Cost optimal investment in energy efficiency measures and energy supply system in a neighbourhood in Norway

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Building renovation is a key measure to reduce energy consumption and Greenhouse gas (GHG) emissions, and ease the transition to a fully renewable energy system. This paper applies the IEA EBC Annex 75 methodology for investigating the cost optimal and environmental trade-off between investment in energy efficiency measures on the building envelope and energy supply, on a residential neighbourhood in Norway. Combination of different energy efficiency measures and energy supply systems are investigated with an optimal investment model. The cost and environmental impact of the combinations are evaluated. An important outcome is that within the evaluated combinations, the choice of energy supply system has little impact on the cost effectiveness of the energy efficiency measures. However, it has a significant impact on the GHG emissions. The results also highlight the importance of performing energy efficiency measures in coordination with other renovating measures, both regarding cost effectiveness and environmental impact. The results will not give a finite answer to what is the best solution but serves at a useful set of inputs for overall evaluations.

1 Introduction

Building renovation is a key measure to reduce energy consumption, and GHG emissions, increase resource utilisation, and ease the transition to a fully renewable energy system. Given that the majority of the world's building stock for the next 30 years already exists today, consideration of renovation of existing building stock represents one pathway towards a more sustainable future [1]. Europe's roadmap for making the EU's economy sustainable (The European Green Deal) aims at doubling the renovation rate as important measure to reach the climate neutral goal of 2050 [2]. However, investigating measures at single building level can often result in sub-optimal solutions that are not to the benefit of the overall energy system [3]. The potential impact from renovation of existing buildings can be significant when the results from individual buildings are scaled across district or urban scale. The district scale allows to investigate the cost-effective balance between energy efficiency measures and renewable energy sources at a higher level, by also including district energy solutions. Also working on district or urban scale makes it possible to take advantage of interactions and synergies between different buildings, as well as speeding up the process of reducing energy consumption and associated GHG emissions in the building sector [4].

This work is part of the IEA EBC Annex 75 and applies the developed methodology to find the cost and environmentally optimal balance between energy efficiency measures on the building envelope and renewable energy for heating.

2 Method

IEA EBC Annex 75 focus on cost-effective building renovation at district level combining energy efficiency measures and renewables. Within the Annex, a methodology is developed for assessing the most cost-effective balance between energy efficiency measures and measures on the energy supply system. Terés-Zubiaga et al [5] present the key elements of the methodology and show how it can be successfully applied at a Portuguese district. An extensive description is to be published at the Annex 75 website [6]. Below, a brief description of the assessment procedure is given.

2.1 The Annex 75 assessment procedure

The first step of the assessment is the definition and characterization of investigated districts. This involves gathering information of the existing (and potentially planned new) buildings and district solutions, such as building dimensions and envelope parameters, existing energy supply system etc.

The second step is to define and assess the reference case. The reference case should be based on the current status of the district but include the cost of "anyway"-renovations. Anyway-renovations are renovations that are necessary for restoring or sustaining the functionality of the buildings, but without related energy efficiency measures. This could be painting of facades or repairing roofs. It also includes necessary renovations or replacement of the existing energy supply system.

The third step is the definition and assessment of renovation scenarios. This involves defining sets of renovation measures for improved energy efficiency of

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the buildings and alternative solutions for the energy supply systems. Different scenarios for energy efficiency measures and energy supply systems are combined in the solutions and assessed with regards to cost, energy consumption and GHG emissions. The evaluated energy efficiency measures and energy supply systems are described in section 3.2 and 3.3, respectively.

The key parameters that are considered in the assessment are: annualized cost (EUR/year), annual GHG emissions (kgCO$_2$/year) and annual primary energy consumption (kWh/year).

2.2 Building simulation

The building energy demands for the reference case and all the energy efficiency measure scenarios are calculated with the simulation tool SIMIEN [7]. SIMIEN is a Norwegian building energy simulation tool often used for validation against national building regulations. The tool provides hourly energy profiles for heating, cooling, and electricity demand. These profiles are then used for energy supply system analysis. For this case, 31 individual buildings are modelled.

2.3 Energy supply system evaluation

The assessment of different solutions for energy supply systems are performed with the cost optimization tool BUTLER. BUTLER is a two-stage deterministic Mixed-Integer Linear Program is used to find the optimal technology sizes while taking a series of costs into consideration. In addition, the cost of operation is minimized, given time series of costs, efficiencies and load profiles for energy use [8]. Below, the main equations of the optimization problem are shown. The parameters and variables are defined in Table 1.

