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Energy performance and scenario analyses of a multistorey apartment building in Norway BuildSim-Nordic 2022, Copenhagen

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Abstract

Plus Energy Buildings are perceived as a strategy in the energy transition and to promote decarbonization of the building stock. This paper presents the design development of a plus energy demonstration project based on building performance simulations performed with IDA-ICE for energy strategies and future scenarios.

The objective of the design strategies was to reduce the primary energy consumption, while ensuring a satisfactory indoor environment. Future scenarios for climate change, user behavior, and energy flexibility were developed to analyze the impact on the building's energy performance.

Results from the analyses reveal the expected building performance with respect to energy and indoor environment standards, and robustness with respect to meeting the standards under different scenarios for occupant behavior and climate conditions. According to the simulation results, the building design is robust and can adapt to changes in exterior conditions.

Introduction

In EU, the building stock accounts for 36% of the greenhouse gas emissions, and only 25% of the building stock is energy efficient (European Commission, 2020).

Climate change is disrupting our society, and we are now experiencing more extreme weather (IPCC, 2021). Therefore, resilience needs to be accounted for. Buildings need to adapt to new exterior conditions, with more extreme rainfall, drought, and heat. In the electrification of the built environment and cities, it is becoming increasingly more important to ensure a resilient energy supply system.

A substantial replication strategy of new construction and renovation to a zero emission building standard in the Norwegian building stock can reduce the GHG emissions from energy use by 36 to 58% compared to the current level, despite a 21% increase in building stock from 2020-2050 (Sandberg et al., 2021). Moving from centralized to decentralized energy systems has the potential to free up energy for other uses, such as the electrification of the industry and transportation sector.

To achieve a decarbonized building stock in 2050, the integration of building applied photovoltaics (BAPV) and building integrated photovoltaics (BIPV) in existing and new buildings are promising options. Magrini et al. (2020) underline the importance of perceiving plus energy buildings (PEB) as integrated parts of their neighbourhood, and being conscious of the purpose and distribution of excess energy.

Occupancy patterns are difficult to predict in residential buildings, where both passive (internal gains) and active (operation and equipment use) effects impact the energy balance (Hensen & Lamberts, 2019). Burak Gunay, O'Brien and Beausoleil-Morrison employed different occupancy schedules in EnergyPlus. Despite the large variation in patterns, the simulation results responded similar to the design changes (Gunay et al., 2016).

Nearly Zero Energy Building (NZEB) is defined in the EU regulation, but the definition of PEB is currently under development (Tuerk et al., 2021). There are several definitions of plus/positive energy buildings (PEB) in research projects (Ala-Juusela et al., 2021). The research project syn.ikia defines PEB as "a building that produces more energy from renewable sources than it consumes to achieve appropriate indoor environmental quality and cover the building energy needs (excluding plug loads)"(Salom et al., 2020). According to Kurnitski et al. (2021) plus energy buildings have a surplus of energy production from local sources onsite. In general, the common perception is that a building needs to produce more energy than it consumes onsite to achieve PEB status.

Syn.ikia

Syn.ikia is an European research project led by NTNU and funded through Horizon 2020. It aims to develop Sustainable Plus Energy Neighbourhoods (SPEN) in four different climate zones in Europe; sub-arctic, continental, marine and mediterranean climates (L. Finocchiaro et al., 2021). The case study described in this paper, is the Norwegian (sub-arctic) demonstration project of syn.ikia.

Research questions

The objective of the study was to analyze different design options and their effect on the energy performance and primary energy of the case study building. Further, scenarios regarding climate change, user behavior and energy and power flexibility were developed to analyze the robustness of the design. The following research questions were formulated based on the syn.ikia goal of creating sustainable plus energy neighbourhoods (Salom et al., 2020):

What is the effect of different design options on the primary energy use of the building?

Is the building able to reach a net plus energy balance with respect to EPB uses (heating, cooling, ventilation, DHW, and lighting)?

How robust is the design with respect to meeting the goals of energy performance and indoor climate, given changes in occupancy patterns and future climate scenarios (IPPC A2 and B1)?

Table 1: Overview of building code regulations and case study design values for energy efficiency.

Energy efficiency measures	TEK17 – Apartment building*	NS3700 Passivhus	Panorama (Case study building)
U-value			
Exterior wall	≤ 0.18 [W/(m²K)]	0.10-0.12** [W/(m²K)]	0.10 [W/(m²K)]
Roof	≤ 0.13 [W/(m²K)]	0.08-0.09** [W/(m²K)]	0.08 [W/(m²K)]
Floor	≤ 0.10 [W/(m²K)]	0.08** [W/(m²K)]	0.13 [W/(m²K)]
Windows and doors	≤ 0.8 [W/(m²K)]	≤ 0.8 [W/(m²K)]	0.85 [W/(m²K)]
Normalized thermal bridge value	≤ 0.07 [W/(m²K)]	≤ 0.03 [W/(m²K)]	0.03 [W/(m²K)]
Ventilation heat recovery	≥ 80%	≥ 80%	85%
SFP	≤ 1.5 [kW/(m³/s)]	≤ 1.5 [kW/(m³/s)]	1.0 [kW/(m³/s)]
Air tightness, ACH at 50 Pa	≤ 0.6	≤ 0.6	0.6
Total net energy need	95 [kWh/m² yr]	Heating: 15 [kWh/m² yr]	-

*TEK 17 §14-2 by Direktoratet for Byggkvalitet (2017a)

**Recommended in NS 3700:2013

Case study

The case study is located in Fredrikstad, Norway, (Latitude: 59° 13' 5.16" N, Longitude: 10° 55' 47.28" E). It is a multistorey apartment building with six floors and a parking basement, and nine different apartment typologies. Each floor has four apartments, except for the 5th and 6th floors, which have two apartments extending over two floors. The building has a compact body, shaped like a box, to ensure minimal heat loss through the envelope. The windows oriented towards south, east and west have integrated exterior screens with manual operation. Each apartment has a balcony with an open and an enclosed glazed part. All apartments have an open floorplan for the kitchen and living room. The roof is tilted 8 degrees towards the Southeast and is covered in photovoltaic panels.

The design principles are following the Norwegian passive house standard for residential buildings, NS3700 Passivhus (Standard Norge, 2013), with a highly insulated and efficient envelope (Table 1).

A ground source heat pump (GSHP) supplies the building with thermal energy for heating and domestic hot water. The auxiliary thermal energy is supplied by district heating. The apartments have radiant floor heating and balanced mechanical ventilation with heat recovery, with individual air handling units for each apartment.

Methods

Building performance simulations were used to analyze the energy and indoor environmental performance of the apartments. Thermal building envelope models were created in the simulation software IDA-ICE (EQUA Simulation AB, 2022). Since the study focuses on energy performance at the apartment level, it was decided to create separate models for the two apartments selected.

