D6.3d - Performance of the Studied Systemic Renovation Packages - Office Buildings

Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems

iNSPiRe

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Table of Contents

1 Executive Summary

This report is part of a series of reports summarizing and analysing simulation results for renovated buildings, residential as well as offices, in European climates. This particular report covers the office buildings.

1.1 Methodology

The simulation results shown in this report concern office buildings built within 1945-1970 ("period I") and 1980-1990 ("period III"), renovated with air source heat pump (ASHP), gas or pellet boiler, combined with two different distribution systems: radiant ceiling panels and fan coils. The boiler systems were complemented with split units, in order to also cover the cooling demand. All cases also had mechanical ventilation with heat recovery (MVHR) with 85% thermal efficiency. The fan coil systems had some dehumidification of the air in summer, although not with a fixed humidity limit, while the radiant ceiling systems did not include any humidity control. The size of the office buildings has been varied widely, and thereby the S/V ratio, with floor areas 162 or 324 m² per floor, and with three, five or seven floors. In the report, the smaller variant of the office buildings, with 162 m² per floor, is referred to as "OFF1", while the larger variant with 324 m² per floor is referred to as "OFF2". The building model had six zones: two zones representing the ground floor, two zones representing a middle floor and two zones representing a top floor. Each floor had one zone on the south side and one on the north side. The zones were taken to be adiabatic to one another, and no air exchange was considered between them. Buildings with five or seven floors were simulated by multiplying the inputs and outputs for the middle floor.

The buildings from period I were renovated to two different levels of heating demand, 45 kWh/m²y and 25 kWh/m²y, by adding insulation on roof and façade and using better quality windows. The amount of insulation and the type of windows was varied to meet these levels in each climate for a building with five floors, and the same amount of insulation was assumed for buildings with three and seven floors. In the report, the 45 kWh/m²y energy level is referred to as "EL45", and the 25 kWh/m²y energy level is referred to as "EL25". The office buildings from period III were assumed to be constructed with non-bearing curtain walls and were renovated with prefabricated wall elements, including new windows and 100 mm insulation, the same for all climates and all sizes of the building. Thus, the level of heating demand varied between the different climates and building sizes.

Extra insulation thickness and choice of windows were adapted for each climate to attain the two energy levels 25 and 45 kWh/m²y for period I offices (1945-70), while those for period III (1980-90) were renovated with the same curtain wall construction for all climates.

Solar PV energy production and usage were calculated in post-processing based on hourly weather data for each climate and the hourly use of electricity for each case. PV panels were assumed to be placed either on the south-east façade (45° azimuth, 90° tilt) or on the roof, facing south-east (45° azimuth, 30° tilt). For façade mounted PV systems, the total area was 30%, 60% or 90% of the opaque part of the façade. For roof mounted systems the total area was 25%, 30% or 50% of the roof area. Since all configurations of the office buildings had flat roofs, the roof area that was used to size the PV systems was equal to the floor area of one storey, i.e. either 162 m² or 324 m².

The control system implements a 2 °C set-back temperature outside of office hours, resulting in high heating loads before the arrival of the office workers. In some cases, the office is heated before work hours, but then cooled again for most of the day due to internal loads. No smart control was implemented to limit this. There is also no air flows between the north and south offices, something that would in practice occur to a greater or lesser extent. Thus the peak heating/cooling loads per zone simulated here are probably larger than those that would occur in practice.

The heating and cooling systems were sized to match the maximum 2 hours average heating or cooling load, whichever was highest for the respective case. That is, the total heating and cooling loads of the whole building were calculated on a 2 hour-basis over the whole year, and then the maximum value was used to size the heating and cooling generation system. The distribution system was sized for the maximum load of each zone in the building. The sizing was done for each climate and each size of the building individually.

Each case was also simulated with two different levels of supply temperature for the heating system. For radiant ceiling panels the supply temperatures were 35 °C and 30 °C, and for fan coils 45 °C and 35 °C. Domestic hot water was not included in the simulations, as it constitutes only a small part of the total energy consumption in office buildings. For a more detailed description of the boundary conditions, modelling, system sizing, simulations and calculations, please refer to report D6.3a (methodology) [2].

1.2 Main Results

This is a summary of the most important results from the simulation of renovated office buildings. Detailed results are found in section 2, section 3 and in Annex I – Simulation results. More conclusions regarding the general differences between the systems can also be found in report D6.3b (single family houses) [3].

1.2.1 Energy use

With radiant ceiling panels, the energy use was higher than with fan coils. This is partly due to the fact that convective temperature was used to control the heating/cooling and the fact that convective heating dominates with fan coils, whereas radiant ceiling panels transfer heat mainly by radiation. Compared to the heating demand of existing buildings, the energy use for heating was up to 66% lower with the simulated envelope renovation measures and radiant ceiling panels, or from 3 to 150 kWh/m²y. The corresponding figures with fan coils were 69% or from 10 to 157 kWh/m²y. The savings in final energy or primary energy could even higher, due to the change of energy generation, distribution and emission systems. The largest reductions were seen for the buildings renovated to a heating demand level of 25 kWh/m²y, and particularly for the Northern Continental and Oceanic climates, where the energy standard for existing buildings is not very good. Buildings in the Nordic region are quite well insulated even in their existing state, and in Southern Europe the heating demand of existing buildings is lower due to the warmer climate.

For cooling, the effect of renovation showed no correlation with the heating energy used. The resulting cooling energy varied with the climatic conditions, but showed no correlation with the renovation level and the used energy for heating. The variation, compared to the existing buildings, goes from a 175% reduction to a 49% increase, or -36 kWh/m²y to +1 kWh/m²y, if radiant ceiling panels were used for cooling distribution. With fan coils the used energy for cooling compared to the existing buildings varied from -36% to -197%, or -1 kWh/m²y to -47 kWh/m²y.

The used energy for cooling varied with the climatic conditions, but showed no correlation with the renovation level and the used energy for heating.

Looking at the total final energy consumption for heating, cooling and ventilation, the simulated renovation measures using heat pumps enable levels in the range 15 – 36 kWh/m²y without solar PV panels, and down to 8 kWh/m²y with PV. This corresponds to a primary energy consumption of 42 – 82 kWh/m²y without PV and down to 23 kWh/m²y with PV. For systems with a boiler, the final energy demands are dominated by the heating load and in only a few cases is it below 50 kWh/m²y without PV. It is possible, in many of the studied cases, to achieve the primary energy target of 50 kWh/m²y. For the Oceanic climate, this level can be reached for the period III office building and for the period I office building with a heating demand of 25 kWh/m²y without PV. For other climates it is possible to go below 50 kWh/m²y primary energy consumption for almost all variations of the 25 kWh/m²y buildings from period I, as well as for the majority of the 45 kWh/m²y from period I and the period III buildings if solar PV is added to the system. The most difficult cases are the period III buildings in the Nordic and Northern Continental climates, due to the relatively high heating demand, and the period I buildings with a heating demand of 45 kWh/m²y in the Southern Dry and Mediterranean climates, which have a high heating demand as well as a high cooling demand. A greater area of PV is required to reach the target for the systems with boilers, and there are greater numbers of cases where the target cannot be reached at all, even with the largest PV areas.

The primary energy target of 50 kWh/m²y is achievable for most of the studied office buildings after renovation, in many cases with help of solar PV panels on the building. The systems with boilers require a larger area of PV to achieve this target than those with heat pumps.

Despite a wide range of sizes of the building and the PV system, the variation in percentage self-consumption is relatively narrow. For the system with ASHP and radiant ceilings, the self-consumption of PV electricity during winter varies in the Nordic climate from 51% to 59% and during summer from 71% to 76%, with overall self-consumption varying from 64% to 69%. The self-consumption for the HVAC system itself (only those with heat pumps), assuming that it is satisfied before other loads, varies more widely: up to 100% during winter, and 48% to 94% over the whole year. This means that as the total electricity load (heat pump, ventilation, pumps and electrical appliances) is much larger than the PV production, the amount of self-consumption does not vary so much and it is not dependent on whether the PV modules are mounted on the façade or on the roof. For the systems with boilers, the annual self-consumption varies from 51 to 76%, with the lower values being for the 3 floor buildings and largest PV field. The self-consumption for systems with boilers is surprisingly similar for all climates as the increased PV yield is matched to a large extent by the increased cooling demand in the more southerly climates.

The produced electricity with solar PV panels can, to a large extent, be self-consumed, as the total electricity load is substantially higher than what a PV system mounted on the roof or the façade can cover. This is true even for the boiler based HVAC systems, although the level of self-consumption is slightly lower than for those with heat pumps.

As the heating and cooling systems operated according the average air temperature of the zones in the building, it was not possible to have occasions with simultaneous heating and cooling. In a real building, however, this situation could occur, causing the total heating and/or cooling demand to increase.

1.2.2 Thermal comfort

With radiant ceiling panels, the convective temperature in the zones was kept within the range set in the boundary conditions, i.e. above 20.5 °C in winter and 24.5 °C in summer, with exception for a few hours per year for some combinations of climate and building. The operative temperature is, with radiant panels, close or equal to the convective temperature.

With fan coils there were a few more hours per year with temperature out of the desired range, but mostly the comfort was good also with this distribution system. Taking into consideration both temperature and humidity in the zones, the results show that both systems were able to keep the conditions within the recommended range for thermal comfort during most of the time, in both cold and warm climates, although the lack of air humidity control in the studied systems allowed the humidity level to exceed this range.

The number of hours outside the comfort zone due to high humidity was greater for radiant panels than fan-coils, as the fan-coils do dehumidify the air to a certain extent. In practice, external dehumidification is required for the radiant panels as the results indicate that condensation would occur for quite a few hours without it.

With no humidity control and radiant panels, there are a significant number of hours with too high humidity in the cooling season in some climates. For many of these hours condensation would occur, and thus control on water temperature inlet would be necessary if dehumidification is not implemented. Fan-coils, with the 7 °C supply temperature used here, do not control the humidity but they do reduce it to acceptable levels.

Thermal comfort was essentially the same regardless of the energy generation system and varied only with the method for distribution of heating and cooling.

1.2.3 Investment and running costs

The annualised costs for the renovation measures without PV lie within the range 660 – 1120 €/m^{2}y for ASHP and radiant ceiling panels, 650 – 1110 €/m^{2}y for ASHP and fan coils, 650 – 1100 €/m^{2}y for gas boiler and radiant ceiling panels (680 – 1150 €/m^{2}y with pellet boiler) and 650 – 1100 €/m^{2}y for gas boiler and fan coils (680 – 1150 €/m^{2}y with pellet boiler).

The lowest costs for renovation are evident for the period I buildings on the 45 kWh/m^{2}y level in the Mediterranean climate, where no insulation is applied. In general, the costs for insulation and windows are lower for EL45 than for EL25, while the costs for generation and distribution systems are lower for EL25. For the period III buildings, the costs for insulation and windows are the same regardless of the climate, as the same curtain wall is applied for all cases.

The total yearly renovation costs, including purchased energy, operation and maintenance, amount to 33 – 45 €/m^{2}y for the period I buildings and 41 – 54 €/m^{2}y for the period III buildings with ASHP and radiant ceilings. The corresponding figures with ASHP and fan coils are 33 – 45 €/m^{2}y for the period I buildings and 42 – 58 €/m^{2}y for the period III buildings. For the system with boiler and radiant ceilings, the total renovation costs are 32 to 53 €/m^{2}y, with lower costs for the larger offices. The costs for this system are very similar for the energy levels 25 and 45, and these are significantly lower than the costs for the curtain wall buildings, especially the smaller ones.

The fan coils have a lower initial investment cost than the radiant ceiling panels, but the shorter technical lifespan means they need to be replaced once within a 30 year timeframe. The annualised cost over 30 years is almost exactly the same for both systems (1 – 3% higher with radiant ceilings), and the difference in cost between air source heat pump and gas or pellet boiler is also small (within 1 – 3%).

The total costs are the lowest for the buildings from period I renovated to the 25 kWh/m^{2}y level. This is due to the reduced costs for energy generation and distribution systems and for purchased energy. The difference between the EL25 and the EL45 buildings is rather small though, only 1 €/m^{2}y on average.

Despite the higher initial upfront costs, it is more economic to renovate to a heating demand level of 25 kWh/m^{2}y than 45 kWh/m^{2}y, due to the lower costs for energy systems and purchased energy.