First, consider the optimization problem as consisting of two stages, with the objective function:

$$\min(c^{\text{inv}} + c^{\text{op}}) \qquad (1)$$

Where c^{inv} is the cost of investing in the technologies, and c^{op} is the cost of operation. The terms are written out as

$$c^{\text{inv}} = \sum_{i \in \mathcal{I}} x_i C_i^{\text{inv}} + \delta_i C_i^{\text{fxd}} \qquad (2)$$

$$c^{\text{op}} = \sum_{i \in \mathcal{I}} x_i C_i^{\text{run}} + \sum_{t \in \mathcal{T}} dh_{i,t} P^{\text{dh}} + \sum_{t \in \mathcal{T}} y_t^{\text{imp}} P^{\text{el}} \qquad (3)$$
$$- \sum_{t \in \mathcal{T}} y_t^{\text{exp}} P^{\text{spot}}$$

Where $\mathcal{I}$ is the set of available technologies and

$$P^{\text{el}} = P^{\text{spot}} + P^{\text{grid}} + P^{\text{tax}} \qquad (4)$$

Furthermore, we have the balancing constraints $\forall t \in \mathcal{T}$:

$$D_t^{\text{el}} = y_t^{\text{imp}} - y_t^{\text{exp}} - \sum_{i \in \mathcal{I}_{el}} \left(y_{i,t}^{\text{sh}} + y_{i,t}^{\text{dhw}} \right) + y_t^{\text{pv}} \qquad (5)$$

$$D_t^{\text{sh}} = \sum_{i \in \mathcal{I}} q_{i,t}^{\text{sh}} + q_t^{\text{hs}} \qquad (6)$$

$$D_t^{\text{dhw}} = \sum_{i \in \mathcal{I}} q_{i,t}^{\text{dhw}} + q_t^{\text{hwt}} \qquad (7)$$

Furthermore, the production in each time step must be limited to the installed capacity $\forall t \in \mathcal{T}$, $\forall i \in \mathcal{I}$:

$$q_{i,t}^{\text{sh}} + q_{i,t}^{\text{dhw}} = q_{i,t}^{\text{ht}} \leq x_i \qquad (8)$$

In addition, efficiencies must be respected $\forall t \in \mathcal{T}$, $\forall i \in \mathcal{I}_{el} \setminus \mathcal{I}_{hp}$, where $\mathcal{I}_{hp} = \{ASHP, GSHP, A2A\}$:

$$q_{i,t}^{\text{sh}} = \eta_i y_{i,t}^{\text{sh}} \qquad (9)$$

$$q_{i,t}^{\text{dhw}} = \eta_i y_{i,t}^{\text{dhw}} \qquad (10)$$

For $\forall t \in \mathcal{T}$, $\forall i \in \mathcal{I}_{hp}$:

$$q_{i,t}^{\text{sh}} = COP_{i,t}^{\text{sh}} y_{i,t}^{\text{sh}} \qquad (11)$$

$$q_{i,t}^{\text{dhw}} = COP_{i,t}^{\text{dhw}} y_{i,t}^{\text{dhw}} \qquad (12)$$

For the heat pump $A2A$, $COP_{A2A,t}^{\text{dhw}} = 0 \; \forall t \in \mathcal{T}$, i.e. it only delivers space heating. For the case with a centralized distribution system ("cen_dh" and "cen_gshp"), the following holds $\forall t \in \mathcal{T}$:

$$COP_{gshp,t}^{\text{sh}} = COP_{gshp,t}^{\text{dhw}} \qquad (13)$$

i.e. the heat is delivered at the same temperature, irrespective of use. Hence, equations (space heating and dhw) can be merged, which yields a total heat balance:

$$D_t^{\text{ht}} = \sum_{i \in \mathcal{I}} q_{i,t}^{\text{ht}} + q_t^{\text{hs}} \qquad (14)$$

where q_t^{hs} can be viewed as the heat released from a *central* heat storage tank.