The study consisted of two parts; (1) assessing design strategies based on annual primary energy consumption; (2) assessing future scenarios and their effects on the building performance. Design strategies were developed and tested based on primary energy consumption and thermal comfort.

Thermal energy model

IDA-ICE version 4.8 (EQUA Simulation AB, 2022) was selected to perform building performance simulations due to the possibility to model the building as a 3D model with detailed modelling of the envelope, HVAC, energy systems and different occupancy patterns. Simulations were performed to evaluate the energy performance and indoor environment quality of the building. IDA-ICE is an equation based software in Neutral Model Format (NMF) (EQUA Simulation AB, n.d.). Differential algebraic equations are used to model dynamic systems, and are solved with numerical methods (EQUA Simulation AB, 2013). The software performs detailed annual dynamic multizone simulations. IDA-ICE is

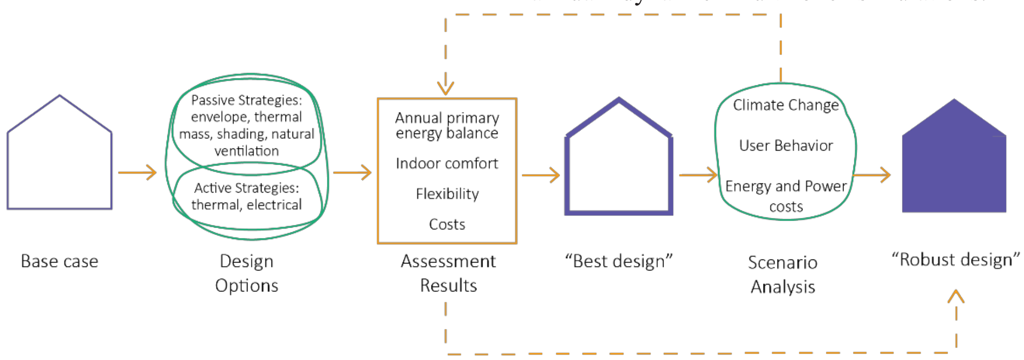

Figure 1: Overview of method for analyses (source: syn.ikia project).

validated in accordance with EN 15255-2007 and EN 15265-2007, the CEN standards for validation of simulation software for thermal performance of buildings (EQUA Simulation AB, 2010), and the Norwegian adoption of the European Standard NS-EN 15265 (T. Persson, 2016). IDA-ICE provides indoor temperatures as the mean temperature and the operative temperature. The mean temperature is the room air dry bulb temperature and the operative temperature is the average of the mean radiant temperature and air temperature at a given point (EQUA Simulation AB, 2013). This is the temperature closest to the human sensation.

PVsyst V7.2.12 was used to perform photovoltaic system simulation for panels on the roof (PVsyst AS, 2021), which were rough estimates due to limited project information, and the same for all design options and scenarios.

The nonrenewable primary energy balance was calculated with Equation (1), based on the methodology of the syn.ikia research project (Salom et al., 2020):

$$E_{P,nren} = \sum_i E_{p,nren,del,i} - \sum_i E_{p,nren,ext,i}$$
$$= \sum_i \int P_{del,i}(t) \times w_{del,nren,i}(t)dt$$
$$- \sum_i \int P_{exp,i}(t) \times w_{exp,nren,i}(t)dt \quad (1)$$

Where,

$E_{p,nren}$ is the nonrenewable primary energy (kWh/m^2 y), $E_{p,nren,del,i}$ is the delivered nonrenewable primary energy per carrier i (kWh/m^2 y),

$E_{p,nren,exp,i}$ is the exported nonrenewable primary energy per carrier I (kWh/m^2 y),

$P_{del,}$i is the delivered power on site or nearby for energy carrier i (kW/m^2),

$w_{del,nren,i}$ is the nonrenewable primary energy factor of the exported energy for energy carrier i,

$P_{exp,i}$ is the exported power on site or nearby for energy carrier i (kW/m^2)

$w_{exp,nren,i}$ is the nonrenewable primary energy factor of the exported energy for energy carrier i.

The supply cover factor was calculated based on hourly values from the PV simulations and the energy performance simulations. It includes all electrical energy consumption onsite, EPB uses and equipment use. The supply cover factor was calculated with Equation (2), from the methodology of syn.ikia research project (Salom et al., 2020):

$$Y_{supply} = \frac{E_{prod,used}}{E_{prod,tot}} = \frac{\int \min[P_{prod}(t), P_{used}(t)]\, dt}{\int P_{prod}(t)dt} \quad (2)$$

Where, $E_{prod,used}$ is self-consumed on-site production (kWh)

$E_{prod,tot}$ is total electricity produced on-site (kWh)

P_{prod} is on-site produced power (kW)

P_{used} is on-site consumed power (kW).

Model description

Two apartments were selected as representative apartments for the building, based on orientation and size. One apartment faces Northwest (Apartment 01) and one apartment faces Southeast (Apartment 03). The apartments were simulated individually with adiabatic surfaces for walls, ceilings, and floors towards neighbouring apartments. The balconies were simulated without railing as the railing will be of glass, and the simulation software did not include glazed railing. Figure 2 shows the model of Apartment 03 in IDA-ICE.

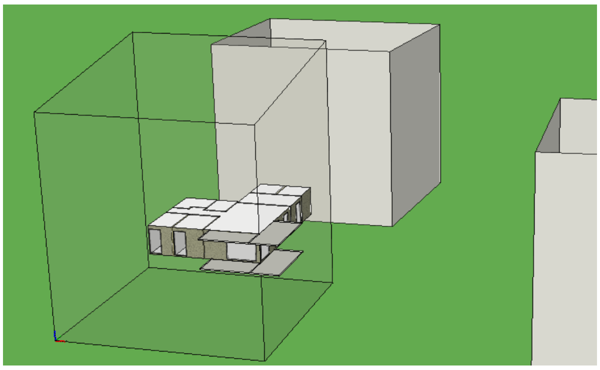

Figure 2: Thermal energy model of apartment 03 in IDA-ICE

The thermal transmittance of the building elements were calculated based on NS-EN ISO 6946:2017 (Standard Norge, 2017). In IDA-ICE, the elements were built up to achieve the calculated U-value. The walls were wood framed, with an assumed center distance of 0.6 m and wood content to insulation of 12 % for the outer layer and 9 % for the innermost insulation layer (Sintef & NTNU, 2018). The design values in Table 1 (Panorama Case study building) for thermal properties, ventilation heat recovery, SFP, and air tightness were used in the models. The common key data input for the IDA-ICE models is shown in Table 2. The occupancy schedule was simulated in accordance with NS3700.

The ventilations rates were calculated for the apartments, based on requirements in NS 3031:2017 (Standard Norge, 2014) for apartment buildings. An average ventilation rate was used in the model. The ventilation rate was calculated based on the minimum ventilation rate, nominal rate in operating hours and maximum supply for bedrooms and exhaust for kitchen and bathrooms. To allow for airflow between zones, interior doors were simulated with an opening of 0.2 m^2.