The renovation costs for buildings from period III are not directly comparable to those for buildings from period I, given the different starting points and approaches to renovation. Nevertheless, it can be noted that much of the difference can be attributed to the larger glazed area of the period III buildings, leading to higher investment costs for new curtain wall.

2 Air Source Heat Pump with Radiant Ceilings

In the following sections, results for the system with air source heat pump and radiant ceiling panels are reported, including used energy, thermal comfort, Seasonal Performance Factor (SPF) of the heat pump, utilisation of solar PV energy, final and primary energy consumption and economic evaluation.

2.1 Used energy

With air source heat pump and radiant ceiling panels, the used energy for heating compared to existing buildings could be reduced by 4% – 66%; in absolute numbers from 3 to 150 kWh/m²y. The used energy for cooling varied from a 1 kWh/m²y increase to a 35 kWh/m²y reduction compared to existing buildings. While the cooling demand is strongly connected to the climatic conditions, the results show no correlation between used energy for cooling and used energy for heating.

The system was simulated twice for the same case, once with a design supply temperature of 30 °C and once with 35 °C, with relevant radiant panel sizes. Thus, there are two points for each combination of climate and energy level. Supply temperature for the cooling season has been fixed at 15°C.

Insulation thicknesses vary from one case to the other from a maximum of 15 cm for the Northern Continental climate, energy level 25 kWh/m²y, down to no insulation for the energy level 45 kWh/m²y in the Mediterranean climate. Even with no insulation, the resulting heating demand with new windows and MVHR was lower than 45 kWh/m²y in this climate. If the same windows are used, a larger office building requires less insulation than a small office building to achieve a certain heating demand, as a consequence of the lower S/V ratio. As the insulation thickness and windows for period I were defined to reach heating demand levels 25 and 45 kWh/m²y for office buildings with five floors, there is a variation around these levels for buildings with three or seven floors. The used energy for heating for the 25 kWh/m²y buildings varies from 17 kWh/m²y (Mediterranean climate, OFF2, 7 floors) to 35 kWh/m²y (Southern Dry, OFF2, 3 floors), and for the 45 kWh/m²y buildings from 27 kWh/m²y (Mediterranean climate, OFF2, 7 floors) to 64 kWh/m²y (Southern Dry, OFF1, 3 floors). With respect to the heating demand levels 25 and 45 kWh/m²y, the simulated heating demands for period I buildings with 5 floors were, in most cases, slightly higher, with a few exceptions: Mediterranean, EL45 (as mentioned above); Mediterranean, EL25, OFF2; Nordic, EL45, OFF2.

The heating demand for the office buildings from period III showed a wide variation between different climates, since the same windows and the same amount of insulation were applied for all cases. In the Mediterranean, Southern Dry and Southern Continental climates, the resulting used energy for heating was between 11 kWh/m²y (Mediterranean climate, OFF2, 7 floors) and 37 kWh/m²y (Southern Continental, OFF1, 3 floors). In the Nordic and Northern Continental climates the used energy for heating for an office building with 3 floors and 162 m²/storey was 62 kWh/m²y and 65 kWh/m²y, respectively.

Figure 1 shows the used energy for heating and cooling for buildings with 5 floors and with 162 m²/storey and 324 m²/storey, respectively (for buildings with 3 and 7 floors, see Annex I – Simulation results, section 6.1.1). The values shown are the average of the whole building. The intermediate floors have lower heating demands compared to the ground floor and the top floor, since these zones have no heat losses through the floor or the ceiling. The heating demand is higher in the zones on the North side of the buildings, while the cooling demand is higher on the South side, as a result of the higher solar gains to the South side.

Compared to the heating demand of existing buildings, the used energy for heating was reduced by 4% to 66% after renovation, or in absolute numbers from 3 to 150 kWh/m²y. The savings in final energy or primary energy could even higher, due to the change of energy generation, distribution and emission systems. The largest reductions were seen for the buildings renovated to a heating demand level of 25 kWh/m²y, and particularly for the Northern Continental and Oceanic climates, where the energy standard for existing buildings is not very good. Buildings in the Nordic region are quite well insulated to begin with, and in Southern Europe the heating demand of existing buildings is lower due to the warmer climate.

For cooling, the effect of renovation on the used energy varied from a 49% increase to a 175% reduction, compared to existing buildings. In absolute numbers, increases of up to 1 kWh/m²y and reductions of up to 36 kWh/m²y were seen. Reductions of used energy for cooling were mainly seen for all climates, except for the Oceanic climate. The results show no correlation between used energy for cooling and used energy for heating.

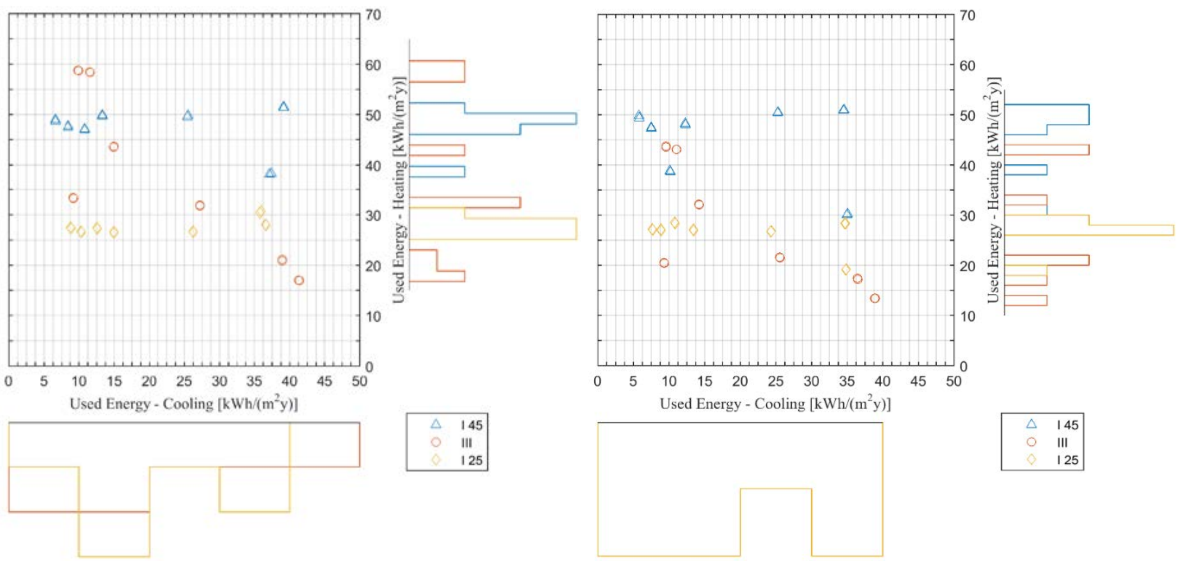


Figure 1 - Used energy for heating and cooling for office buildings with 162 m² per storey and 5 floors (left), and for office buildings with 324 m² per storey and 5 floors (right)

2.2 Thermal comfort

The radiant ceiling panels were able to keep the temperature within the set limits during almost every hour of office time during the year. Lower temperatures could sometimes be observed in the first hour of the day, just after the controller switched from the -2 °C night time setback to the ordinary set temperature for heating. Without dehumidification there is risk for condensation on the panels during the cooling season, if supply temperature is not controlled properly.

Radiant ceiling panels cover both heating and cooling demands, in the latter case acting only for the sensible contribution. The radiant panels were sized for the maximum between the heating and the cooling load of the building, individually for each case (3/5/7 floors, 162/324 m²/storey). Penalty functions for heating and cooling were calculated based on the additional energy needed, compared to the energy provided by the HVAC system in the simulation, to keep the convective air temperature in the office within the desired range during office hours.

Figure 2 shows the penalties for heating and cooling for all cases, divided into heating supply temperature and for different building types and sizes, respectively. Each point represents the penalties for a full year simulation. The heating penalties were very low, less than 1%. Figure 2 shows that with a supply temperature of 35 °C, the system is able to meet the heating demand to a higher extent than with a supply temperature of 30 °C. From Figure 3 it can be seen that in most cases the heating penalties were lower for larger buildings. This is most likely a result of the smaller S/V ratio of these buildings.

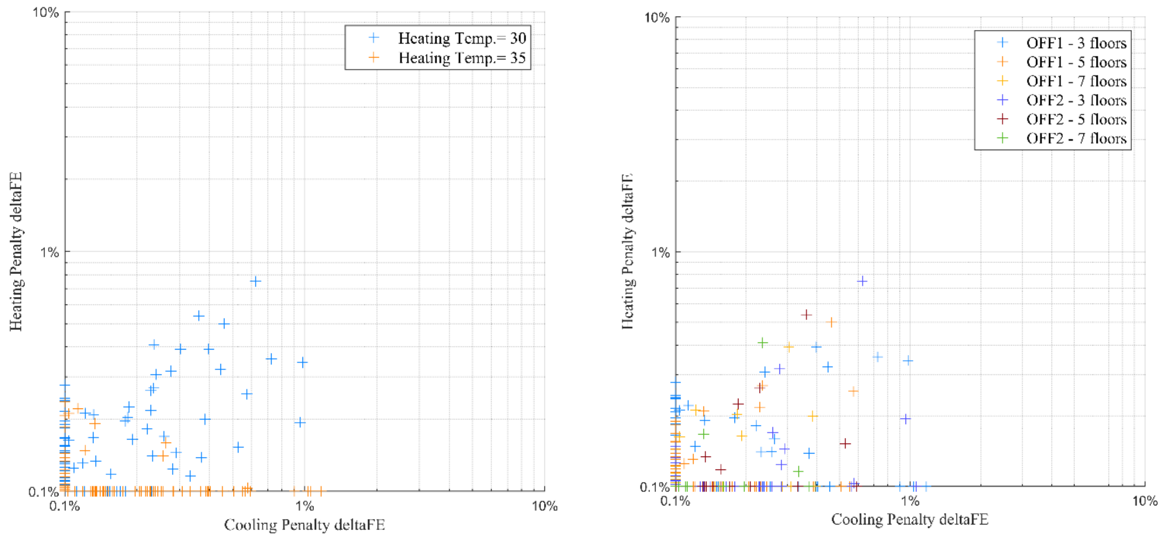


Figure 2 – Cooling and heating penalties for different water supply temperatures (left) and for different sizes of the building (right).

The cooling penalties were on average slightly higher than the heating penalties, although still very low. This can be due to the fact that the temperature controlling the heating and cooling was the minimum of the convective temperature in the six zones of the model, rather than the average. The highest penalties for cooling were seen in the Mediterranean, Southern Dry and Southern Continental climate.

Looking at the air temperature in the building, the system seems to provide good thermal comfort over the whole year. The average convective temperature in the zones is, in all cases, 20.5 °C in the winter and 24.5 °C in the summer, with only a few hours per year with temperatures below or above the range between the average winter and summer temperatures. These occurrences are spread out over the season, i.e. there is never a situation where the temperature is below or above the desired range for several consecutive hours. The risk of temperatures below the set point is highest in the mornings, when the set point switches back from the -2°C setback. The cooling penalties, on the other hand, are highest in the late afternoon, when the office has been heated up by solar radiation and internal gains.

Plots of temperature and relative humidity in the six zones of the building, from South – 1st floor to North – 5th floor, are shown for two specific cases in Figure 3. In both the Nordic and the Mediterranean climate the temperature and humidity lie within the recommended range (red dotted line), or in any case the set points, during most of the time. In the Nordic climate the indoor air can sometimes be perceived as dry, with a few hours with relative humidity below 20% at room temperature 22 – 25 °C. In both cases there are also periods with relative humidity above the recommended values for the corresponding temperatures, up to 90% and sometimes even higher. This is due to the fact that no dehumidification was included in the HVAC system model. With these conditions, without dehumidification, there would a risk for condensation on the radiant ceilings at relative humidity above 61% during the cooling season, due to 15°C supply temperature. Thus for climates such as the Mediterranean dehumidification or proper inlet temperature control are needed.