To force satisfactory backup in heat pump systems as discussed in section 3.3, the following constraints are introduced for the point source and waterborne systems, respectively.

$$x_{ERH} \geq max\left(D_t^{\text{sh}}\right) \qquad (15)$$

$$x_{EB} \geq max\left(D^{\text{sh}} + D^{\text{dhw}}\right) \qquad (16)$$

For the PV, we have

$$y_{pv,t} = x_{pv} Y_{pv,t} \qquad (17)$$

Heat storage

A heat storage $i \in \{HS, HWT\}$ is defined by the following equations $\forall t \in \mathcal{T}$:

$$z_{i,t} \leq x_i \qquad (18)$$
$$z_{i,t} = z_{i,t-1}\left(1 - \beta_i^{\text{loss}}\right) + q_t^i \qquad (19)$$
$$-\beta_i^{\text{ch}} x_i \leq q_t^i \leq \beta_i^{\text{ch}} x_i \qquad (20)$$

In addition, the end-state must be equal to the initial state:

$$z_{i,0} = z_{i,|\mathcal{T}|} \qquad (21)$$

Heat pump model

The coefficient-of-performance (COP) and availability factor (P) for each heat pump type is found by linearizing between operating points given in the Norwegian standard SN-NSPEK 3031 [9]. The COPs used as base for these interpolations are 3.00, 4.55 and 4.59 for the A2A, ASHP and GSHP, respectively.

PV systems

The performance of the PV system is pre calculated and imported as a timeseries with hourly production per kW$_{\text{peak}}$ installed. Details of the PV performance calculations can be found in [10].

Distribution system

Distribution of hot water for thermal energy use is modelled as a fixed heat loss. Heat loss from the distribution system will be vary with both distribution temperature and ambient temperature, but a constant heat loss is found to be at better assumption than a fraction of delivered heat.

Table 1: Parameters and variables in the BUTLER model

Pars	Description	Unit
C_i^{inv}	Specific investment cost, $i \in \mathcal{I}$	€/kW
C_i^{fxd}	Fixed investment cost, $i \in \mathcal{I}$	€
C_i^{run}	Operating cost, $i \in \mathcal{I}$ (% of C_i^{inv})	-
P^{dh}	Energy cost, district heating	€/kWh
P^{el}	Energy cost, electricity	€/kWh
P^{spot}	Electricity spot price	€/kWh
P^{grid}	(EP) grid tariff (+ konstant ledd)	€/kWh
P^{tax}	Electricity tax (el-avgift)	€/kWh
β_i^{loss}	Heat storage loss from	-
β_i^{ch}	Heat storage charge rate limit	-
$COP_{i,t}^{\text{sh}}$	COP for SH at time step t, $\forall i \in \mathcal{I}_{hp}$	-
$COP_{i,t}^{\text{dhw}}$	COP for DHW at time step t, $\forall i \in \mathcal{I}_{hp}$	-
η_i	Efficiency, $\forall i \in \mathcal{I} \setminus \mathcal{I}_{hp}$	-
D_t^{el}	Specific electric load at $t \in \mathcal{T}$	kW
D_t^{sh}	Space heating load at $t \in \mathcal{T}$	kW
D_t^{dhw}	Domestic hot water load at $t \in \mathcal{T}$	kW
$Y_{pv,t}$	Potential PV-production at $t \in \mathcal{T}$	kWp/kW
Vars		
x_i	Installed capacity, $i \in \mathcal{I}$	kW(h)
δ_i	Binary activation variable for $i \in \mathcal{I}$	-
$dh_{i,t}$	District heat import at $t \in \mathcal{T}$	kW
y_t^{imp}	Electricty import at $t \in \mathcal{T}$	kW
y_t^{exp}	Electricty export at $t \in \mathcal{T}$	kW
$y_{i,t}^{\text{sh}}$	Electricity for SH, $i \in \mathcal{I}_{el}$, $t \in \mathcal{T}$	kW
$y_{i,t}^{\text{dhw}}$	Electricity for DHW, $i \in \mathcal{I}_{el}$, $t \in \mathcal{T}$	kW
y_t^{pv}	Electricity from PV, $t \in \mathcal{T}$	kW
$q_{i,t}^{\text{sh}}$	Heat for SH from $i \in \mathcal{I}$, $t \in \mathcal{T}$	kW
$q_{i,t}^{\text{dhw}}$	Heat for DHW from $i \in \mathcal{I}$, $t \in \mathcal{T}$	kW
q_t^{hs}	Heat from HS, $t \in \mathcal{T}$	kW
q_t^{hwt}	Heat from HWT, $t \in \mathcal{T}$	kW
$z_{i,t}$	SOC for $i \in \{HS, HWT\}$, $t \in \mathcal{T}$	kWh

3 The case study

3.1 Description of the neighbourhood

The selected case study is a housing cooperative located in the central part of Norway. The neighbourhood was developed in 1970s and consists of about 1000 apartments. The façades and roofs were renovated in the mid-1990s. As part of this renovation, an extra layer of insulation of 10 and 5 cm was added to the façades and roofs, respectively. No façade refurbishment is therefore included in the reference scenario. The windows are of similar age and is expected to be replaced within near future. A new set of windows with the same thermal properties as the existing once is therefore included in the reference scenario.