The intent of part one of the study was to assess the annual energy consumption. Therefore, simple occupancy models based on deterministic schedules were perceived as sufficient for the simulations (Dabirian et al., 2022). Internal heat gain and power and energy use for lighting, equipment, domestic hot water, and people were calculated according to NS 3700 (Table A1, Standard

Norge, 2013). The passive house standard requires that buildings larger than 250 m^2 have a heating demand equal to or less than 15 kWh/m^2-year (Standard Norge, 2013). The thermal bridge for the gable wall and long wall was averaged over the distance, and one value was used for the whole perimeter.

NS 3700 require that the cooling load and satisfactory thermal comfort should be covered by passive measures and to not be provided by mechanical cooling systems. The upper limit temperature for thermal comfort is 26°C in TEK17, which cannot be exceeded in more than 50 hours during a year (Direktoratet for Byggkvalitet, 2017b). For housing without cooling systems there is an exemption to this regulation due to users' ability to influence their environment, for example by opening windows.

Table 2: Input data for energy simulations in IDA-ICE.

Parameter	Value/state	Comment
Location	Rygge, Norway	No climate file for Fredrikstad
Climate	NOR_RYGGE_014940: Annual Mean Dry-bulb temperature: 6.9 °C Total Direct normal radiation: 844 kWh/m^2 year Total Diffuse radiation on horizontal surface: 531 kWh/m^2 year	
Thermal supply	District Heating	
Ventilation strategy	Decentralized AHU for each apartment w. balanced ventilation, Ventilation rate: Apartment 01: 22.3 l/s Apartment 03: 35.8 l/s	Supply in bedrooms and living room, Exhaust in bathrooms and kitchen.
Supply air	19 °C	
Heating set point	21 °C with night setback 19 °C	
Lighting, mean annual power need	1.95 W/m^2	Schedule: 06:00-22:00
Equipment, mean annual power need	3 W/m^2	Schedule: 06:00-22:00
Occupants	0.01 person/m^2	Always present
DHW, annual energy need	29.8 kWh/m^2	Uniform

Design options

The base case design has an energy efficient envelope, heating based on radiators, and district heating for thermal energy supply. Active and passive design strategies were developed with the aim to reduce the energy consumption, while ensuring satisfactory indoor environment (Table 3). Each option was applied to the base case design individually to assess the impact on energy consumption and indoor temperatures. Then, the most efficient strategies were combined in one final design.

The passive design options were thermal mass (TM) with exposed concrete floor with a thickness of 0.1 m, solar shading (SS) with external blinds on the east, west, and south façades, and natural ventilation (NV) with window openings when the zone operative temperature exceeds 25 °C. Active options were radiant floor heating (FH) and a ground source heat pump (GSHP) with a COP of 4.0.

The base case (BC) and solar shading (SS) were also simulated with an ideal cooling unit (BC+C and SS+C).

Table 3: Overview of design options for the two apartments used in the energy simulations in IDA-ICE.

Design options	
BC	Base case Radiators, District Heating Internal floor construction, from below: 100 mm counter ceiling with 12,5 mm gypsum, 265 mm hollow core concrete slab, 55 mm acoustic insulation, 50 mm screed, 15 mm floor coating
BC+C	Base case w. cooling Radiators, District Heating Ideal cooler to assess hypothetical cooling load
TM	Thermal mass Radiators, District Heating Internal floor construction as the base case, but the screed is increased to 100 mm and is exposed as flooring (no floor coating)
SS	Solar shading Radiators, District Heating External blind: East West and South façade. Operating schedule: Sun – blinds activated at radiation level of 100 W/m^2
SS+C	Solar shading + cooling (see SS)
NV	Natural ventilation Radiators, District Heating Window opening: Operative Temperature >25 °C
FH	Radiant floor heating, District Heating
GSHP	Ground source heat pump Radiators, heat pump COP = 4, Space heating and DHW
Final	Final design Include: Radiant floor heating, GSHP, Solar shading (SS) and Natural ventilation (NV)

Scenarios

Scenarios for climate change, user behavior, and energy and power flexibility were created.

In this study, the IPPC scenarios A2 and B1 were used (WMO and UNEP, 2000), in line with the syn.ikia methodology (L. Finocchiaro et al., 2021). The EPW climate files (Appendix A) were generated with Meteonorm (Meteotest AG, 2020).

The user behavior scenarios include an active and a passive user profile, where the active user is energy conscious and take actions to reduce the energy consumption, while the passive user does not consider the energy consumption.

The flexibility scenarios include changing setpoints for the DHW and heating and charging of electric vehicles (EV). The EV charging scenario is based on the study by Sørensen et al. (2021), which found an average connection time of 12.8 hours for private charging points (CP) at a residential neighbourhood, with 4.4 charging sessions per week. Average energy charged was 11.2 kWh per charging session for private users. There was no direct relation between energy charged and connection time. Private CP's typically have longer connection time, and therefore longer non-charging idle time, providing a larger flexibility potential (Sørensen et al., 2021).

Table 4: Scenarios simulated with IDA-ICE

Scenario	**Parameters describing input in the simulation model**
Cl1	Climate scenario based on IPCC A2 for 2050
Cl2	Climate scenario based on IPCC B1 for 2050
Ub1 Active User	DHW: reduced 20% compared to base case
	Heating setpoint : 19 °C
	Lighting: Adjusted schedule: 06-08 and 17-22.
Ub2 Passive User	DHW demand: 35 kWh/(m^2 yr)
	Natural ventilation: Livingroom: Windows opened 50% for 1 hr/day independently of outdoor temperature .
	Heating setpoint : 24 °C
	Artificial lighting : Same as base case
Epc1 Heating setpoint	Setpoint for space heating is increased by 1°C during the whole day and the DHW setpoint increased by 5 °C
Epc2 EV charging	EV charging scenario based on results from Sørensen et al. (2021) 1 EV per apartment with private charging points (CP) of 3.6 kW power
	EV: Average charging session is set to 11 kWh with 13 hours connection time. Charging session: 17-23 → 40% power, 23-06 → 10 % power
	EV charged 4.4 times per week = 2563 kWh per year (28 kWh/m^2 per year for the building)

The climate, user behavior and flexibility scenarios were combined in two perceived pessimistic and optimistic scenarios to understand the added impact of the scenarios (Table 5). IPPC A2 (Cl1) was selected as the pessimistic climate option. In the syn.ikia methodology (L. Finocchiaro et al., 2021) it is understood as the one with the greatest global warming impact of the two. It was combined with a passive user profile (Ub2) and increased setpoints for heating and DHW for flexibility (Epc1). The optimistic version is based on climate scenario IPPC B1 (Cl2), and combined with an active user profile and the use of EV charging.