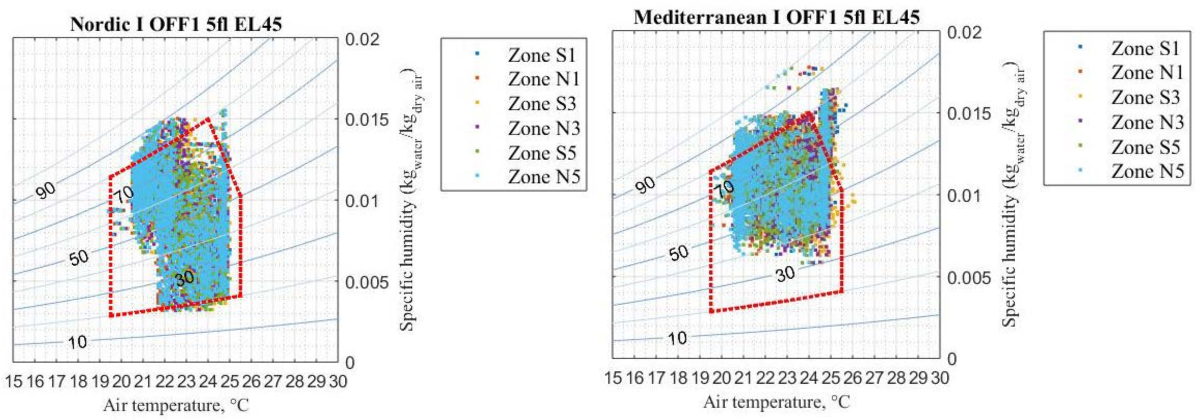


Figure 3 – Psychrometric chart of Nordic and Mediterranean climate, period I, OFF1, 5 floors, EL45. The recommended range for thermal comfort is indicated by the red dotted line.

The operative temperature is, with radiant ceiling panels, close or equal to the convective temperature. Regarding the over-temperatures in summer, the operative temperature does not exceed 27 °C, which is most of the times acceptable for a limited time when the outdoor temperature at the same time is well above 30 °C.

2.3 Final energy and SPF

In cold climates, space heating is the primary user of final energy, ahead of cooling and ventilation, while in warm climates cooling can be predominant. The highest final energy consumption was seen for the retrofit energy level 45 kWh/m²y in the Southern Dry climate, where both heating and cooling demand are high. The results also show a trend with higher heating demands for buildings with higher S/V ratio.

Figure 4 and Figure 5 show the final energy consumption of the H&C system simulated for office buildings following the reported energy uses (distribution water temperature 30°C). The cases here reported are for both periods (I and III) and for all sizes of the building. All cases are with no use of solar energy.

For smaller buildings (OFF1), the final energy consumption is lower than 30 kWh/m^{2}y in all cases apart for Southern Dry climate and retrofit energy level 45 kWh/m²y (Period I). Similarly for larger buildings (OFF2), apart from two cases (3 floors and 7 floors) in the Southern Continental climate.

In the coldest climates, the final energy consumption for space heating is significantly larger than for cooling. In the warmest climates, the final energy consumption for space cooling is larger than for heating, except for the cases with retrofit energy level 45 kWh/m²y. In those cases, the energy consumption for heating and cooling is similar. The Southern Dry climate retrofit energy level 45 kWh/m²y has the largest final energy consumption (>30 kWh/m²y). This is because it has the highest cooling demand as well as the largest heating demand. The Mediterranean climate has a similar cooling demand, but as the heating demand is lower, without any additional insulation, the total final energy demand is lower.

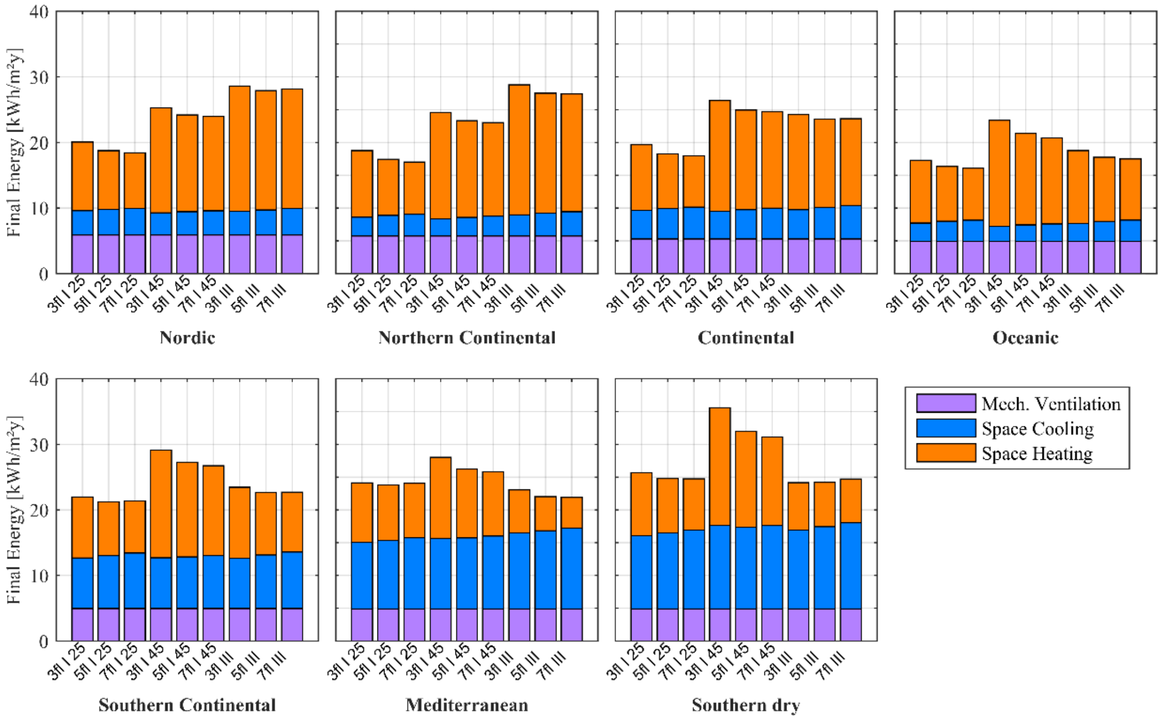


Figure 4 – Final energy distribution without solar PV systems for office buildings with a floor area of 162 m² per storey and a distribution temperature for heating of 30 °C.

The final energy consumption for space heating slightly increases (1-3%) when the supply temperature of heating system increases from 30°C to 35°C. Specific heating demand decreases with the number of floors while the specific cooling demand increases with number of floors as well as the number of offices. For the smaller offices with higher S/V ratio (OFF1) the heating demand is more dominant, which is why the building with 3 floors has higher final energy demands. For the larger offices (OFF2), the cooling demand can become dominant, so there are several cases where the building with 7 floors has the highest final energy demand and in most cases the 5 floor building has least final energy demand.

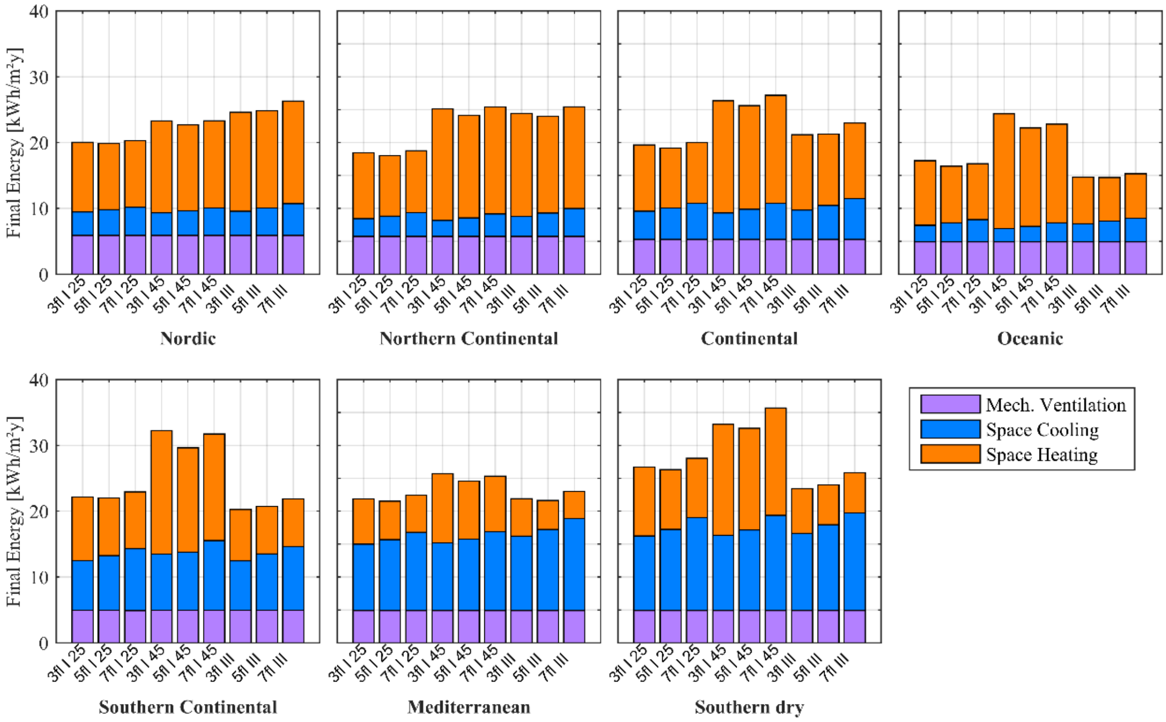


Figure 5 – Final energy distribution without solar PV systems for office buildings with a floor area of 324 m^2 per storey and a distribution temperature for heating of 30 °C.

The share of total final energy caused by the demand of mechanical ventilation is larger in the coldest climates than in the warmest climate and in the case of retrofit energy level 25 kWh/m²y more than 45 kWh/m²y due to the overall lower final energy demands, as the absolute value for the ventilation is more or less the same in all cases. Energy used for the de-frosting is also included in the calculation.

The values of SPF for space heating (see Annex I – Simulation results, section 6.1.2), with no use of solar, vary within the range of 2.7 (lowest value for the Nordic climate) to 3.9 (highest value for the Mediterranean climate). SPF is higher for retrofit energy level 45 kWh/m²y and in Period I more than in Period III. Moreover, SPF is higher in the case of small buildings (OFF1, 3 floors) and in the warmest climates more than in the coldest ones. The use of solar augmented the value of SPF by more than 20% in the best case scenario. The PV area has a larger impact on SPF than PV inclination.

The SPF for cooling, with no use of solar, varies within the range of 2.6 (lowest value for the Nordic climate) to 3.5 (highest value for the Mediterranean climate). The SPF is higher in the case of small buildings (OFF1, 3 floors) and in the warmest climates more than in the coldest ones and in the Oceanic climate. In the Nordic climate, SPF is higher for retrofit energy level 25 kWh/m²y, while in the Mediterranean climate the values of SPF are more or less identical for all retrofit levels. The PV production has more influence on the buildings with lower cooling demand, thus with those with fewer floors and in the colder climates.

The overall SPF including ventilation, but with no use of solar, varies in the range of 1.8 to 3.0. Note that these values are calculated without calculating the heat saved/added by the MVHR unit, only the electricity used by it.

2.4 Solar PV energy utilisation

The self-consumption of solar PV electricity does not vary much between small and large PV systems, as the electricity load of the building is much larger than the PV production. The share of self-consumption is more or less the same for small and large buildings, as the larger buildings have larger areas available for PV, and also larger electricity loads.

Figure 6 shows the utilisation of the PV electricity to drive the HVAC system (red), lighting and appliances (orange), and the surplus production fed to the grid (yellow) for office buildings with 5 floors (for buildings with 3 and 7 floors, see Annex I – Simulation results, section 6.1.3). Calculations are made considering the hourly production/consumption without any battery. Note that the PV size is smaller for 90° (façade) than 30° (roof) and for the period III buildings due to the smaller available surface area.

Total PV production ranges from 1600-1700 kWh/y (~15 m^2 and 90° tilt angle) to 41500-42000 kWh/y (~360 m^2 and 90° tilt angle) in the northern regions and similarly from 1900-2400 kWh/y to 57800-58200 kWh/y in the southern regions.

In the Nordic climate the self-consumption during winter varies from 51 – 59% and during summer from 71% to 76%, with overall self-consumption varying from 64% to 69%. These are relatively narrow ranges for the wide range of conditions (PV size, slope and building size), but the self-consumption for the HVAC system, assuming that it is satisfied before other loads, varies more widely. In fact up to 100% of the PV output during winter can be self-consumed in winter by the HVAC system, and over the whole year the self-consumption possible in the HVAC system varies from 48% to 94% for the range of PV sizes studied. However, the main conclusion is that as the electricity load is much larger than the PV production, the amount of self-consumption does not vary so much and it is not dependent on whether the PV modules are mounted on the façade or on the roof.