The heat is supplied through a district heating system. The district heating is distributed from a primary substation (P-sub) to 20 secondary substations (S-sub) through three main distribution lines. At the S-subs, the heat is split into separate circuits for space heating (SH) and domestic hot water (DHW). More details on the layout can be found in [11].

The heat supply system, from the P-sub to the radiators are in need of renovation, and estimated costs of this are included in the relevant scenarios.

For this case study it was decided to study one of the three branches from the P-sub. This branch supplies 30490 m^2 gross heated floor area (GHFA) which is about 30% of the total GHFA of the neighbourhood. It consists of 6 S-subs, 34 buildings and a total of 351 apartments.

3.2 Evaluated measures on the building envelope

A total of five different energy efficiency measures on the building envelope are evaluated (
Table 2).

Table 2: Evaluated energy efficiency measures.

Name	Description
F1	Add 10 cm insulation of façades. Reduces U-value from 0.27 to 0.18 W/m^{2}K
R1	Add 5 cm insulation of roof. Reduces U-value from 0.18 to 0.05 W/m^{2}K
W0	Replace existing windows with new window this same thermal properties (1.6 W/m^{2}K)
W1	Install new windows with U-value of 1.2 W/m^{2}K instead of the existing 1.6 W/m^{2}K
W2	Install new windows with U-value of 0.8 W/m^{2}K instead of the existing 1.6 W/m^{2}K
V1	Install heat recovery ventilation with thermal efficiency of 85%

The energy efficiency measures (given under
Table 2) are composed of five different renovation
scenarios, in addition to the reference scenario. These
are denoted c01-c05 according to Table 3.

Table 3: Scenarios for energy efficiency measures

Scenario	Energy efficiency measures
Ref	W0
c01	W1
c02	W2
c03	F1+R1+W1
c04	F1+R1+W2
c05	F1+R1+W2+V1

3.3 Evaluated energy supply systems

Five different heat supply systems are considered.
They are split into three main heat distribution concepts:
central distribution (cen), decentral waterborne
distribution (wb) and point source (ps).

The central distribution concept (cen) is based on
utilization of the district heating network already in
place, with a central heat production/distribution from
the existing P-sub. Two heat production systems are
considered for this option: renovation of the existing DH
substation or installation of a ground source heat pump
system (GSHP).

The decentral waterborne distribution (wb) concept
is based on installation of new heat production units at
the location of the existing S-subs, discarding the P-sub
and the distribution system between the P-sub and the S-
subs. GSHP and air source heat pump (ASHP) systems
are considered for this option. For both "cen" and "wb"
options, the system can invest in hot water tanks (HWT)
for energy storage. There are no HWTs present in the
current system. The "cen" and "wb" scenarios also need
to invest in a renovation of the existing hydronic heating
(HY) systems inside the buildings. All heat pump
systems are designed with the heat pump as a base load
unit and an electric boiler (EB) as backup and peak load.
To ensure full backup from the EB, the capacity is
forced to be equal to the peak demand, according to
equations 15 and 16.

The point source (ps) concept is based on individual
heat supply to each individual apartment. This requires
installation of individual hot water boilers for DHW
production (EB DHW) and a combination of electric
resistance heaters (ERH) and air-to-air heat pumps
(A2A) for space heating. Similar as for the waterborne
heat pump systems, ERH are dimensioned to cover the
full space heating demand.

All the different heat supply systems are coupled
with all the energy efficiency measure scenarios,
yielding a total of 25 cases.

In addition, all cases are modelled with and without
a solar PV system. An evaluation of the performance of
a PV system for this neighbourhood was performed by
Sorensen et al. [10]. The hourly production profile from
this study is used as input to the system optimization
tool. As investment in solar PV is not cost effective
under the predefined conditions, the model is forced to
invest in a fixed size PV system. Based on the result

from Sorensen et al. [10], a total system size of 600 kW$_p$
(4080 m^2) is used.