The primary energy conversion factors were selected based on the syn.ikia report by L. Finocchiaro et al. (2021). The primary energy factor for grid electricity in Norway is calculated according to the report from Energy Norway (ADAPT Consulting, 2013). The selected factor is based on the method EN 15603:2008. Electricity from onsite photovoltaic panels were assumed to be 100% renewable energy with a primary energy factor of 1. There is no regulated value for the primary energy factor of district heating in Norway. The general recommendation is to estimate the PEF according to the energy mix. For the area of study, the largest share comes from waste heat (Fjernvarme, 2021).

Table 5: Pessimistic and optimistic scenarios simulated.

Scenario	Parameters
Pessimistic: Cl1+Ub2+Epc1	Climate: Fredrikstad-A2 Passive user Higher setpoints for heating and DHW
Optimistic: Cl2+Ub1+Epc2	Climate: Fredrikstad-B1 Active user EV charging

Table 6: Primary energy conversion factors of syn.ikia (L. Finocchiaro et al., 2021)

Primary Energy Factors		**Renewable Factor**	**Non-renewable factor**	**Total**
Electricity	Grid	0.94	0.6	1.54
Electricity	PV	1	0	1
Env. heat	DH	1	0.07	1.07

Apartment 03 was selected for scenario analyzes as it was perceived as the worst case in terms of possible overheating issues due to the south orientation.

Results

Design options

The simulations resulted in a higher heating demand for Apartment 01 (Figure 3) compared to Apartment 03 (Figure 4), and significantly more solar gains and possible overheating for Apartment 03. The heating demand is significant from November to March for the two apartments, while there is no energy use for cooling as the apartments do not include cooling systems. In the scenarios BC+C and SS+C, the base case and solar shading were simulated with a hypothetical cooling load (ideal cooling unit) to see the impact of the solar shading. The simulations gave a low heating demand in the context of the Norwegian climate, and the largest share of the energy consumption is from DHW. Detailed results are in Appendix B. The PV simulations resulted in 38 kWh/m^2 year, and is the same for all design options.

The results for the base case of Apartment 01 (Figure 3) gave a total primary energy consumption for EPB uses of 60 kWh/m^2 year, with a nonrenewable primary energy consumption of -9.8 kWh/m^2 year, which indicates a surplus of onsite renewable energy generation. The supply cover factor was 0.6. Results indicate a poor indoor thermal comfort with 3790 overheating hours (above 26 ℃), a mean PMV of 0,72 and a mean PPD of 38 % (International Organization for Standardization,

2005) for the living room and kitchen (Appendix B). The thermal mass option (TM) reduced the heating demand from 13,6 to 12,3 kWh/m^2 year, but had an insignificant effect on the indoor thermal comfort. Solar shading (SS) and natural ventilation (NV) proved efficient for improved indoor thermal comfort, with a mean PMV of 0.1 and -0.24, a mean PPD of 24 and 9, and 2747 and 25 overheating hours for the living room and kitchen respectively.

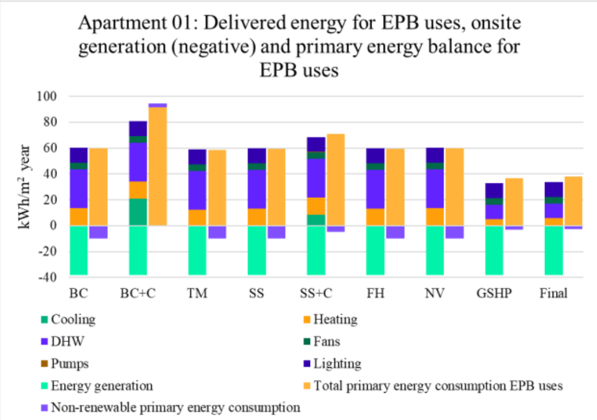

Figure 3: Annual Results for Apartment 01 design options. Negative nonrenewable primary energy consumtpion means that there is a surplus of renewable energy onsite compared to EPB uses.

The cooling consumption for the base case with cooling was 21 kWh/m^2 year, with a mean PMV of -0.15, a mean PPD of 10 % and no overheating hours. In comparison, the delivered energy for cooling for the design option with solar shading and cooling was 8.6 kWh/m^2 year, with a mean PMV of -0.27 and PPD of 11 %.

The option with thermal supply from a ground source heat pump reduced the total primary energy consumption for EPB uses to 37 kWh/m^2 year, with a nonrenewable primary energy consumption of -3 kWh/m^2 year. The supply cover factor increased to 0.68 due to a higher electricity consumption with heat pump for space heating and DHW, as opposed to district heating for the base case.

Solar shading and natural ventilation were most effective to improved indoor thermal comfort, and the ground source heat pump reduced the primary energy consumption significantly. The perceived best options were combined in a final design. Floor heating was selected for the final design based on the assumption that it increases user satisfaction for the thermal environment. The final design included solar shading (SS), natural ventilation (NV), radiant floor heating (FH) and a ground source heat pump (GSHP). The total primary energy consumption for EPB uses was 38 kWh/m^2 year, with a nonrenewable primary energy consumption of 2.6 kWh/m^2 year and supply cover factor of 0.68 for the final design. The mean PMV and PPD was -0.3 and 10 % respectively, with 24 overheating hours for the living room and kitchen. Results were similar for the bedrooms.

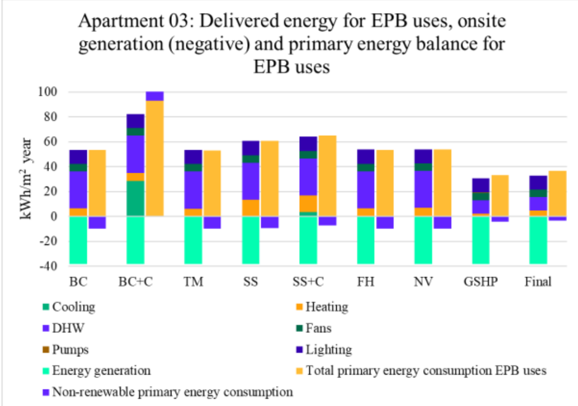

Figure 4: Annual Results for Apartment 03 design options. Negative nonrenewable primary energy consumption means that there is a surplus of renewable energy onsite compared to EPB uses.

Energy simulations for Apartment 03 (Figure 4) resulted in significant solar gains due to large south and east facing windows and a highly insulated envelope. The heating demand for the base case was 6.4 kWh/m^2 year, while it was 13.4 kWh/m^2 year for the design option with solar shading. Thus, the heating demand doubled when solar shading was implemented. The mean PMV was 0.99 and the PPD was 44 % for the living room and kitchen for the base case, while for the solar shading option it was -0.25 and 15 % (Figure 5). The results indicate problematic overheating issues when windows are closed and without any solar shading (Figure 5). The base case with cooling resulted in a cooling consumption of 29 kWh/m^2 year, while it was 3.4 kWh/m^2 year for the option with solar shading and cooling.

