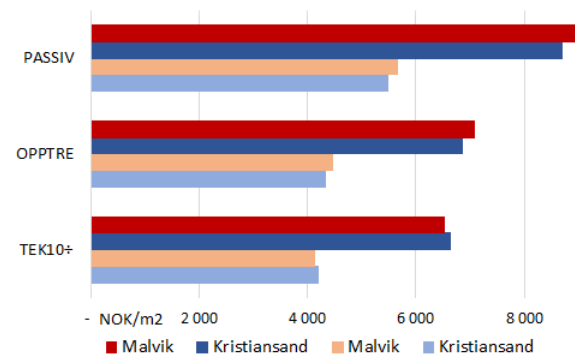


Fig. 1 - Specific cost of envelope upgrading: pale colours show the cost with the discounted residual value.

Tab. 3 - Description of the different HVAC combinations: heat pump and ventilation system.

Combination	Description
BalVent	Electric panel heaters, electric floor heating in bathroom (as for the reference scenario) Balanced mechanical ventilation with heat recovery
A2A	Air-to-air heat pump, electric panel heaters, electric floor heating in bathroom. Balanced mechanical ventilation with heat recovery
A2Asolar	Air-to-air heat pump, electric panel heaters, electric floor heating in bathroom. Solar collectors for heating of domestic hot water. Balanced mechanical ventilation with heat recovery
A2W	Air-to-water heat pump for space heating and domestic hot water. Hydronic distribution system. Balanced mechanical ventilation with heat recovery
GSHP	Ground source heat pump for space heating and domestic hot water where the borehole heat exchanger does not exist and should be created. Hydronic distribution system. Balanced mechanical ventilation with heat recovery
CHP	Compact heat pump unit for heating of domestic hot water. Electric panel heaters, electric floor heating in bathroom. Balanced mechanical ventilation with heat recovery integrated in HP unit.
CHPcomb	Compact heat pump for space heating and heating of domestic hot water, and some ventilation air heating Hydronic distribution system. Balanced mechanical ventilation with heat recovery integrated in HP unit.
EAHPDHW	Exhaust air heat pump for heating of domestic hot water. Electric panel heaters, electric floor heating in bathroom.
EAHPcomb	Exhaust air heat pump for space heating and heating of domestic hot water. Hydronic distribution system.

2.6 Cost of HVAC combinations

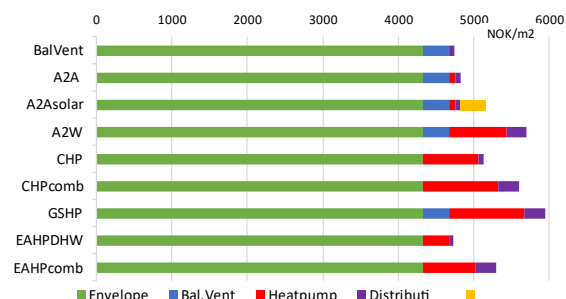


Fig. 2 - Total specific investment costs for both envelope and HVAC systems for the OPPTRE scenario: residual values are discounted

Maintenance costs, replacement costs and residual value were included in the analysis. As this paper is limited to Norwegian dwellings and climate, the costs are based on the current Norwegian market. Most of

the costs were collected directly from suppliers and building companies or their webpages. Where this was not possible, generic costs from reports and statistics were used (12, 13). Uncertainty on costs was considered by collecting several prices and using a cost range (i.e., uncertainty). Systems were dimensioned according to simulated net heating demand for the different scenarios. An example of total investment costs for both the envelope and HVAC systems are shown in Fig. 2.

2.7 Energy analysis

The energy performance was evaluated using the dynamic software IDA-ICE, in compliance with the Norwegian Standard NS-NSPEK 3031 (14). Ventilation airflow rates are adjusted to follow the requirements in the Norwegian building regulations. Only Oslo-climate was used in the simulations.

2.8 Heat pump efficiency

The seasonal performance factors (SPF) of the heat pump system in our simulations are shown in Fig. 3 while the energy coverage factor is shown in Fig. 4. Among key factors influencing the energy coverage factor and the SPF, it can be mentioned: the power coverage factor of the heat pump, the type of space-heating distribution subsystem, the layout of the floor plan and the share of DHW covered by heat pumps. As it can be seen, the energy coverage factor has a strong influence on the system SPF. To make sure that the simulation results are realistic, the SPF value can be compared to the literature, here shown

in Table 4. The literature generally reports slightly more favorable SPF than our simulations.