However, the absolute values change with both PV array size and positioning (façade or roof), with ~17% more electricity being self-consumed for a roof mounted PV array compared to the façade. Similar trends can be seen in the southern climates, but here the ranges are slightly larger with total self-consumption ranging from 67% to 77%. Thus the percentage self-consumption is higher than in the northern climates in addition to the total PV production for the same PV area being much higher (over 50% higher in Southern Dry compared to Nordic). The difference between PV self-consumption on the façade and on the roof is also larger in southern climates, being up to 38% higher. A roof mounted PV array produces 61% more electricity on the roof (30° slope) in Southern Dry climate compared with Nordic, while the difference in PV production for the façade is only 39%. The percentage self-consumption values for the larger office building (OFF2) are more or less identical to those for OFF1 as the load is much larger than the production and the possible surface areas for mounting PV arrays is also twice as high for OFF2 than OFF1, as is the floor area.

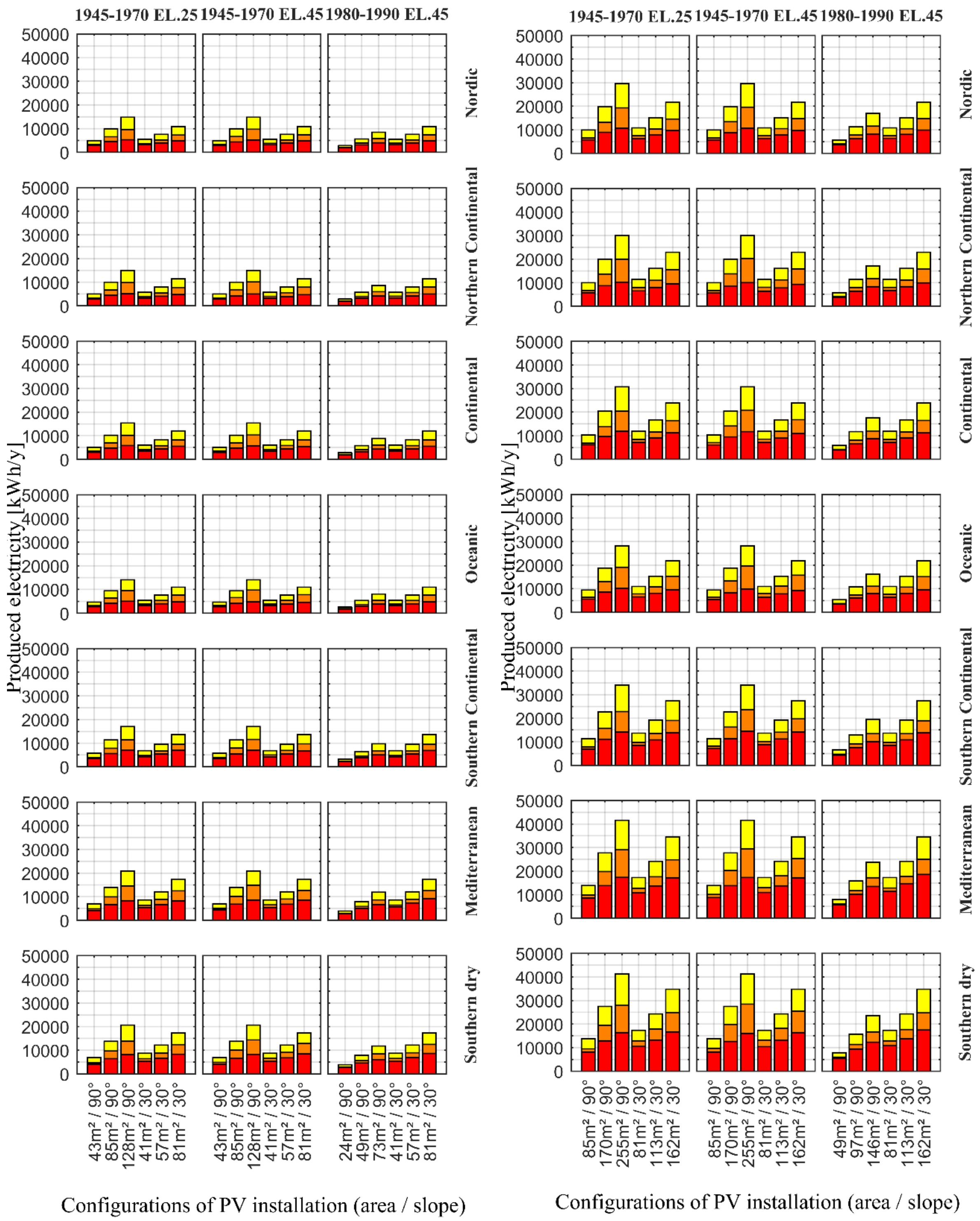


Figure 6 – Self-consumption and PV electricity to grid for office buildings with 5 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

2.5 Final energy and primary energy considerations

The primary energy target of 50 kWh/m^{2}y could be achieved without PV only for the EL25 building in moderately tempered climates. In most other cases it could be achieved with small or large PV systems. For cases with very high heating demands, such as the curtain wall buildings in the coldest climates, or cases which have high heating as well as high cooling demand, such as the EL45 buildings in the warmest climates, the target could not be achieved even with PV.

Figure 7 and Figure 8 show the final energy (left) and primary energy (right) consumption for the renovated office buildings with 162 m^2 and 324 m^2 per storey, respectively. A conversion factor between final and primary energy of 2.88 was used [2]. The red marker represents the average value of all considered cases, the blue box contains 2/3 of all cases, while the black markers show the maximum and minimum values assessed. The black line in the primary energy charts indicate the target level of 50 kWh/m^{2}y primary energy consumption.

As seen in the figures, this level is achieved without PV only for a few cases, most of them being for the Oceanic climate and EL25 or curtain wall (period III) renovation packages. For Nordic and Northern Continental climates, the target can be reached for the EL25 renovation standard with relatively small PV fields, while for the other renovation levels (EL45 period I and period III) it cannot be reached even with the largest PV fields simulated (90% of available façade area / 50% of floor area on roof). For the Continental and Southern Continental climates, only small PV areas are required to reach the target for EL25, while it is not possible to reach for EL45. For the period III (curtain wall) it can be achieved with the largest PV areas. For the two hottest climates, Mediterranean and Southern Dry, the target can be reached for EL25 and the curtain wall construction with moderate to large PV areas, while the largest areas of PV are required for the EL45. For Southern Dry the target is not possible to reach for the EL45. The target is easiest to reach for the “middle” climate, Oceanic, requiring in the most difficult case, only moderate PV areas.

This shows that both cold and hot climates make it difficult to achieve the target of 50 kWh/m^{2}y primary energy use, and that only in the Oceanic climate is it relatively easy to reach. Despite the increased PV production and higher percentage self-consumption in the hotter/southern climates, larger PV areas are required there compared to the colder/northern climates to achieve the same primary energy use due to the very high cooling demands (the heating demands being the same for EL25 and EL45 in all climates). For the curtain wall construction, the same for all climates, the higher heating demands in the colder climates have a bigger impact than the high cooling demands in the warmer climates, as solar energy is less available during the heating season than the cooling season. As a result, it is not possible to achieve the target for the period III buildings in the colder climates while it is in the warmer climates.

The number of floors can make a significant difference due to the lack of insulation to the ground and the large surface area of the top floor. For the colder and moderate climates, the heat demand dominates, and the specific primary energy decreases with increasing number of floors, the biggest difference being between 3 and 5 floors. For climates with a significant amount of cooling, 5 floors has significantly lower specific primary energy use than 3 floors, but in most cases the 7 floor buildings of all renovation packages have a greater or same specific primary energy as than the 5 floor buildings. This effect is more pronounced for the larger office building (OFF2), having an increase of up to 9 kWh/m^{2}y primary energy use compared to a maximum of 3 for the smaller office building (OFF1).

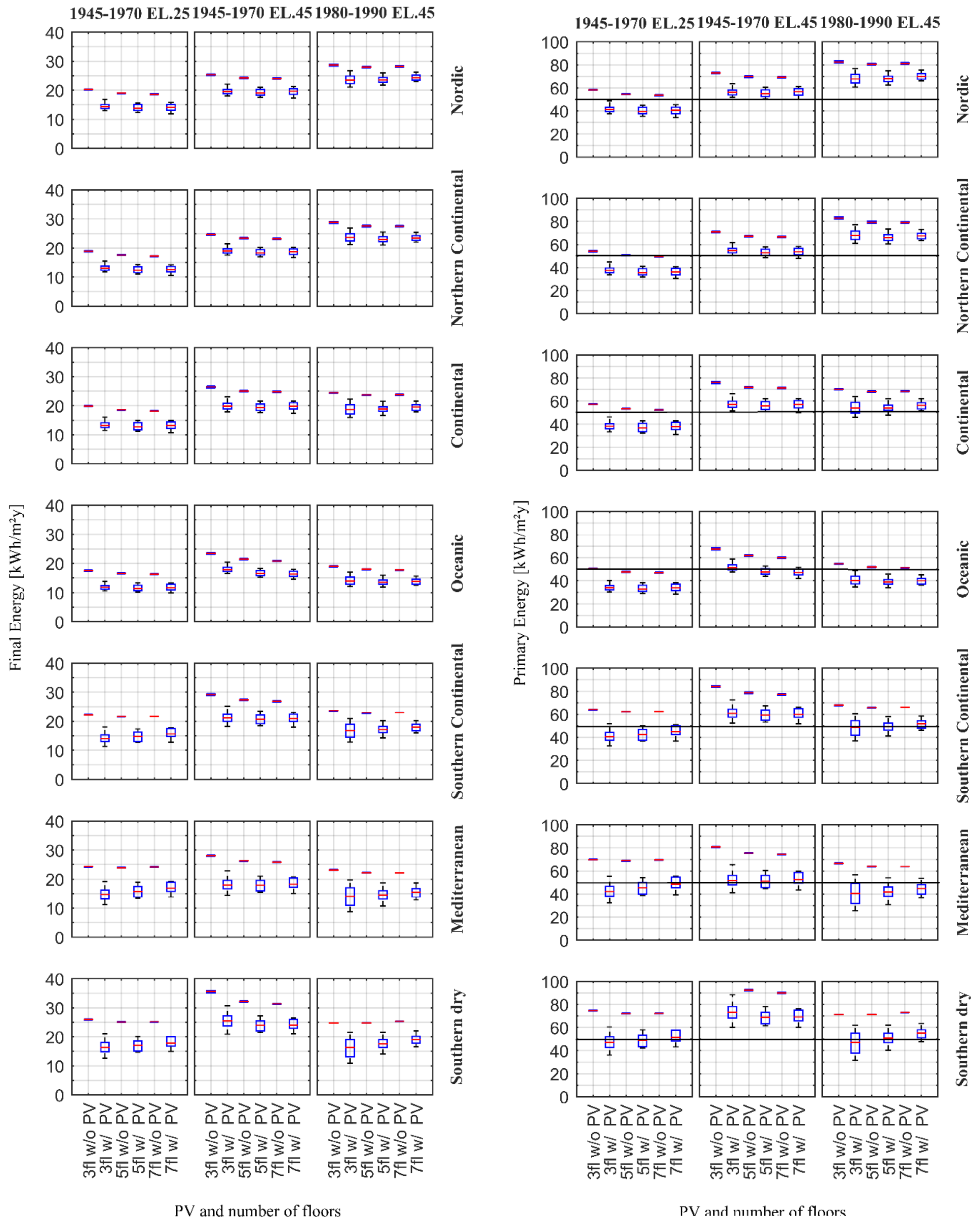


Figure 7 – Final energy (left) and primary energy (right) consumption for the renovated office buildings with 162 m² per storey