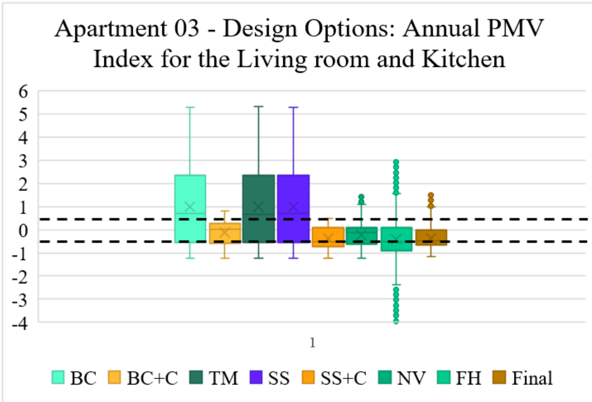

Figure 5: A comparison of the Fanger (1970) thermal comfort index results for PMV in the living room and kitchen for Apartment 03 (the southeast apartment with most overheating).

For Apartment 03, the total primary energy consumption for EPB uses was 53 kWh/m^2 year with a nonrenewable primary energy consumption of -10 kWh/m^2 year for the base case. For the design option with a ground source heat pump the results were 33 kWh/m^2 and -4 kWh/m^2 year. Similar to Apartment 01, the supply cover factor increased from 0.6 to 0.68 from the base case to the ground source heat pump option.

The simulations resulted in high indoor operative temperatures during the summer months for all zones in both apartments. Natural ventilaiton did not affect the heating consumption compared to the base case, while it reduced the overheating and improved the indoor thermal comfort in all zones. The operative temperature of the living room and kitchen reached a maximum temperature of 30˚C for the natural ventilaiton option (NV) with 26 overheating hours, while it was 41˚C and 4744 overheating hours for the base case (Figure 6). The mean PMV was -0.23 and the mean PPD was 9 % with natural ventilation. Figure 6 shows two spikes in indoor operative temperature for all three cases, which corresponds to two peaks in the outdoor temperature (see Figure B.1, Appendix B for comparison with outdoor temperature).

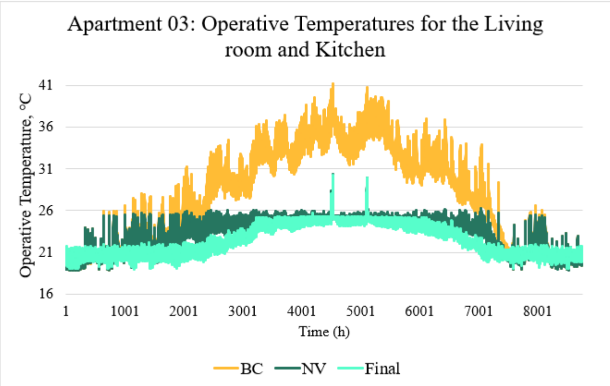

Figure 6: Comparison of the base case with a natural ventilation strategy and the final design for Apartment 03.

The final design for Apartment 03 resulted in a primary energy consumption for EPB uses of 37 kWh/m^2 year and a nonrenewable energy consumption of -3 kWh/m^2 year, with a supply cover factor of 0.68. Although it includes solar shading, the energy consumption for heating is reduced compared to the base case due to the heat pump.

Scenarios

Apartment 03 final design was used for scenario simulations (Figure 7). Both climate scenarios Cl1 and Cl2, based on IPPC A2 and B1, gave a slightly increased heating consumption, from 4.9 to 5.5 and 5.4 kWh/m^2 year, but the indoor thermal comfort conditions remained similar to the final design. Detailed results for all scenarios are in Appendix C.

User behaviour scenarios had significant effects on the primary energy consumption for EPB uses, with result of 24 kWh/m^2 year for the active user (UB1) and 71 kWh/m^2 year for the passive user (UB2). The supply cover factor increased for the passive user (0.65) due to increased electricity consumption during hours of PV electricity generation. Figure 8 show surplus of renewable energy generation in the summer period. The mean PMV (Figure 9) and PPD for the active user was -0.5 and 14%, and -0.37 and 11% for the passive user (Appendix C).

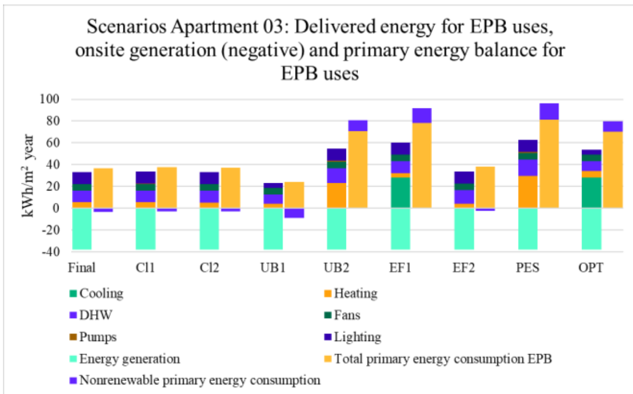

Figure 7: Annual Results for scenarios for Apartment 03. Negative nonrenewable primary energy consumption means that there is a surplus of renewable energy onsite compared to EPB uses.

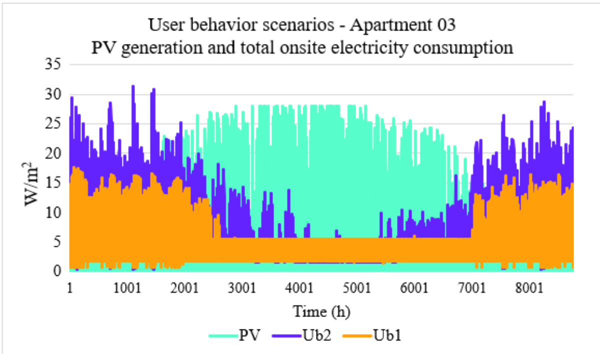

Figure 8: Annual energy generation from PV panels and energy consumption for two user behaviour scenarios, active (UB1) and passive (UB2) user

The energy flexibility scenario with EV charging (EF1) increased the primary energy consumption for EPB uses to 79 kWh/m^2 year, with a nonrenewable energy consumption of 13 kWh/m^2 year. Further, the supply cover factor did not improve significantly. Scenario EF2, with increased set-points for space-heating and DHW, resulted in a slightly higher DHW consumption and a minor improvement of the supply cover factor. The primary energy consumption and PMV and PPD was almost unchanged from the final design.

The pessimistic scenario had a worse indoor thermal comfort with a mean PMV of -0.7 and PPD of 19 %, compared to the optimistic scenario with a mean PMV of -0.5 and PPD of 14 % (Figure 9). None of the two scenarios have a negative nonrenewable primary energy consumption, with 15 kWh/m^2 year for the pessimistic scenario and 9 kWh/m^2 year for the optimistic scenario. However, the optimistic scenario includes EV charging, which is an annual electricity load of 28 kWh/m^2 year. Without the EV charging, the nonrenewable primary energy consumption for the optimistic scenario is -8 kWh/m^2 year. The primary energy consumption for EBP uses for the pessimistic scenario is 81 kWh/m^2 year and the optimistic scenario results in 70 kWh/m^2 year.