Tab. 4 - SPF values in cold climate reported in literature.

Heat pump	Reported SPF	Study
Air-to-air	2.1	Fältmätning
	2.1	Nordman et al (15)
Air-to-water	3.1 - 3.3	Nordman et al (16)
	2.1 - 4.2	Miara et al (17)
GSHP	3.3 - 4.7	Nordman et al (16)
	2.2 - 5.4	Miara et al (17)
Compact	1.7 - 2.4	O'Sullivan et al (18)
EAHF	1.43	Saini et al (19)
	1.91 - 2.09	Thalfeldt, et al (20)

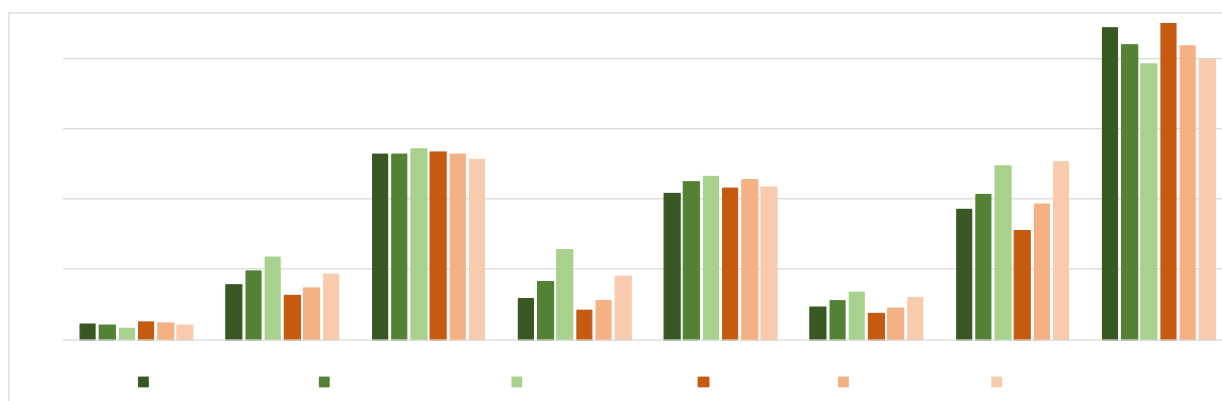


Fig. 3 - Seasonal performance factor for heat pump system in both houses.

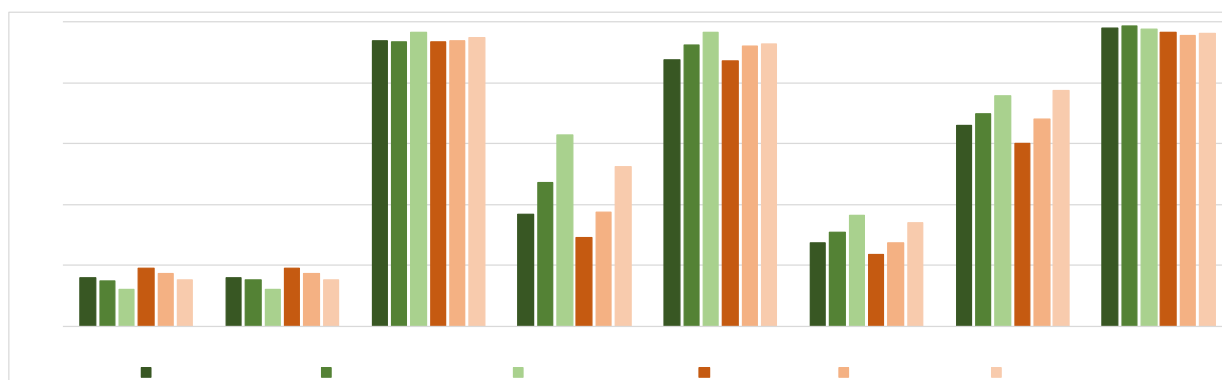


Fig. 4 - Energy coverage factor of the heat pump in both houses (i.e., fraction of heat demand covered by heat pump).

2.9 Prebound effect

The most common way to evaluate energy measures is to use standardised energy calculations before and after renovation. However, the real energy use can be different, typically due to the occupants' behaviour (i.e. the performance gap). The measured delivered electricity was available in five of the six case houses in the OPPTRE architecture competition and the average deviation was 60% of the standardised calculation. This indicates a large prebound effect. The reasons for this performance gap are unknown. It can be caused by lower temperatures and thermal zoning, or low ventilation airflow rates. Sandberg et al. analysed a larger set of buildings and found a prebound effect of 25% for houses of this segment, which is used for the assessment in this paper (21).