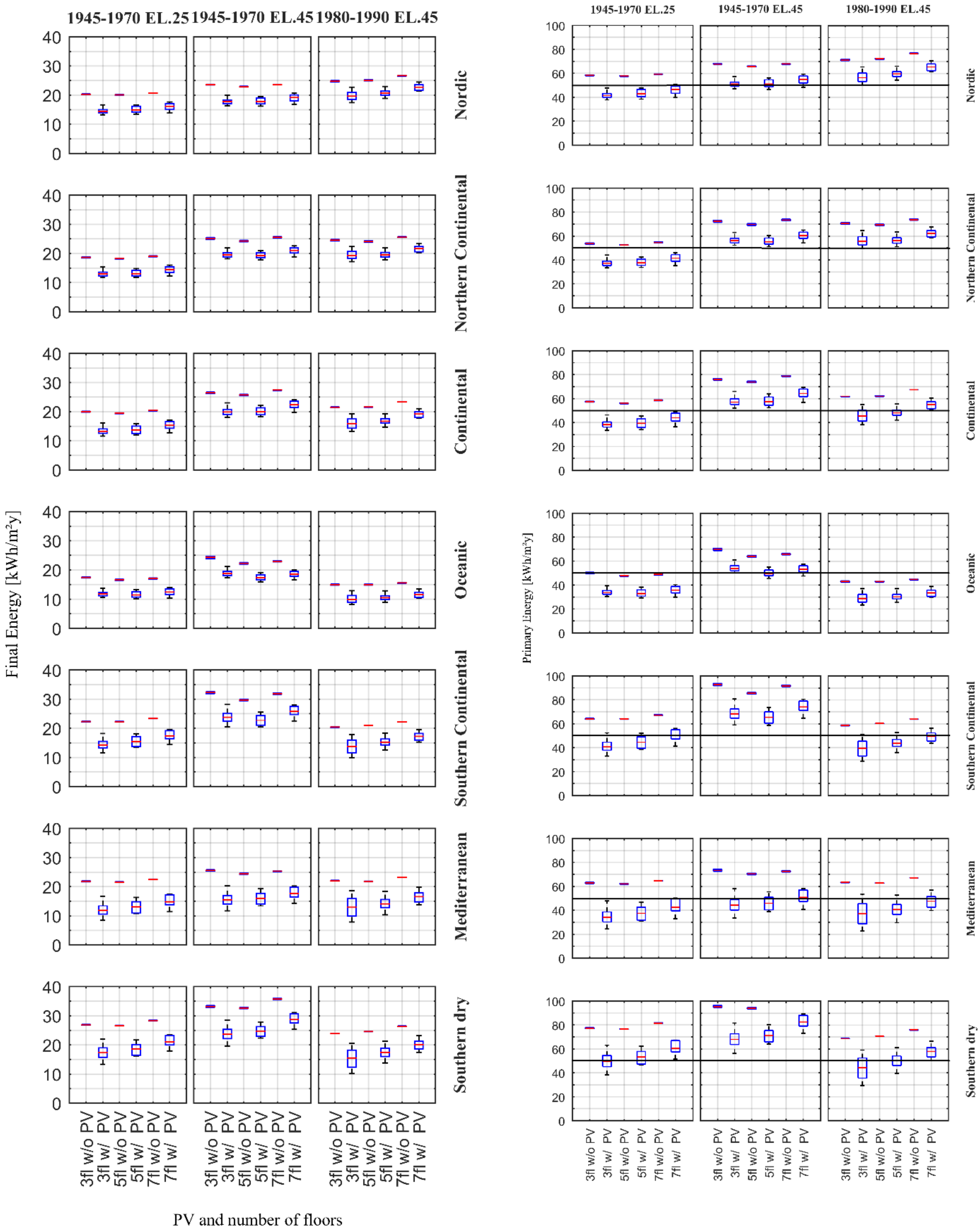


Figure 8 – Final energy (left) and primary energy (right) consumption for the renovated office buildings with 324 m² per storey

The curtain wall has the same windows and insulation level in all climates, whereas the other 2 renovation packages have been adapted to each climate and current building insulation standard to achieve the energy levels of 25 and 45 kWh/m^{2}y primary energy use. The primary energy use for the curtain wall is greater than for the other 2 renovation packages for the coldest two climates (Northern Continental and Nordic) while it is lower than the other 2 renovation packages for the two hottest climates (Mediterranean and Southern Dry). For the other three climates its energy use is in between those of the other two packages.

Compared to the existing buildings, the final energy consumption for heating and cooling (not including ventilation) is reduced by up to 87% after renovation (see also section 2.1), with the largest reductions for the 25 kWh/m^{2}y level buildings from period I. The effect on the primary energy consumption depends on which energy sources were used before renovation.

2.6 Economic evaluations

While the investment costs are in most cases lower for the EL45 buildings than the EL25, it is often more economical to renovate to EL25 if operation, maintenance and energy costs in a life cycle perspective are taken into account. The energy generation and distribution system constitutes nearly 50% of the total costs over 30 years, while envelope renovation and O&M + purchased energy hold about 25% each.

Figure 9 and Figure 10 show the investment costs per floor area, including both the initial and the annualised costs. The initial costs for building envelope renovation measures (insulation and windows) are larger than for the energy generation and distribution systems. However, in a 30 year perspective the annualised costs for the generation and distribution systems are as high as or higher than those for the envelope measures. This is due to the assumed technical lifespan, which in this case is 30 and 25 years for insulation and windows, respectively, and 15 years for the heat pump. Thus, a reinvestment cost for the generation system has to be considered. For radiant ceiling panels, the technical lifespan is 30 years.

The total investment costs range from around 390 €/m^2 to 870 €/m^2. The lowest costs are evident for the period I buildings on the 45 kWh/m^{2}y level in the Mediterranean climate, where no insulation is applied. In general, the costs for insulation and windows are lower for the 45 kWh/m^{2}y level than for the 25 kWh/m^{2}y level, while the costs for generation and distribution systems are lower for the 25 kWh/m^{2}y level. On average, the investment costs for the 45 kWh/m^{2}y level buildings are 30 €/m^2 lower than for the 25 kWh/m^{2}y level buildings. For the period III buildings, the costs for envelope renovation (including both insulation and windows) are the same regardless of the climate, as the same curtain wall is applied for all cases.

The total annualised costs lie within the range 660 – 1120 €/m^{2}y. The trends for lowest/highest costs are the same as for the initial investment costs, even though the annuity calculations affect the envelope measures and the generation and distribution systems differently, as mentioned earlier.

If solar PV panels are added to the system, the investment costs increase by up to 27 – 51 €/m^2 (maximum increase for each case), or 3 – 13%. The annualised costs increase by up to 44 – 82 €/m^{2}y, or 4 – 12%. The smallest PV areas considered, 25% of the roof area or 30% of the opaque part of the southern façade, give only negligible increases of the investment costs, in some cases less than 1%.

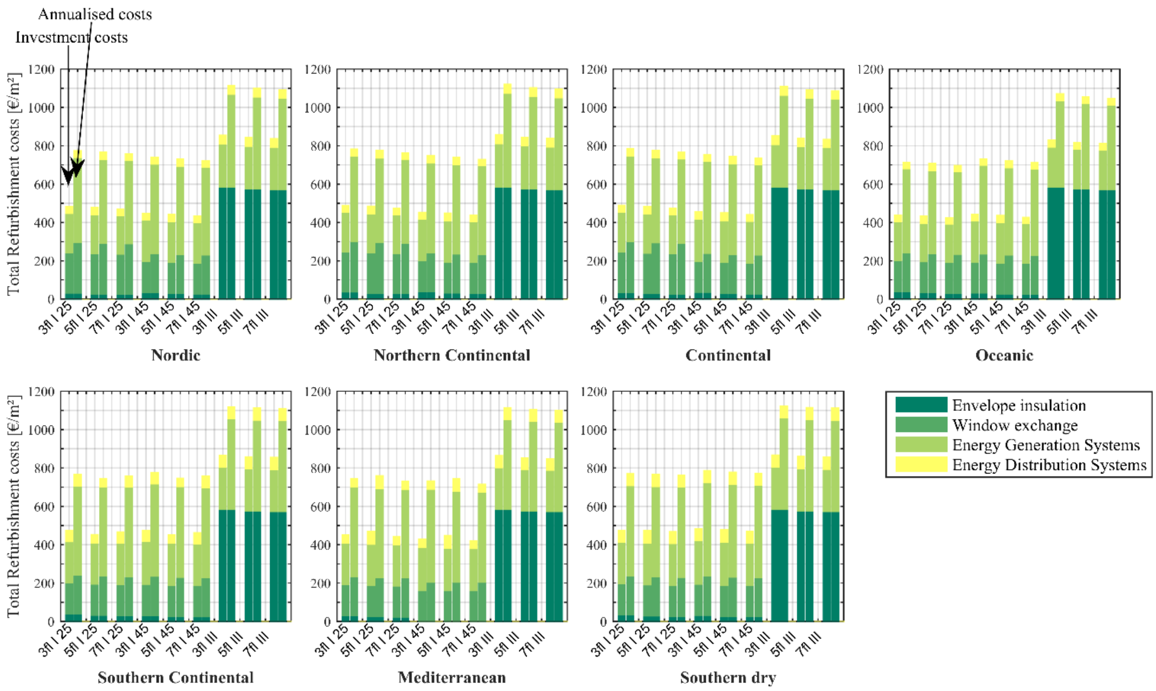


Figure 9 – Investment costs distribution (first year investment and annualised costs over 30 years) for ASHP with radiant ceilings without solar PV, for office buildings with a floor area of 162 m^2 per storey

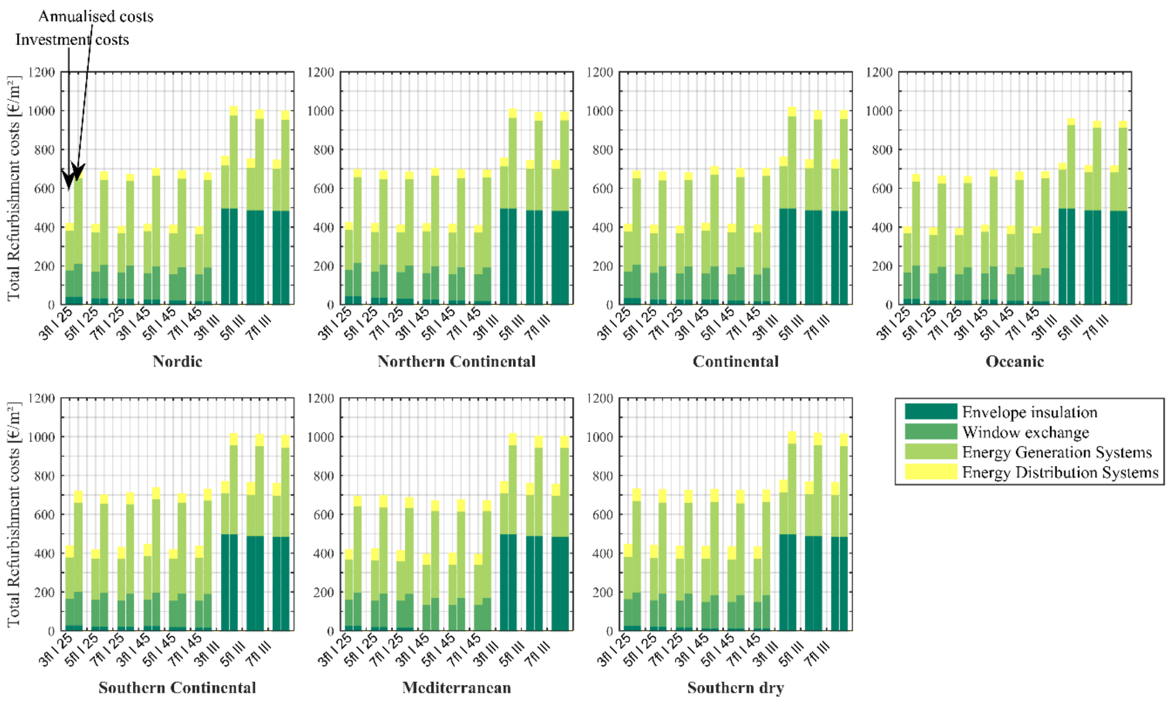


Figure 10 - Investment costs distribution (first year investment and annualised costs over 30 years) for ASHP with radiant ceilings without solar PV, for office buildings with a floor area of 324 m^2 per storey