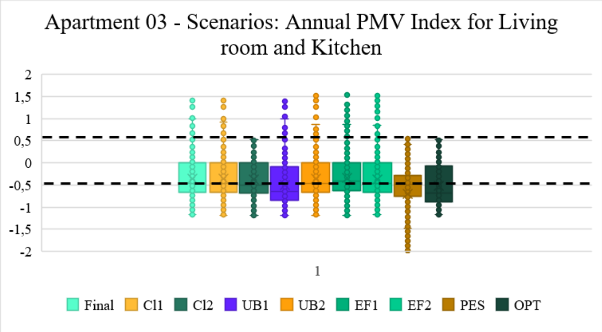

Figure 9: PMV results for the scenarios in the living room and kitchen for Apartment 03.

Discussion

What is the effect of different design options on the primary energy use of the building?

The ground source heat pump effectively reduces the primary energy consumption for heating and DHW, while the other options do not affect the primary energy consumption considerably.

The simulation results show significant overheating in the apartments if the windows are always closed. The ventilation system is not sufficient for keeping the indoor temperature in a comfortable range. Natural ventilation is necessary in the apartments to prevent overheating. The heating demand is low compared to the Norwegian building code, and the calculated U-value of the exterior wall is 0,1 W/(m^{2}K).

The natural ventilation strategy is an ideal case where it is assumed that occupants open then windows when strictly necessary to achieve operative indoor temperature below 25 °C. Real occupancy patterns and operational schedules could deviate significantly from assumptions, affecting heating consumption, indoor thermal comfort and energy use.

Experience from built residential projects indicate that the simulations underestimate the space-heating load. It is a theoretical heating consumption with a set-point of 21˚C and night-set-back of 19˚C, but occupants might use the space very differently.

Solar shading, especially for the south facing apartment, improved the indoor thermal comfort. Thermal mass does not have distinct effects on the heating demand or the indoor thermal comfort. However, larger quantity of exposed thermal mass could change the impact.

It should be noted the selected reference value of the district heating factor might overestimate the related primary energy use.

Is the building able to reach a net plus energy balance with respect to EPB uses (heating, cooling, ventilation, DHW, and lighting)?

The final design for both apartments reaches a net plus energy balance with respect to EPB uses. The total primary energy consumption is low due to efficient envelope design with a ground source heat pump, and the onsite renewable energy generation covers the building EPB uses.

How robust is the design with respect to meeting the goals of energy performance and indoor climate, given changes in occupancy patterns and future climate scenarios (IPPC A2 and B1)?

The IPPC climate scenarios A2 and B1 result in slightly increased energy demand for heating. In both A2 and B1 (derived from Meteonorm software) the mean annual temperature and the mean monthly direct and diffuse radiation present lower values compared to the current climate date (from IDA-ICE).

The user behaviour scenarios show that the energy balance is highly impacted by the occupants, and will not necessarily reach a net plus energy balance in the case of high consumption users. Further, the energy balance is affected by the utilization of onsite renewable energy consumption. The energy flexibility scenario does not assume an ideal charging period or a smart charging system, but rather a conventional user which charges the car after work until the next morning. Thus, the utilization of solar energy is limited. The optimistic scenario without the EV charging shows an improved energy balance compared to the final design and a surplus of onsite renewable energy. In contrast, the final design results in a high primary energy consumption and positive nonrenewable primary energy consumption.

The building has nine different apartment sizes, and two representative ones were selected. The thermal energy models include separate zones for all rooms, which allow for detailed simulations of the thermal environment. The model represented in this study is appropriate for analysis on the apartment level, and further work should consider the whole building including the energy use for the common areas.

Conclusion

The apartments reached a net plus energy balance and have a low primary energy consumption for EPB uses. Natural ventilation (in addition to the ventilation system), solar shading and ground-source heat pump significantly improved the indoor thermal comfort and primary energy consumption of the apartments. User behaviors have a significant impact on the space-heating, DHW and lighting consumption, and the nonrenewable primary energy consumption. The design is robust against the IPPC climate scenarios A2 and B1. Energy flexibility can enable the matching between onsite renewable energy generation and consumption to improve the supply cover factor and not increase the consumption of nonrenewable primary energy. Pessimistic and optimistic scenarios show the impact of combined scenarios for climate, user behavior and energy flexibility on the primary energy consumption. The pessimistic scenario more than doubles the primary energy consumption compared to the final design.

Acknowledgement

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Nomenclature

ACH	Air Change Rate
COP	Coefficient of Performance
EV	Electrical Vehicle
GHG	Greenhouse Gas Emissions
GSHP	Ground Source Heat Pump
HP	Heat Pump
PEB	Plus Energy Building
PMV	Predicted Mean Vote
PPD	People Percent Dissatisfied
PV	Photovoltaic
SFP	Specific Fan Power

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Appendix

Appendix A

1. Current Climate

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED203/A6V1F (educational license)
Object: Climate file
Description:
Date: 2021-01-01 - 2021-12-31
Saved: 18.01.2022 12:12:14

	Variables						
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s	Cloudness, %
January	-3.5	92.7	28.7	9.5	0.6	1.3	60.9
February	0.7	82.4	67.0	22.5	1.0	1.2	56.7
March	0.2	77.9	100.1	50.2	0.7	2.0	59.5
April	6.0	75.1	128.0	79.6	0.2	1.6	69.0
May	11.0	67.1	165.2	113.4	0.2	0.6	56.8
June	14.1	71.4	154.6	126.6	0.5	1.1	61.9
July	17.3	77.5	147.4	120.0	0.4	1.9	54.6
August	16.0	76.3	126.1	93.1	-0.4	-0.2	62.7
September	11.3	80.1	118.8	61.2	-0.6	0.6	54.6
October	6.8	85.6	63.1	31.4	-0.3	0.7	61.7
November	2.4	88.6	33.3	11.8	0.2	0.4	70.3
December	-0.2	88.0	23.0	6.0	0.3	1.2	68.1
mean	6.9	80.2	96.4	60.6	0.2	1.0	61.4
mean*8760.0 h	60388.3	702775.5	844170.0	531206.0	1869.3	9008.3	537985.0
min	-3.5	67.1	23.0	6.0	-0.6	-0.2	54.6
max	17.3	92.7	165.2	126.6	1.0	2.0	70.3

2. A2 Climate

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED203/A6V1F (educational license)
Object: Climate file
Description:
Date: 2021-01-01 - 2021-12-31
Saved: 12.04.2022 13:01:03