3. Results and discussion

3.1 Delivered energy

The delivered energy is shown in Figs. 6 and 7. There is a large spread in the energy performance: 51 to 135 kWh/m² annual delivered electricity. Several different combinations can be used to achieve a low energy demand. Most of the analysed combinations are below the target on delivered energy in the OPPTRE architecture competition, of 108 kWh/m², see Figs. 6 and 7. This target can be reached by different means, and different balance between energy measures on the building envelope versus the HVAC systems. Combinations with efficient heat pumps and hydronic distribution show the lowest energy use (GSHP, A2W, CHPcomb). The hydronic distribution allows a high energy coverage factor for the heat pump. This indicates that the contribution

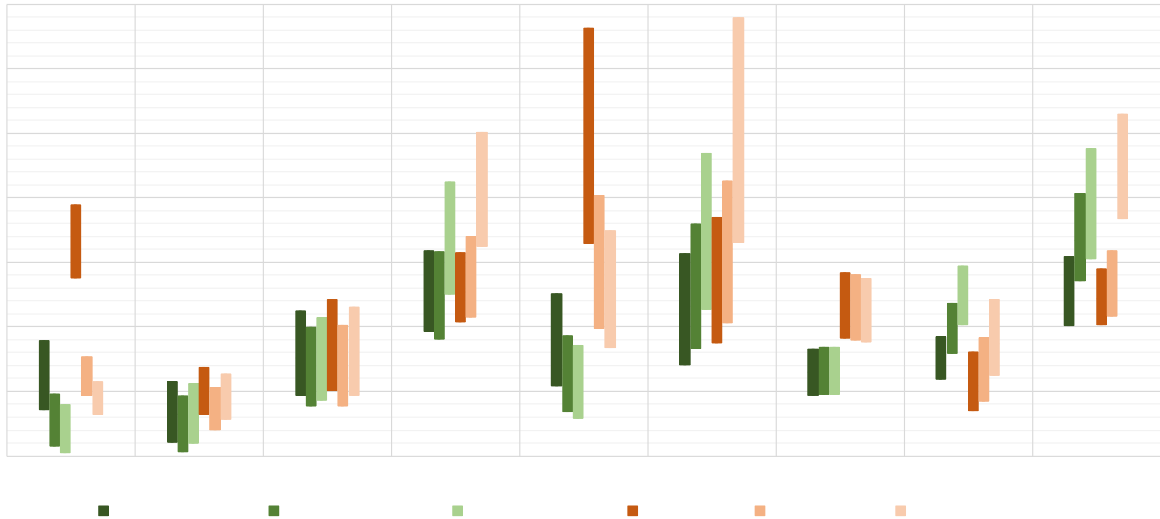


Fig. 5 – Payback time for the analysed HVAC combinations.

from these heat pumps is important. The figure also illustrates that, by using heat pump systems with high SPF, like GSHP, the OPPTRE target can be reached with lower insulation levels than in our study.

3.2 Payback time

Payback times for the HVAC combinations are presented in Fig. 5. Most combinations have a payback time close to the calculation time period, i.e. 20 years, which is critical. The combinations with the lowest payback times for both case houses are A2A. For the BalVent combination, the payback time decreases with a better performing building envelope. This can be explained by the reduced infiltration, causing a larger part of the air change to pass through the heat exchanger. For most of the

combinations with a heat pump used for space heating, the payback time increases along with the increasing insulation level of the building envelope. The reason for this is the reduced space-heating needs for higher insulation levels, resulting in less energy saved by installing more efficient energy supply solutions. This is clearly seen for combinations with high investment and a high energy coverage factor: A2W, CHPcomb, EAHPcomb and GSHP. This indicates that efficient energy supply solutions with higher investment costs are less profitable for buildings with low heating demand. The payback time of the combinations mainly covering domestic hot water are less affected by the insulation level of the building envelope, as illustrated by the EAHPDHW. This is because the DHW heating needs are unaffected by the different levels of the envelope retrofit.