3.4 GHG emission calculation

Life cycle assessment methodology is used to
evaluate GHG emissions. A functional unit of 1m^2 of
heated floor area over 60 years' service life. The system
boundary is defined following the life cycle modular
principles as outlined in EN15978 [12]. The modular
life cycle principle includes four main life cycle stages:
product stage (Modules A1-A3), construction stage
(Modules A4-A5), use stage (Modules B1-B7) and end
of life stage (Modules C1-C4). In addition, the optional
stage (Module D) account for the consequences on
reuse, recycling and energy recovery outside of the
system boundary. In this study, the system boundary is
limited to modules A1-A3 (where A1 – raw material
supply, A2 – transport and A3 – manufacturing) and B6
(operational energy use). The life cycle impact is
calculated in terms of Global warming potential (GWP)
measured in CO$_{2eq.}$

3.5 Input data

This section lists the most important input data for
the assessment of energy efficiency measure scenarios.
Table 4 gives an overview of input data on cost and
embodied emissions (GWP) .

Table 4: Input data for assessment of energy efficiency
measure scenario

Case	Cost [kEUR]	GWP [kgCO$_{2eq}$/y]
ref	5597	14 490
c01	5702	14 490
c02	5911	14 490
c03	10890	23 832
c04	11099	23 832
c05	13538	26 170

Cost data for renovations and technologies are
collected from data published by the Norwegian Energy
Agency [13] and a national construction cost database
(Norwegian Pricebook) [14]. Norwegian Pricebook is a
cost database which contains cost of a building project,
as well as GHG emission and life cycle costs per year
building. In addition, case specific costs where collected
separately by Sartori et.al [15]. The embodied GHG
emission factors for A1-A3 life cycle stages of façade
and roof elements are taken from average Norwegian
Environmental product declaration (EPD) data [16]. For
energy systems, embodied GHG emission factors from
the Norwegian Pricebook are used.

Table 5 shows the fixed and specific investment
costs and estimated lifetime of each technology used in
the economic optimization.. The cases with a centralized
distribution systems ("cen") have an additional
maintenance cost of 72000 €/year, which covers
renovation of the central heat distribution system.

Table 5: Investment cost parameters for assessment of energy supply system solutions

	Fix. [€/per unit]	Spec. [€/kW]	Lifetime [years]
Common			
PV	-	1182	25
HWT	-	125	20
PS			
ERH	3000	-	20
EB DHW	3500	-	20
A2A	570	671.9	20
WB			
ASHP	-	744	20
GSHP	-	1628	20
EB	-	154	20
HY	585000	-	30
CEN			
DH	240000	-	50
GSHP	-	1628	20
HY	3510000	-	30

The energy costs are based partly on the Annex 75 template (assumption of constant spot price), and partly on reported prices for the regional system operator Tensio (grid tariffs) [17]. A discount for district heating is assumed, with basis in local conditions and Norwegian law [18]. The currency conversion rate used is 0.1 €/NOK. The energy prices are shown in Table 6.

Table 6: Energy prices

Name	Fixed [€/per unit]	Spec. [€/kWh]
P^{el}	-	-
P^{spot}	-	0.04
P^{grid}	255	0.042
P^{tax}	-	0.0163
P^{dh}		$P^{el} - 0.01$

According to the Norwegian standard for GHG calculations for buildings [19], the GHG emission assessment from operational energy use should be performed with two emission factors for electricity, one with Norwegian energy consumption mix (NO) and one with an European energy consumption mix (EU28). Both should be estimated averages within the assessment period. This yields the following factors: NO=17 gCO2/kWh and EU28=123 gCO2/kWh. The corresponding emission factors for district heating are based on estimated production mix in 2030 from the local DH company: NO=11 gCO2/kWh and EU28=35 gCO2/kWh [20].The emission factor for DH is very low, since about 75 % of the heat is generated from waste incineration, and the emission from this process is not allocated to the DH. This is further discussed below.