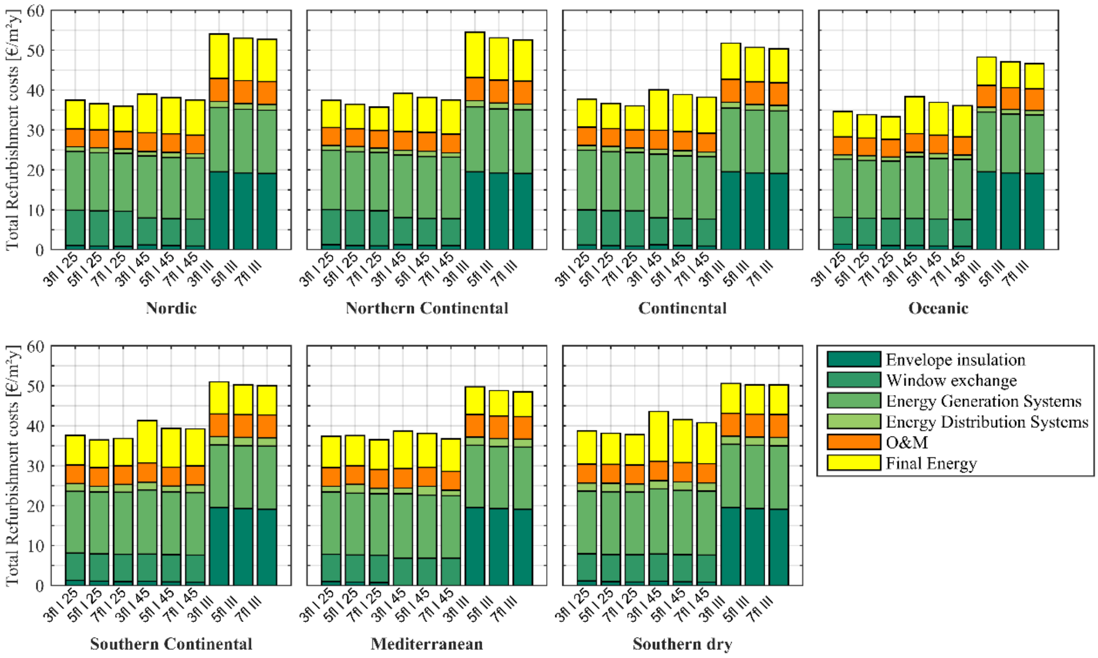


Figure 11 – Distribution of yearly annualised costs for ASHP with radiant ceilings for office buildings with a floor area of 162 m² per storey without solar PV systems

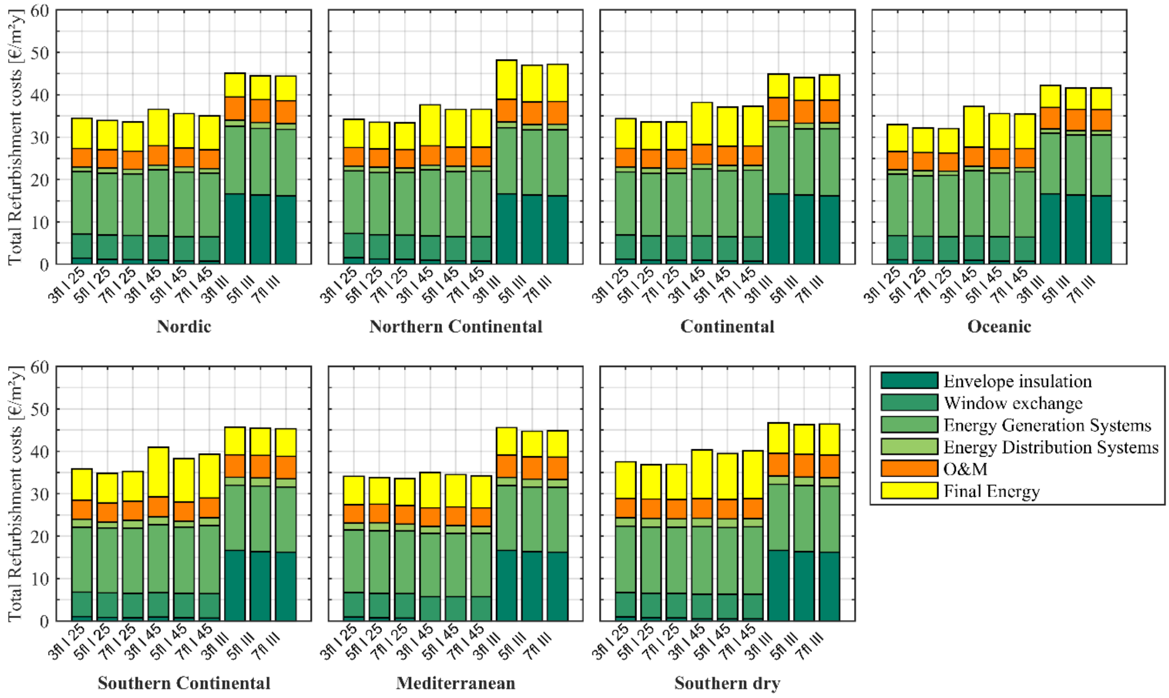


Figure 12 – Distribution of yearly annualised costs for ASHP with radiant ceilings for office buildings with a floor area of 324 m² per storey without solar PV systems

Figure 11 and Figure 12 report on the yearly annualised costs for generation and distribution system, envelope and windows, plus the costs of final energy, operation and maintenance, for office buildings with a floor area of 162 m^2 and 324 m^2 per storey, respectively. The investment costs have been divided by 30 years, to give the annualised cost (€/m²y) and to make them comparable with the yearly maintenance and energy costs.

The total costs are in most cases the lowest for the buildings from period I renovated to the 25 kWh/m^2y level, due to the reduced costs for energy generation and distribution systems and for purchased energy. The difference between these and the 45 kWh/m^2y buildings is not very significant though, in most of the cases only 1 – 2 €/m²y.

The total annualised renovation costs for the period I buildings amount to 32 – 40 €/m²y for EL25 and 34 – 45 €/m²y for EL45, and for the period III buildings 41 – 54 €/m²y. The period III buildings should not be compared directly to the period I buildings, since they have different starting points and were assessed with a different strategy for renovation. On average, 24% of the total costs for the period I buildings are investment costs for envelope renovation, 44% are costs for the energy generation and distribution system and 32% are costs for purchased energy, operation and maintenance. The corresponding numbers for the period III buildings are 37% for envelope renovation, 36% for the energy system and 27% for energy, operation and maintenance. The most variable part is the envelope renovation costs, while the energy system costs around 15 €/m²y for all cases, the maintenance cost is more or less the same for all cases and the variations in energy costs are smaller (in absolute numbers).

The O&M costs are in all cases similar to and, in some cases even exceed, the costs for energy for the renovation packages without PV. With economic assumptions made, the largest maintenance costs are for the ventilation system, while those for the windows and generation systems are more or less the same, varying depending on the S/V ratio.

Adding PV to the energy system (not shown in figure) increases the annualised investment costs by 1.5 €/m²y, on average, while the final energy costs are reduced by approximately the same amount and the maintenance cost increases by 0.5 €/m²y. The effect of the extra investment on the total costs is therefore almost neutralised by the contribution of free electricity during sunny hours.

3 Air Source Heat Pump with Fan Coils

For the configuration with fan coils, the case has been simulated twice, once with a supply temperature for the heating at 35°C and once at 45°C with relative sizes. The supply temperature for cooling is 7°C.

The results regarding solar PV are essentially the same as for the system with ASHP and radiant ceilings, but the system with fan-coils has a marginally higher self-consumption. Graphs for solar PV utilisation are found in Annex I – Simulation results, section 6.2.3.

3.1 Used energy

The used energy is lower with fan coils than with radiant ceilings, due to the fact that convective temperature is used for control of the heat distribution and the prevailing convective contribution to heating provided by fan coils, whereas radiant ceiling panels transfer heat mainly by radiation.

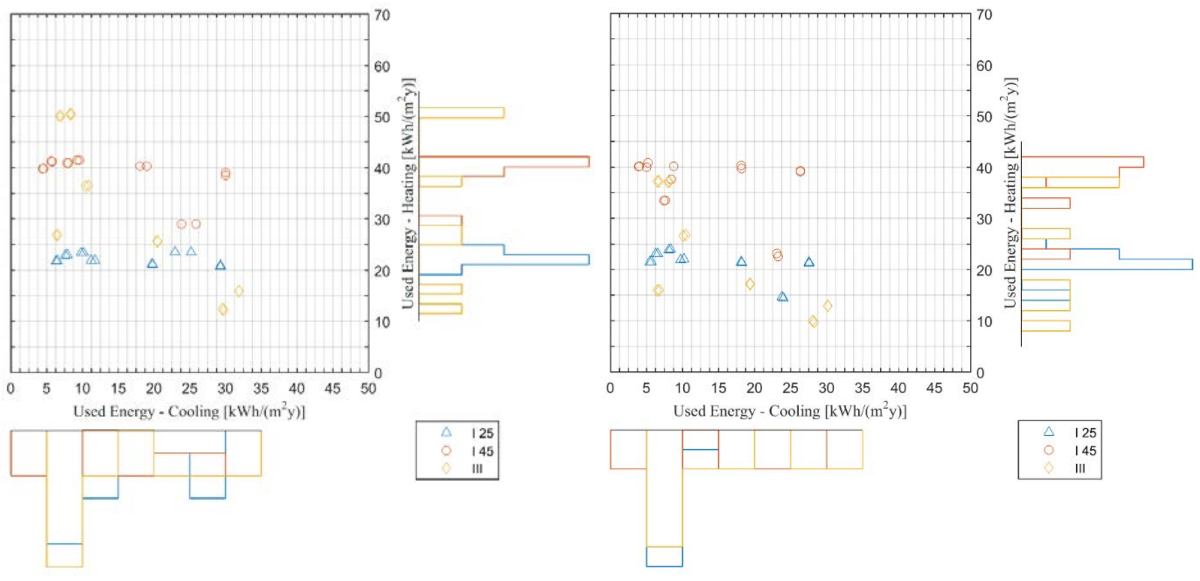


Figure 13 – Used energy for heating and cooling for office buildings with 162 m^2 per storey and 5 floors (left) and for heating and cooling for office buildings with 324 m^2 per storey and 5 floors (right)

Figure 13 shows the used energy for heating and cooling for buildings with 5 floors and with 162 m^2/storey and 324 m^2/storey, respectively (for buildings with 3 and 7 floors, see Annex I – Simulation results, section 6.2.1). With fan coils the used energy is lower than in the radiant ceilings solutions, for heating as well as for cooling. In most cases the used energy for heating was also lower than the heating demand levels 25 and 45 kWh/m^{2}y for the period I buildings. This is due to the fact that convective temperature is used for control of the heat distribution and the prevailing convective contribution to heating provided by fan coils, whereas radiant ceiling panels transfer heat mainly by radiation. The used heat for energy is often 5 to 10 kWh/m^{2}y lower if fan coils are used as distribution units. A smaller difference would probably result if the operative temperature were to be controlled instead of the convective.

Compared to the existing buildings, the used energy for heating was reduced by up to 69% after renovation, or in absolute numbers from 11 to 157 kWh/m²y. Just as with radiant ceiling panels, the largest reductions were seen for the heating demand level of 25 kWh/m²y, particularly for the Northern Continental and Oceanic climates.

The effect of renovation on the used energy for cooling varied from -36% to -197%, compared to existing buildings, or in absolute numbers from -1 kWh/m²y to -47 kWh/m²y. The largest reductions of used energy for cooling were seen for the Nordic and Mediterranean climates. This means that the cooling demand is lower by 2 – 12 kWh/m²y with the fan coils than with the radiant ceilings, the biggest differences being for the largest cooling demands.

Note that these results compare the demand with an HVAC system together with its control with the original buildings simulated with ideal heating and cooling for the same set temperatures as the HVAC system.

3.2 Thermal comfort

Although not quite as good as the radiant ceiling panels, the fan coils were able to keep the temperature within the set limits during almost every hour of office time during the year. Lower temperatures could sometimes be observed in the first hour of the day.