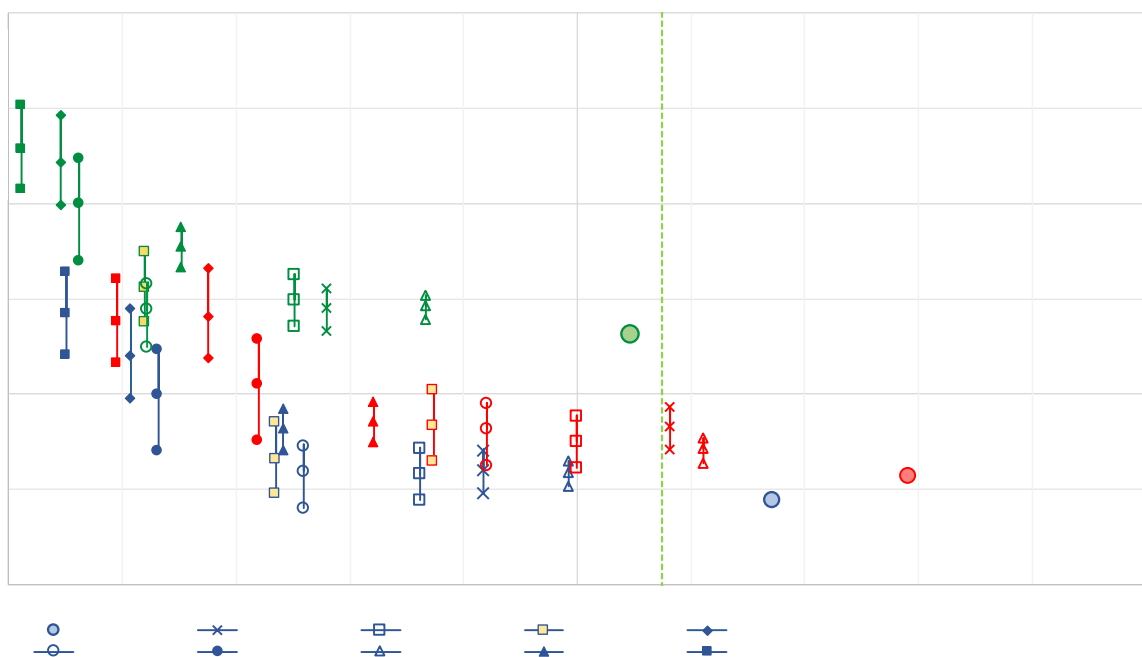


Fig. 6 – Specific global costs and delivered energy of the Kristiansand house: TEK10 in red, OPPTRE in blue, PASSIV in green, and the vertical line shows the minimum energy requirement from the OPPTRE architecture competition.