4 Results and discussion

4.1 Energy demand

This section summerizes the results from evaluation of energy demand of the buildings. Figure 1 shows the yearly heat and electricity demand (red) and peak heat and electricity demand (blue) of the buildings. The reference case has a total heat demand of about 3600 MWh/year. This corresponds to about 118 kWh/m²/year. Adding about 300 MWh/year in heat loss between the S-subs and the apartments, this is in the lower range of what was measured (average 127 kWh/m²/year) by Sørensen et al. [11]. This is expected as the simulations does not take user behaviour into account. The effect of the energy efficiency measures is shown by the reduced energy demand for heating for the different scenarios. Installing the most energy efficient windows (c02) yields a reduction of about 10%. A similar effect can be seen with increased insulation (c03). The combination (c04) yields a reduction of 16%. Adding heat recovery ventilation increases the reduction to 43%. The electricity demand is similar for all the cases except for c05, due to the fans of the ventilation system.
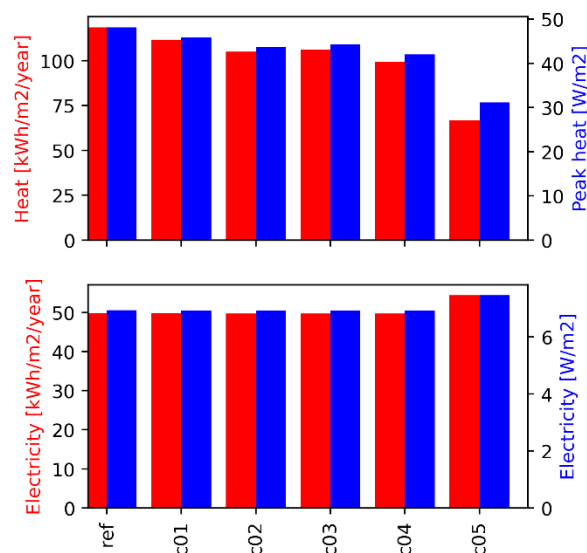

Figure 1: Yearly (red) and peak (blue) heat and electricity demand for the energy efficiency measure scenarios.

4.2 Energy supply system evaluation

This section summarizes the results from the energy system evaluation.

Figure 2 and Figure 3 shows the annual costs vs. the GHG emissions from operational energy use with NO and EU28 emission factors, respectively. The filled markers show results for cases without PV installation, while the markers without filling show results with PV. The marker shape indicates the renovation case, while the marker colour indicates the energy system.

From the results, one can see that the choice of energy supply system has little impact on the cost effectiveness of the energy efficiency measures. For all energy supply systems, solutions c01and c02 together with the reference case, have the lowest annual cost, with very small differences. In most cases the option with the best windows (c02) is most cost effective. In general, the results indicate that for this case it is not cost efficient to perform energy efficiency measures when

they are not performed in relation to other necessary measures (anyway renovations). For the different energy supply systems solutions, the point source option (ps) is most cost efficient, but the difference is small compared to the GSHP and AHSP. As expected, one can see that investment in a PV system is not cost efficient, however the additional annual cost is small.

Looking at the GHG emissions from operational energy, the choice of emission factors for the energy system is very important factor in the analysis of the results for the DH solution. With the NO emission factor, the DH cases have the highest emissions, while with the EU28 emission factor, they have the lowest. In general, the lowest operational emissions are achieved with the cases with lowest energy consumption. However, it is interesting to see that it is more cost efficient to invest in a PV system than performing comprehensive energy efficiency measures, such as adding insulation to the façade and roof, or installing heat recovery ventilation.
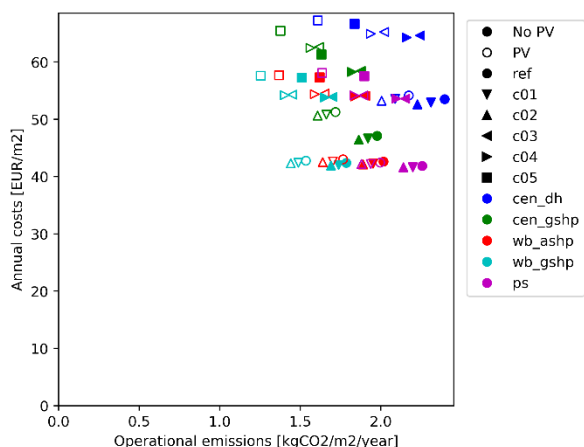