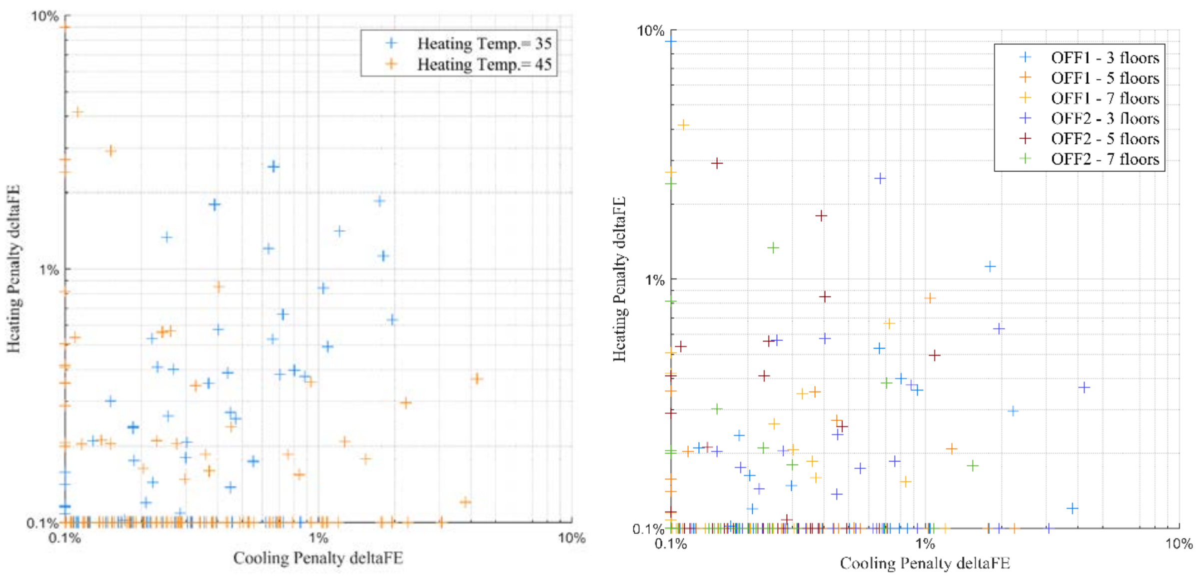


Figure 14 – Cooling and heating penalties for different water supply temperatures (left) and for different sizes of the building (right). The penalty is a measure of how much the room temperature is too high/cold over the year.

Figure 14 shows the penalties for heating and cooling for all cases, divided into heating supply temperature and for different building types and sizes, respectively. The temperature control with fan coils was good, although not as stringent as with radiant ceilings. Both the heating and the cooling penalties were in most cases very low, less than 1%, with some exceptions for higher cooling penalties in warm climates and higher heating penalties in cold climates.

The thermal comfort, judging by the room temperature, was good, although not as stable as with radiant ceiling panels and with a few more hours of temperature out of the desired range.

Just as with radiant ceiling panels, the risk of temperatures below the heating set point is highest in the mornings, while the risk of temperatures above the cooling set point is highest in the late afternoon.

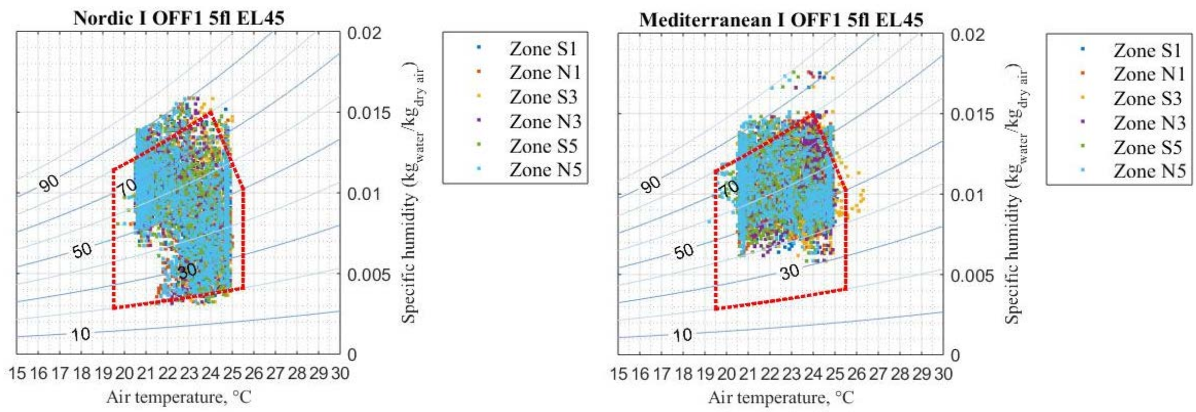


Figure 15 – Psychrometric charts of Nordic and Mediterranean climate, period I, OFF1, 5 floors, EL45. The recommended range for thermal comfort is indicated by the red dotted line.

Plots of temperature and relative humidity in the six zones of the building, from South – 1st floor to North – 5th floor, are shown for two specific cases in Figure 15. In both the Nordic and the Mediterranean climate the temperature and humidity lie within the recommended range (red dotted line) during most of the year. In the Nordic climate there are a few hours with relative humidity below 20% at room temperature 22 – 25 °C, and in both climates there are times when the relative humidity is above the recommended range, due to the lack of humidity control. However, the number of hours is relatively small, much smaller than for the system with the radiant ceilings.

3.3 Final energy, SPF and primary energy

Even though the fan coils distribute less energy to the building, they use more energy due to the electricity consumption of the fans. Thus, the primary energy target of 50 kWh/m²y is harder to achieve with fan coils than with radiant ceilings. Without PV it can only be reached for the EL25 building in the Oceanic climate, and in some cases it cannot be reached even with the largest possible PV systems.

Despite the lower energy delivered to the buildings in the fan coils than in the radiant ceilings cases, the final energy consumption (Figure 16 and Figure 17) is higher in the former due to the electricity needed to run the fans (45 W_{el}/kW_{th}) and the higher distribution temperatures (45 °C and 35 °C compared to 35 °C and 30 °C), which affect the electricity use of the heat pump. As a consequence, also the primary energy consumption is higher with fan coils. The difference in final energy is on average 2 kWh/m²y.

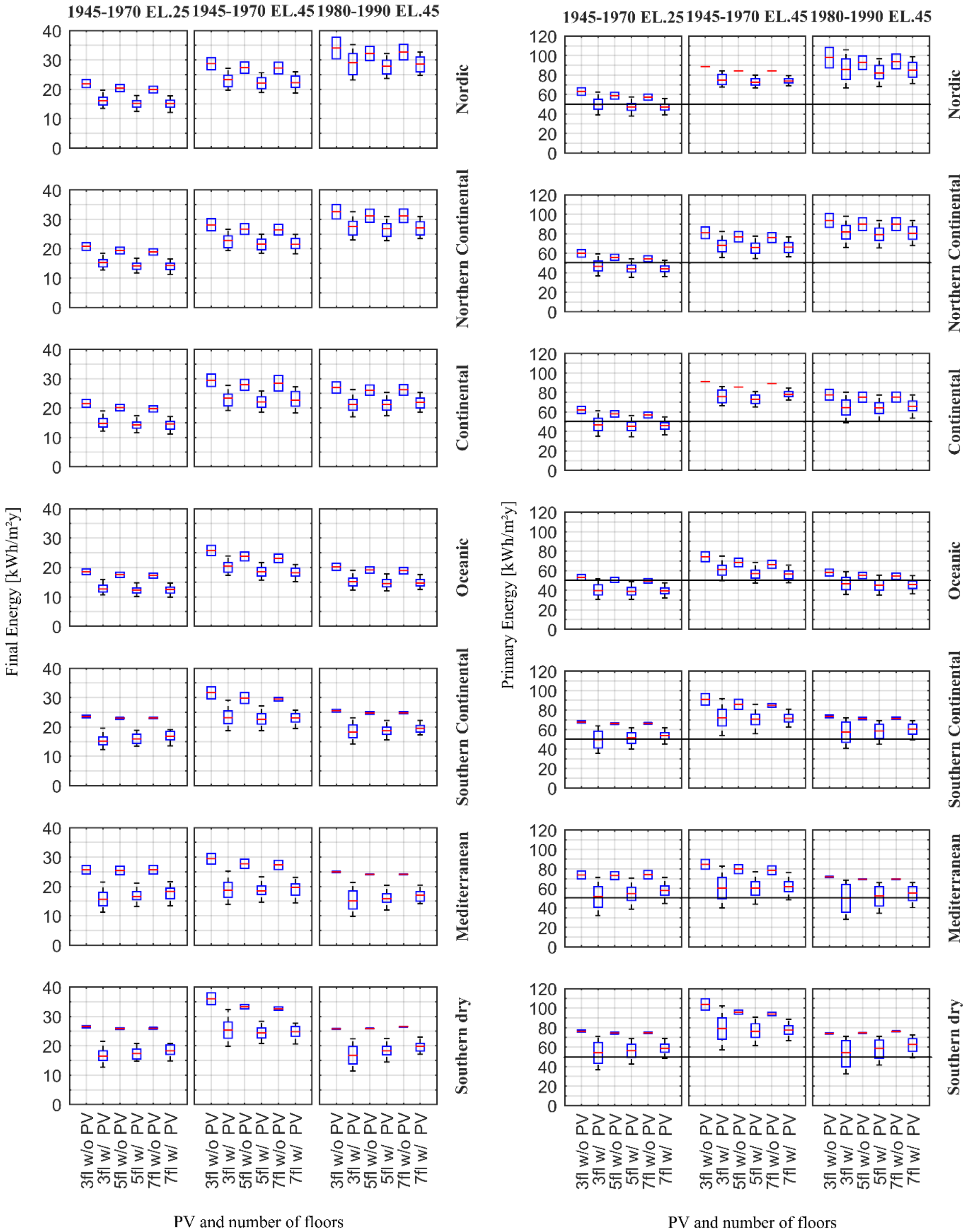


Figure 16 - Final energy (left) and primary energy (right) consumption for the renovated office buildings with 162 m² per storey

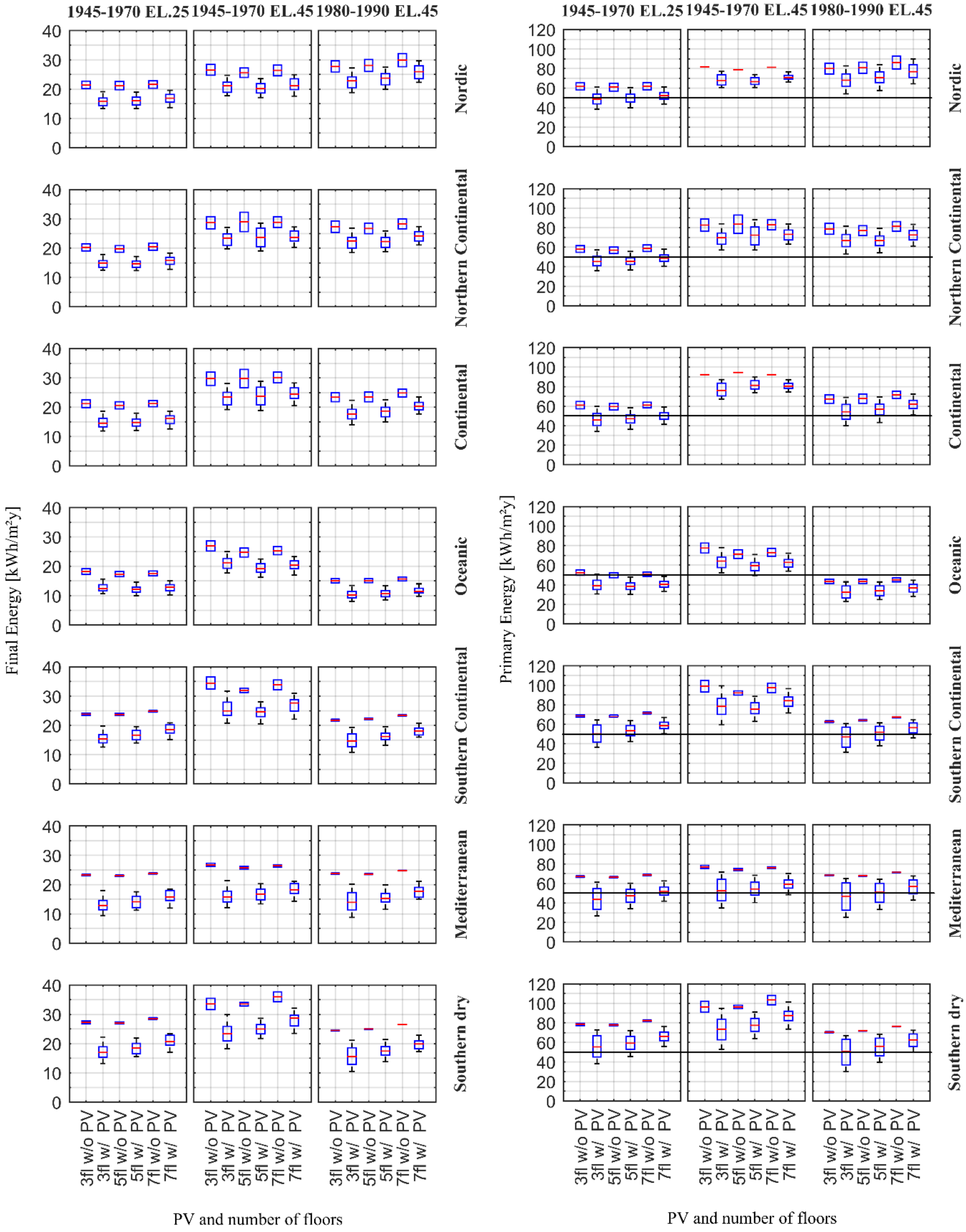


Figure 17 - Final energy (left) and primary energy (right) consumption for the renovated office buildings with 324 m^2 per storey

Comparing the systems at the same distribution temperature (35 °C), the difference in energy consumption is small, less than 0.5 kWh/m²y on average, and for period I buildings renovated to the 45 kWh/m²y heating demand level the final energy consumption is on average 1 kWh/m²y higher with radiant ceiling panels.