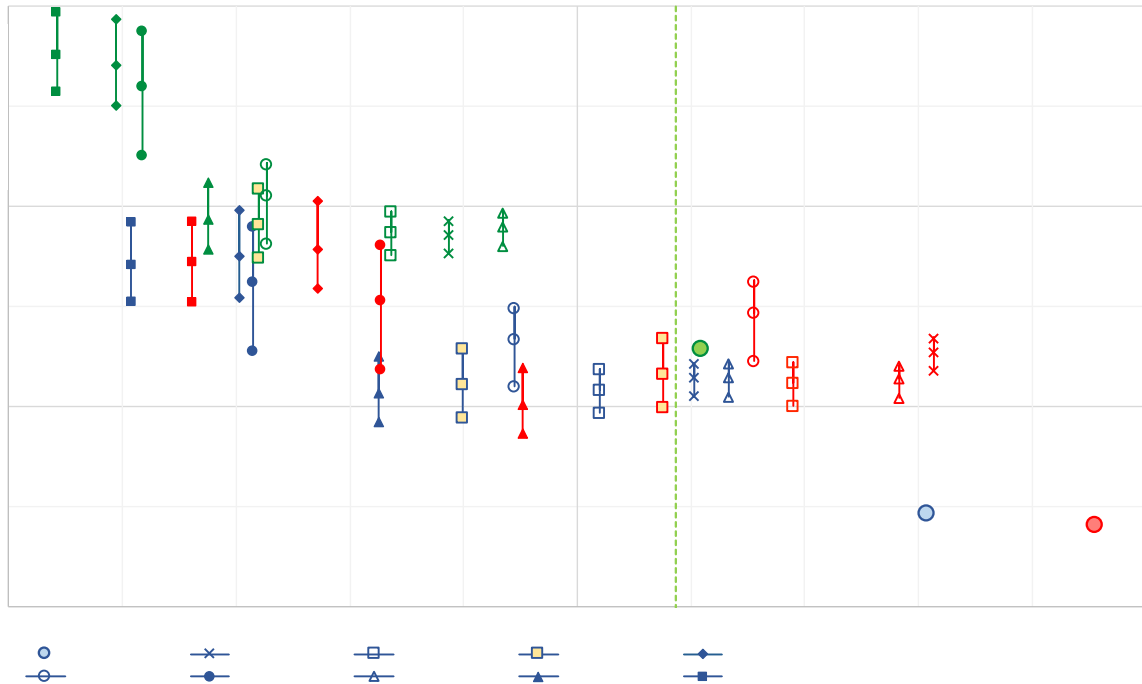


Fig. 7 – Specific global costs and delivered energy of the Malvik house: TEK10 in red, OPPTRE in blue, PASSIV in green, and the vertical line shows the minimum energy requirement from the OPPTRE architecture competition.

3.3 Global costs

Global costs including the investments and energy costs during the calculation period are shown in Figs. 6 and 7. The case only considering the envelope upgrade and the cases also including the HVAC combinations are shown. The Pareto front between 60 and 100 kWh/m²/year is flat, showing many HVAC combinations in the same range of global cost. This leads to the following conclusions:

- In many cases, the cost span inside a combination (resulting from the data range in collected investment costs) is larger than the difference between the neighbouring combinations. This indicates uncertainty regarding which combinations are optimal. The best solution can eventually depend on the choice of HVAC manufacturer and company installing the equipment.
- For both houses, a number of combinations show approximately the same low global cost, but with a wide range in delivered energy. These combinations generally have low or medium investment costs. Among these, the CHP and EAHPcomb, show the best energy performance, for the Kristiansand and Malvik house, respectively.
- No solution is optimal for both energy use and costs. Neither a scenario with low energy use but high global costs, nor a scenario with low global costs but only small improvements in the energy performance are desirable. Therefore, a compromise between achieving low global costs and low energy consumption is preferable, satisfying both the household budget and energy use. For the largest house in Kristiansand, the compact heat pump seems to be the optimal trade-off. For the house in Malvik, the larger

investment in the GSHP can be mitigated by the energy savings so that the total costs remain moderate but with an excellent energy performance.

Comparing the BalVent and the A2A combinations, the balanced ventilation system contributes more to reduced energy use than the air-to-air heat pump, especially for the high performing envelopes. This is more pronounced with the PASSIV scenario, as the low space-heating demand implies a small contribution from the heat pump, while the ventilation heat demand is the same regardless of insulation level. In addition, due to lower air infiltration, more heat is recovered by the AHU. As for payback time, combinations with lower investment (such as BAL, A2A or EAHP) perform relatively better with increasing envelope insulation.

Finally, it is worth mentioning that some of the combinations with low investment costs may provide a lower thermal comfort. With the EAHP for example, supply ventilation air is not preheated. Due to possible cold draft, some occupants may experience this as a less comfortable.

3.4 Electricity price

A calculation with electricity price of 1.0 NOK/kWh is also done. The global costs are then lower, but the measures are clearly less cost efficient. Therefore, the combinations with lower investment costs (EAHP, BalVent, A2A) are relatively more favourable.

3.5 Governmental grants

Governmental subsidies and grants for improving energy efficiency in buildings are not included in the baseline analysis in this study. When including the