Figure 2: Annual costs vs operational emissions with NO emission factors
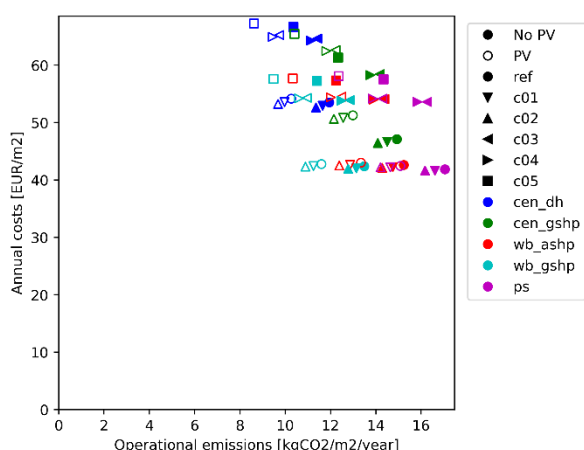

Figure 3: Annual costs vs operational emissions with EU28 emission factors

The amount of self-consumption of the energy produced by the install PV system is important as the selling price for exported electricity is equal to the spot price only and does not include the grid tariff. The import/export balance is calculated on neighbourhood level, and not on individual apartment. This is currently not allowed according to the national regulations, but it is expected that this will change in the future. For the "dh" cases, the self-consumption is about 83% while it ranges from 91 to 97% for the others.

For the solutions with heat pumps, the model is forced to have a peak/backup source that can cover the full demand but can invest in the optimal size of the heat pump, with respect to minimum cost. Figure 4 shows the percentage share of the heat demands that are covered by the heat pumps for case "c02". For all the waterborne systems ("cen" and "wb") the coverage is about 85%, while it is significantly lower for the A2A heat pump as it cannot cover DHW demand. The ASHP has slightly lover coverage than the GSHPs, as its capacity is reduced with reduced outdoor temperature.
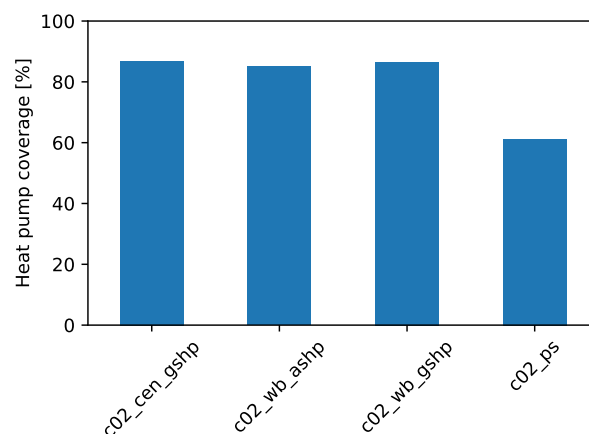

Figure 4: Heat pump coverage of overall heat demand for "c02"

Figure 5 and Figure 6 show the same results as Figure 2 and Figure 3, but include the embodied emissions.

When including the embodied emissions, one can see that the positive effect of reducing the energy demand by adding insulation (c03 and c04) is reduced, due to the emissions from the materials. With the low emission factor for electricity (NO), the total emissions are actually higher, with improved insulation. For the cases with new windows only (c01 and c02), there is no effect, as the same GWP value is used for all window types. One would expect that more materials are needed for more efficient windows, which would result in higher GWP values.

In general, including the embodied emissions emphasises the results from the economic perspective, in that energy efficiency measures should be coordinated with other necessary renovation or rehabilitation works. That is, from both an economical and environmental perspective it makes most sense to improve the energy efficiency of a building component when it needs renovation anyway.
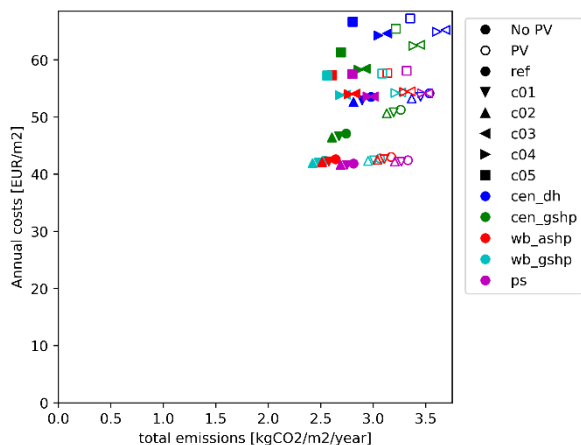
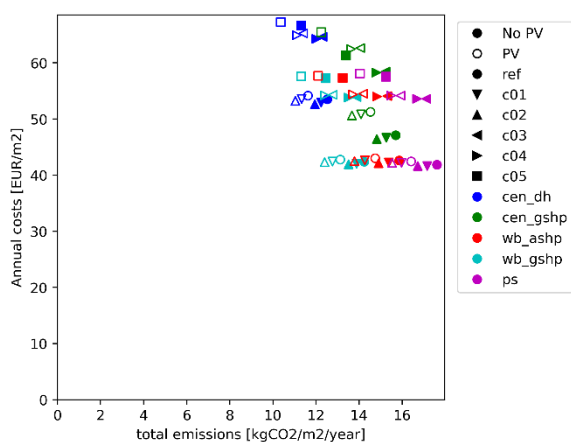Figure 5: Annual costs vs total emissions with NO factors