	Variables						
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s	Cloudness, %
January	-3.4	81.6	18.0	9.0	-0.7	0.2	89.8
February	-3.0	80.2	41.9	19.5	0.3	0.5	78.8
March	0.1	75.0	115.7	43.2	0.2	0.7	59.2
April	4.9	68.5	189.1	70.5	0.5	0.8	51.9
May	10.9	68.5	249.1	83.2	0.7	0.9	45.2
June	15.5	68.6	222.2	112.8	1.0	0.5	57.8
July	17.2	70.1	209.7	107.0	0.8	0.9	57.7
August	15.9	73.6	154.7	92.5	0.9	0.2	62.9
September	11.6	79.6	120.4	63.6	1.0	0.9	68.5
October	7.2	80.0	63.7	31.8	0.4	0.6	73.7
November	1.9	81.4	28.9	10.7	0.4	0.7	79.1
December	-1.5	81.3	10.5	5.5	0.2	1.0	91.6
mean	6.5	75.7	119.0	54.3	0.5	0.7	68.0
mean*8760.0 h	56979.3	662856.8	1042822.0	475476.0	4191.8	5718.3	595260.0
min	-3.4	68.5	10.5	5.5	-0.7	0.2	45.2
max	17.2	81.6	249.1	112.8	1.0	1.0	91.6

3. B1 Climate

Climate file

IDA Indoor Climate and Energy 4.802 License: ICE40X:ICE40X:ED203/A6V1F (educational license)
Object: Climate file
Description:
Date: 2021-01-01 - 2021-12-31
Saved: 04.04.2022 18:25:04

	Variables						
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s	Cloudness, %
January	-3.0	81.7	18.4	8.3	-0.7	0.2	86.5
February	-2.9	80.2	44.5	21.1	0.3	0.5	72.6
March	0.8	75.1	110.9	42.1	0.2	0.7	63.8
April	4.9	68.8	169.2	78.7	0.5	0.8	57.1
May	11.5	67.9	222.4	97.9	0.8	0.9	54.3
June	15.1	70.0	205.8	119.9	1.0	0.5	59.0
July	17.3	69.5	233.0	92.9	0.9	0.9	53.5
August	15.9	73.5	171.7	79.7	0.9	0.2	56.3
September	11.5	80.0	140.2	54.1	1.0	1.0	62.7
October	7.7	80.0	69.2	28.2	0.4	0.7	72.0
November	2.0	81.1	21.4	11.6	0.4	0.7	89.5
December	-1.7	81.2	10.4	5.5	0.2	1.0	93.7
mean	6.6	75.7	118.5	53.5	0.5	0.7	68.4
mean*8760.0 h	58144.7	663352.0	1038008.0	468287.0	4222.8	5712.8	599150.0
min	-3.0	67.9	10.4	5.5	-0.7	0.2	53.5
max	17.3	81.7	233.0	119.9	1.0	1.0	93.7

Appendix B

	Apartment 01									Apartment 03								
Delivered Energy	**BC**	**BC+C**	**TM**	**SS**	**SS+C**	**FH**	**NV**	**GSHP**	**Final**	**BC**	**BC + C**	**TM**	**SS**	**SS+C**	**FH**	**NV**	**GSHP**	**Final**
Cooling		20,7			8,6						28,55			3,42	-			
Heating	13,6	13,6	12,3	13,3	13,3	13,3	13,7	5,2	6,0	6,4	6,6	6,3	13,4	13,4	6,5	6,8	2,3	4,9
DHW	29,8	29,8	29,8	29,8	29,8	29,8	29,8	10,9	10,9	29,8	29,8	29,8	29,8	29,8	29,8	29,8	10,8	10,8
Fans	5,3	5,3	5,3	5,3	5,3	5,3	5,3	5,3	5,3	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
Pumps	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,2	0,1
Lighting	11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,4	11,0
Equipment	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,5	10,1
Total energy use	70,6	70,6	69,3	70,3	70,3	70,2	70,6	43,3	44,1	53,6	82,3	53,6	60,7	64,1	53,8	54,0	30,7	32,8
Energy generation	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0
on-site generated EP	22,8	22,8	22,8	22,8	26,2	22,8	22,8	25,8	25,8	22,8	31,2	22,8	22,8	24,3	22,8	22,8	25,8	25,8
Grid delivered for EP	-6,1	14,6	-6,1	-6,1	-0,9	-6,1	-6,1	7,0	7,8	-5,4	14,8	-5,4	-5,4	-3,5	-5,4	-5,4	4,9	6,9
Total exported Energ	15,2	15,2	15,2	15,2	11,8	15,2	15,2	12,2	12,2	15,2	6,8	15,2	15,2	13,7	15,2	15,2	12,2	12,2
Total primary energy consumption	59,8	91,7	58,4	59,5	71,0	59,5	59,9	36,6	37,8	53,3	92,9	53,2	60,8	65,2	53,4	53,7	33,4	36,5
Non-renewable primary energy	-9,8	2,7	-9,8	-9,8	-4,6	-9,8	-9,7	-3,1	-2,6	-9,8	7,3	-9,8	-9,3	-7,3	-9,8	-9,8	-4,4	-3,1
Supply cover factor	0,6	0,6	0,6	0,6	0,7	0,6	0,6	0,7	0,7	0,6	0,8	0,6	0,6	0,6	0,6	0,6	0,7	0,7
COP Heating	1	1	1	1	1	1	1	4	4	1	1	1	1	1	1	1	4	4
COP cooling	-	1	-	-	1	-	-	-		-	1	-	-	1	-	-	-	
COP DHW	1	1	1	1	1	1	1	4	4	1	1	1	1	1	1	1	4	4
Livingroom and Kitchen zone																		
Max indoor temp	41	26,6	40	34	26	40	30	41	30	41	27	41	31	26	41	30	41	30
Overheating hours (h) Top>26C	3789	0	3755	2747	0	3775	25	3792	24	4744	0	4739	1412	0	4715	25	4696	24
PDH hours of people dissatisfied	1896	479	1967	1200	570	1910	448	1898	429	1779	388	1776	605	490	1726	370	1758	429
Mean PMV	0,7	-0,2	0,7	0,1	-0,3	0,7	-0,2	0,7	-0,3	1,0	-0,1	1,0	-0,3	-0,4	1,0	-0,2	0,9	-0,4
Min PMV	-0,7	-0,8	-0,8	-0,8	-0,8	-0,7	-0,7	-0,7	-0,7	-0,8	-0,8	-0,8	-0,8	0,8	-0,7	-0,8	-0,8	-0,7
Max PMV	3,3	0,3	3,3	1,9	0,3	3,3	0,2	3,3	0,2	3,2	0,4	3,2	0,9	0,3	3,1	0,2	3,1	0,2
Mean PPD	37,8	9,6	39,2	23,9	11,4	38,1	8,9	37,8	9,7	44,1	9,7	44,0	15,0	12,2	42,8	9,2	43,6	10,7
Min PPD	7,4	5,6	7,8	8,9	5,6	7,5	5,2	7,4	5,2	10,3	5,9	10,4	5,5	5,4	9,7	5,3	10,1	5,3
Max PPD	98,8	18,7	98,9	69,2	18,7	90,9	14,6	98,9	15,9	97,3	18,4	97,2	23,7	20,0	96,7	18,4	96,6	16,9
Max indoor temp	40,0	26,0	40,0	34,0	26,0	40,0	30,0	40,0	30,0	43	29	43	32	26	43	30	43	30
Worst Bedroom zone																		
Overheating hours (h) Top>26C	3730	0	3675	2739	0	3717	25	3713	21	4843	313	4822	2177	0	4557	31	4552	24
PDH hours of people dissatisfied	526	136	547	341	163	527	128	526	118	308	67,5	389	217	134	531	109	537	70,5
Mean PMV	0,7	-0,2	0,6	0,1	-0,3	0,7	0,3	0,7	-0,3	1,1	0,1	1,1	0,0	-0,2	1,1	-0,2	0,9	-0,4
Min PMV	-0,7	-0,8	-0,8	-0,8	-0,8	-0,7	-0,7	-0,7	-0,7	-0,7	-0,5	-0,7	-0,7	-0,7	-0,7	-0,7	-0,7	-0,7
Max PMV	3,2	0,4	3,2	1,9	0,4	3,3	0,2	3,2	0,2	3,3	0,7	3,3	1,3	0,3	3,2	0,2	3,3	0,2
Mean PPD	36,9	9,6	38,4	24,5	11,6	37,5	9,0	36,9	9,4	45,7	9,6	45,3	16,8	10,4	44,0	8,4	41,5	10,5
Min PPD	7,4	5,6	7,9	9,0	5,6	7,7	5,1	7,4	5,2	11,3	5,9	11,1	6,0	5,6	9,9	5,2	8,8	5,2
Max PPD	98,7	18,6	98,7	71,1	18,9	90,8	14,5	98,7	15,2	97,6	15,3	97,5	42,1	16,9	97,0	16,1	99,0	16,2