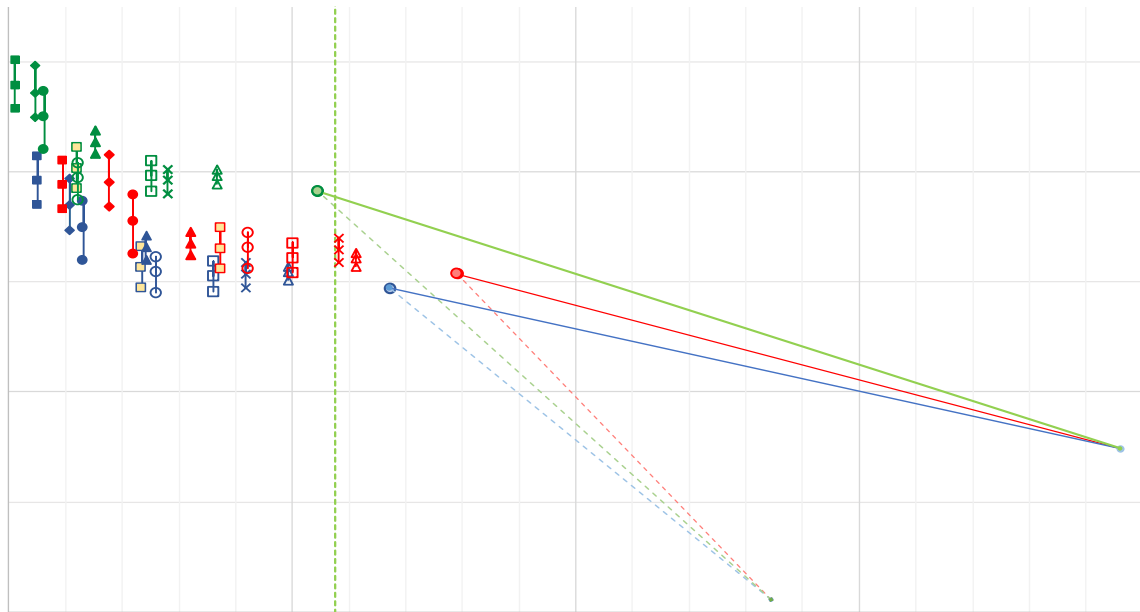


Fig. 8 – Specific global costs and delivered energy of the Kristiansand house with the situation before upgrading to the far right: the lines show the effect of envelope upgrade, dotted lines and the lowest point considers the prebound effect.

Norwegian grants, the global costs of some of the measures with high investment cost are relatively more favoured. However, with the electricity price used in this study, these grants do not seem large enough to support high investment costs in deep energy renovation of detached houses.

3.6 Envelope upgrade level

For both houses, upgrading to the PASSIV envelope shows higher global costs, which means the investment costs are higher than the savings in energy costs it provides. The OPPTRE envelope shows slightly lower global costs than TEK10 for Kristiansand house. This conclusion is stronger if government grants are included.

3.7 Envelope versus technical systems

The results show that low delivered energy demand can be reached with different balance between energy measures on the building envelope versus the HVAC systems. Determining this optimal balance between measures on the building envelope and the technical systems is challenging. Fig. 8 visualises some of these aspects. The starting point before retrofit is to the far right, and the lines represent the upgrade of the envelope only. The other symbols show the situation after also adding the different HVAC combinations. The steeper the line, the larger the increase in global costs per kWh reduction of the annual delivered energy. If the retrofit of the envelope and the HVAC are done in two separate steps, the order of the implementation of these measures influences the analysis. If HVAC measures were implemented first and the economic performance of envelope upgrade was analysed afterwards, the relative contributions would probably be different.

3.8 Prebound effects

The point in the bottom part of Fig. 8 displays the building before upgrading with a prebound effect of 25% lower energy use. When using this as the starting point before renovation, the upgrading measures seem even less profitable. In addition, the literature tends to show a rebound effect for highly-insulated buildings. This rebound effect has not been introduced for the renovated cases in our study and should be investigated in further studies.

4. Conclusions

Results can be summarized as follows:

- Many combinations have longer payback time than the economic lifetime of the project.
- Low energy consumption can be achieved with different balances between investments on energy measures for the building envelope versus HVAC systems. Heat pumps can contribute significantly to the reduction of the energy use (especially with hydronic distribution).
- In many cases, the cost uncertainty within one HVAC combination is larger than the difference between the combinations.
- HVAC combinations with low investment costs (e.g., EAHP, balanced ventilation and air-to-air heat pump) showed lowest global costs, but the highest delivered energy.
- The global cost and delivered energy diagram show a Pareto front so that no HVAC combination is the absolute optimum; a solution is optimal for a given energy use. However, the Pareto front is relatively flat over a long range of energy use (between 60 and 100 kWh/m²/year) so that some combinations can significantly

decrease the energy use for a small increase in global costs. These combinations have a great potential for energy savings. The compact heat pump and the GSHP fall into this category for the Kristiansand and Malvik houses, respectively.

- Increasing envelope insulation favours HVAC combinations with lower investment and higher energy use. Combinations with higher investments are less profitable with the highest envelope performance.
- The most ambitious envelope upgrade, i.e., the Passiv level, shows higher global costs, and only slightly lower energy use compared to the other envelope performance investigated.
- For the investigated cases, the current governmental subsidies in Norway do not seem large enough to make investment in deep energy renovation profitable.
- The rebound effect should be taken into account to make a realistic analysis of the cost performance of energy retrofit.

5. Acknowledgement

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The datasets generated and analysed during the current study are not publicly available because significant pre-processing and structuring of data is required to make it open-access, but will be available upon request.

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