Figure 6: Annual costs vs total emissions with EU28 factors

4.3 Evaluation of solutions

From the results, it is difficult to draw a single conclusion of what solution is best. It depend on the overall goal of the decision makers. Furthermore, social factors such as user acceptance and visual expression are important as part of the evaluation. An important benefit with keeping the DH solution is the low maintenance demands. For a private housing cooperative, low operation and maintenance demands could be a significant factor, beyond the direct economic impact that is already included in the analysis. Looking at a large-scale perspective with EU28 emission factors, a solution with new energy efficient windows, a PV installation and renovation of existing DH network might be an overall good solution. However, this conclusion is very much dependent on the assumption of zero GHG emission allocation to production of district heating from waste incineration. This assumption is under continuous debate, Allocation of GHG emissions from waste incineration to the DH production would give this solution the highest emissions. The same effect can be seen from the embodied emissions for the PV installations. With the applied emission factor, the GHG emissions per produced energy is about 52 gCO_{2eq}/kWh. This is higher

than the emission factor for electricity, with the national Norwegian energy mix, but lower than the EU28 factor. According to the national Norwegian standard [19] the emission factor ranges from 13 to 190. This shows the importance of choosing products with minimum embodied emissions related to materials and production. In addition, the source of background emission data and methodological choices have significant impact on GHG emission results.

4.4 Limitations and implicatoins

The authors acknowledged that the findings from this study are limited and have a number of uncertainties in both the input assumptions and calculation methods. Thus, the study has highlighted the limitations and areas that need further work as follows.

Most of the cost data is based on general empirical values or superficial evaluations. As a next step it will be natural to do a sensitivity analysis on the most important cost factors.

For GHG emission calculation, the system boundary is limited to A1-A3 and B6 life cycle stages and the background data is mainly based on generic emission factors. Further study is needed to evaluate the environmental impact from the whole life cycle with more specific background data and scenario analysis.

For the GSHP systems, large areas for boreholes are necessary. Available areas are available within the neighbourhood, however detailed analysis of the ground has not been performed. Ground properties, such as vertical distance to bedrock or ground water can have significant influence on the cost.

For the systems with fully or partially centralized heat production systems based on electricity ("cen_gshp" and "wb"), there might be additional costs related to upgrading the electric power supply. Depending on the circumstances this could be significant costs.

There are some physical constraints that are not considered directly in the analysis.

It is assumed that there is available space in the existing buildings, where the primary and secondary substations are located, to install heat pumps. If more space is needed, this could completely change the calculated investment costs. With ASHPs and A2A HPs it is also a question about noise and vibrations. It might not be feasible to find adequate locations for the outdoor units. This is especially true for the A2A HPs as it from a visual point of view is not desirable to have a lot of outdoor units scattered all over the façades.

The BUTLER model is an economic optimization model and could in principle just output the most cost-effective solution. To evaluate the trade-off between cost-effectiveness and environmental impact, it is forced to produce out for several fixed systems. However, since the model finds the most cost-effective solution for each system, it might be interesting solutions within each system with lower emissions but at a higher cost. This could e.g., be installation of a larger heat pump, to reduce electricity consumption.

5 Conclusions

This study evaluated different energy efficiency measures on the building envelope in combination with anyway renovations and solutions for the energy supply system for a cooperative housing neighbourhood in Norway.

The results from evaluated cases reveals that the choice of energy supply system has little impact on the cost effectiveness of the energy efficiency measures.

The results also highlight the importance of performing energy efficiency measures in coordination with other renovating measures, both in regard to cost effectiveness and environmental impact. The study

Even if it is difficult to give decisive answer to what is the best solution, this study serves as a useful set of inputs for overall evaluations of investment plans.

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