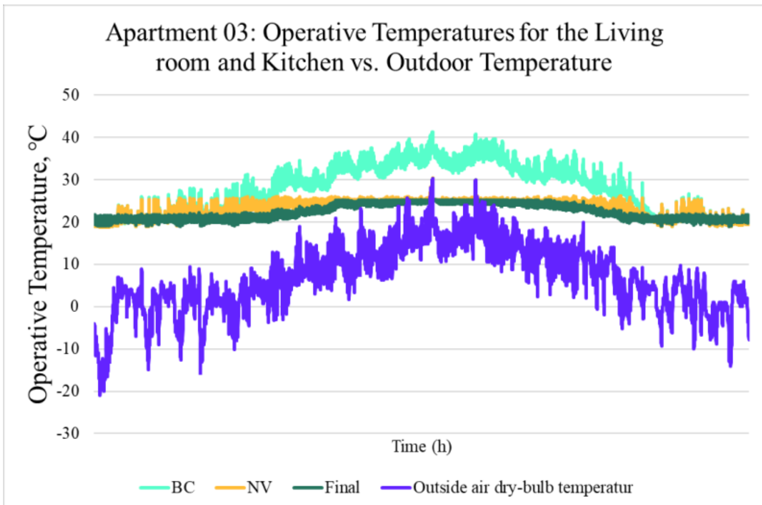

Figure B.1: Comparison of the outdoor temperature with the living room and kitchen temperatures for the base case, the natural ventilation strategy and the final design for Apartment 03.

Appendix C

Delivered Energy	**CL1**	**CL2**	**UB1**	**UB2**	**EF1**	**EF2**	**OPT**	**PES**
Cooling					28,4			28,4
Heating	5,5	5,4	4,1	23,2	3,8	4,0	29,7	6,0
DHW	10,8	10,8	8,6	13,5	10,8	12,7	15,2	8,6
Fans	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
Pumps	0,2	0,2	0,2	0,9	0,2	0,2	0,8	0,1
Lighting	11,0	11,0	4,5	11,0	11,0	11,0	11,0	4,5
Equipment	10,1	10,1	8,1	10,1	10,1	10,1	10,1	8,1
Total energy use	33,5	33,4	23,4	54,6	60,2	33,9	62,6	53,6
Energy generation	38,0	38,0	38,0	38,0	38,0	38,0	38,0	38,0
on-site generated EPB	25,8	25,8	22,4	24,7	26,2	26,2	28,1	22,8
Grid delivered for EPB	7,6	7,5	1,0	29,9	5,5	7,6	34,5	2,4
Total exported Energy	12,2	12,2	15,6	13,3	11,8	11,8	9,9	15,2
Total primary energy consumption EPB	37,6	37,5	24,0	70,7	78,5	38,0	81,3	70,2
Non-renewable primary energy consumption	-2,7	-2,8	-8,7	9,9	13,3	-2,5	14,8	9,4
Supply cover factor	0,7	0,7	0,6	0,7	0,7	0,7	0,7	0,6
COP Heating	4	4	4	4	4	4	4	4
COP cooling	-	-	-	-	-	-	-	-
COP DHW	4	4	4	4	4	4	4	4
Livingroom and Kitchen zone								
Max indoor temp	27	27	30	30	30	30	27	27
Overheating hours (h) Top>26C	0	0	24	24	24	24	0	0
PDH hours of people dissatisfied	445	442	565	429	429	409	779	579
Mean PMV	-0,4	-0,4	-0,5	-0,4	-0,4	-0,3	-0,7	-0,5
Min PMV	-0,8	-0,8	-0,9	-0,7	-0,7	-0,7	-1,3	-0,9
Max PMV	0,1	0,1	0,2	0,2	0,2	0,2	-0,1	0,1
Mean PPD	11,1	11,0	14,1	10,7	10,7	10,2	19,1	14,4
Min PPD	5,3	5,3	5,3	5,3	5,3	5,3	6,7	5,2
Max PPD	17,7	17,6	22,4	16,9	16,9	16,7	34,4	23,6
Max indoor temp	27	27	30	30	30	30	28	27
Worst Bedroom zone								
Overheating hours (h) Top>26C	0	0	20	24	24	24	95	0
PDH hours of people dissatisfied	124	123	160	89	70,5	84	113	167
Mean PMV	-0,3	-0,3	-0,4	-0,4	-0,4	-0,3	-0,2	-0,4
Min PMV	-0,7	-0,7	-0,9	-0,7	-0,7	-0,7	-0,5	-0,9
Max PMV	0,2	0,1	0,2	0,2	0,2	0,2	0,3	0,1
Mean PPD	9,6	9,5	12,4	10,5	10,5	9,9	8,7	12,9
Min PPD	5,2	5,2	5,2	5,2	5,2	5,2	5,3	5,3
Max PPD	15,8	15,8	21,3	16,2	16,2	15,9	13,8	22,5