The primary energy target of 50 kWh/m²y is achieved without solar PV in the Oceanic climate for office buildings renovated to the 25 kWh/m²y heating demand level and for office buildings from period III renovated with curtain wall elements. If solar PV production is added, this target can be achieved in all climates for EL25, in the Southern Dry and Southern Continental for the buildings from period III and for all buildings in the Mediterranean climate.

The utilisation of solar energy has comparable effect as for the cases with radiant ceilings (section 2.4) and thus it is not further discussed in here. Extensive charts summarising such effects are reported in Annex I (section 6.2.3).

Figure 18 and Figure 19 show the final energy consumption of the HVAC system simulated for office buildings following the reported energy uses (distribution water temperature 35 °C). The cases here reported are for both periods (I and III) and for all sizes of the building. All cases are with no use of solar energy.

For all sizes of the building, the final energy consumption is lower than 30 kWh/m²y in all cases apart for Southern Dry climate and Nordic climate and retrofit energy level 45 kWh/m²y. In the Nordic climate and for period III, the final energy consumption is slightly larger (~33 kWh/m²y). The final energy consumption for space heating increases significantly (10 – 13%) when the supply temperature of heating system increases from 35 °C to 45 °C.

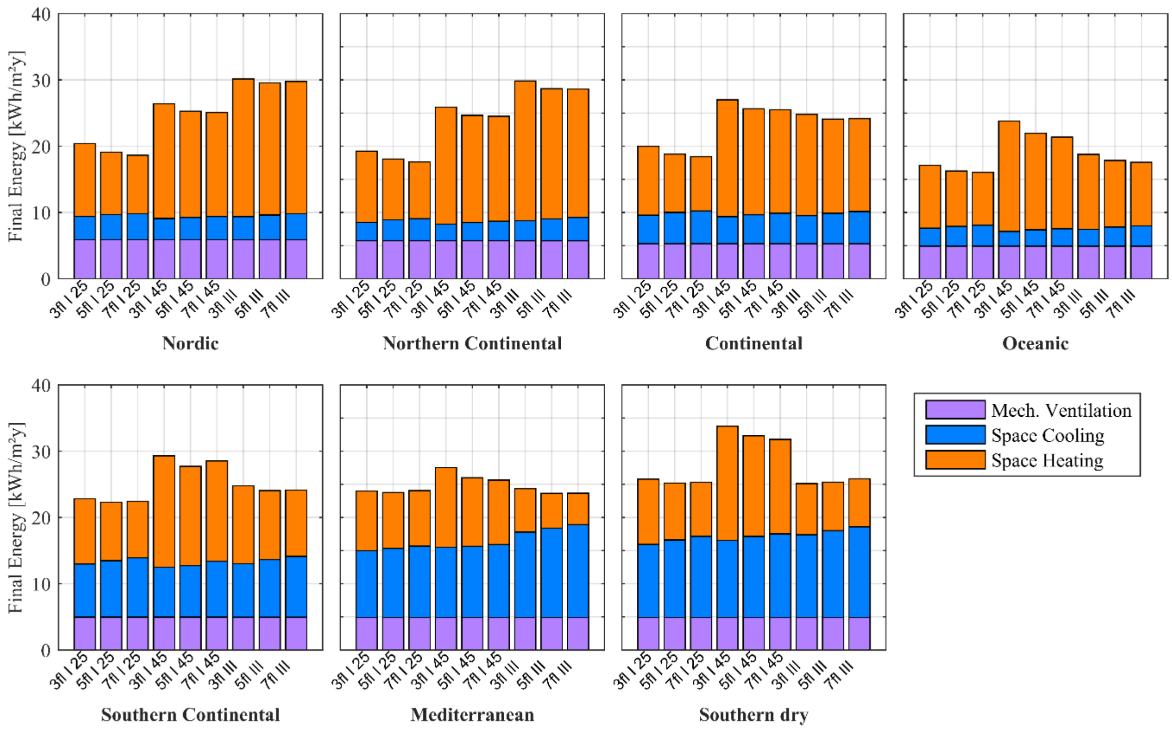


Figure 18 – Final energy distribution without solar PV systems for office buildings with a floor area of 162 m² per storey and a distribution temperature for heating of 35 °C.

The share of total final energy caused by the demand of mechanical ventilation is larger in the coldest climates than in the warmest climate and in the case of retrofit energy level 25 kWh/m²y more than 45 kWh/m²y due to the overall lower final energy demands, as the absolute value for the ventilation is more or less the same in all cases.

The values of SPF for space heating (see Annex I – Simulation results, section 6.2.2), with no use of solar, vary within the range of 1.7 to 2.9. The lowest values are for the larger office and greater number of floors as well as supply temperature of 45°C. All climates apart from Oceanic have values below 1.9. The highest values are all for the Oceanic and Mediterranean climates, with 35°C supply temperature, with smaller building size giving higher SPF. SPF is higher for retrofit energy level 45 kWh/m²y and in Period I more than in Period III. Moreover, SPF is higher in the case of small buildings (OFF1, 3 floors) and in the warmest climates more than in the coldest ones.

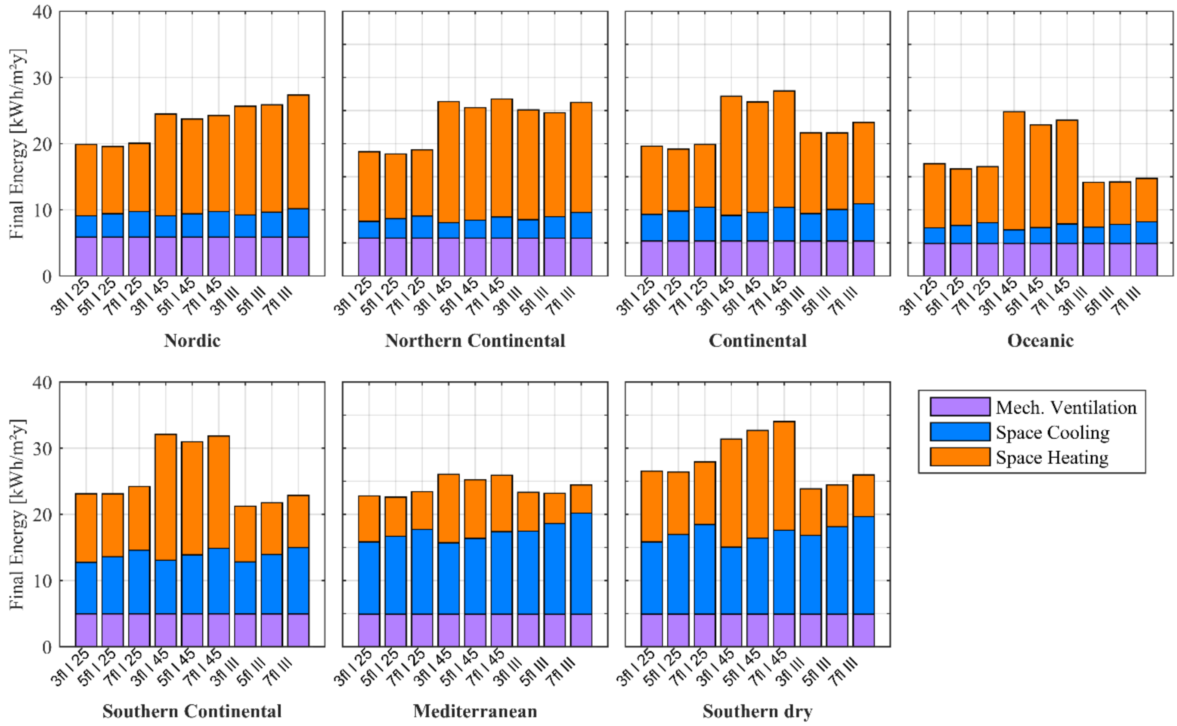


Figure 19 – Final energy distribution without solar PV systems for office buildings with a floor area of 324 m² per storey and a distribution temperature for heating of 35 °C.

The SPF for cooling, with no use of solar, varies within the range of 1.4 (lowest values for the Oceanic and Northern Continental climates) to 2.7 (highest values for the Nordic climate with EL25 and Southern Dry climate with EL25 and curtain wall). The SPF is higher in the case of small buildings (OFF1, 3 floors) and in the warmest climates more than in the coldest ones and in the Oceanic climate. In the Nordic climate, SPF is higher for retrofit energy level 25 kWh/m²y, while in the Mediterranean climate the values of SPF are more or less identical for all retrofit levels.

The overall SPF including ventilation, but with no use of solar, varies in the range of 1.3 to 2.2. Note that these values are calculated without calculating the heat saved/added by the MVHR unit, only the electricity used by it.

3.4 Economic evaluations

The same considerations regarding initial investment costs as for the case air source heat pump with radiant ceilings (see section 2.6) are valid also here. The difference is that while the radiant ceiling panels have a technical lifespan of 30 years, the lifespan of the fan coils is 15 years, which means a reinvestment cost has to be considered in the annualised cost for a 30 year period.

The initial and the annualised investment costs per m^2 are shown in Figure 20 and Figure 21. The initial investment costs range from 360 to 830 €/m^2, resulting in annualised costs between 650 and 1110 €/m^2y. For the period I buildings, the annualised costs for the 25 kWh/m^2y heating demand level were similar to those for the 45 kWh/m^2y level, in some cases being higher and in others being lower. The size of the building makes a significant impact, meaning that in the two coldest climates EL25 has greater annualised costs than EL45 for the smaller office, while they have lower values for the larger office. For all climates, the annualised costs are greatest for the period III offices (curtain wall), with both the colder and hotter climates showing significantly higher values than the period I offices, while for the moderate climates the difference was not as large.

The annualised costs for the curtain wall construction (period III) were higher than for both heating demand levels for period I offices, the differences being highest for the coldest and hottest climates.

With solar PV panels, the investment costs increase by up to 27 – 51 €/m^2 (maximum increase for each case), or 3 – 13%. The annualised costs increase by up to 44 – 82 €/m^2y, or 4 – 12%. The additional costs with the smallest PV areas considered, 25% of the roof area or 30% of the opaque part of the southern façade, are small, in the range 1 – 2%.

Figure 21 and Figure 22 show the total investment and running costs per floor area. The total costs are in all cases the lowest for the buildings from period I renovated to the 25 kWh/m^2y level. The total yearly renovation costs amount to 32 – 41 €/m^2y for the 25 kWh/m^2y level and 33 – 45 €/m^2y for the 45 kWh/m^2y level. The total costs for the period III buildings varied within the range 42 – 58 €/m^2y, and in all cases was higher than for both EL25 and EL45 for the period I buildings. 23% of the total costs for the period I buildings are (on average) investment costs for envelope renovation, 44% are costs for the energy generation and distribution system and 33% are costs for purchased energy, operation and maintenance. For the period III buildings the average distribution of costs is 36% for envelope renovation, 36% for the energy system and 28% for energy, operation and maintenance.

The results also show (not shown in the figures) that the annualised costs are lower (2-3%) for a heating supply temperature of 35°C rather than 45°C, as in most cases the fan coils are sized for the cooling load. As with the ASHP + radiant ceilings system, adding PV to the energy system increases the annualised investment costs by 1.5 €/m^2y, on average, and reduces the final energy costs by approximately the same amount.

Costs for energy generation and distributions systems is the dominating cost for the refurbishments of period I buildings, while the costs for envelope renovation are equally high or even higher for period III buildings.

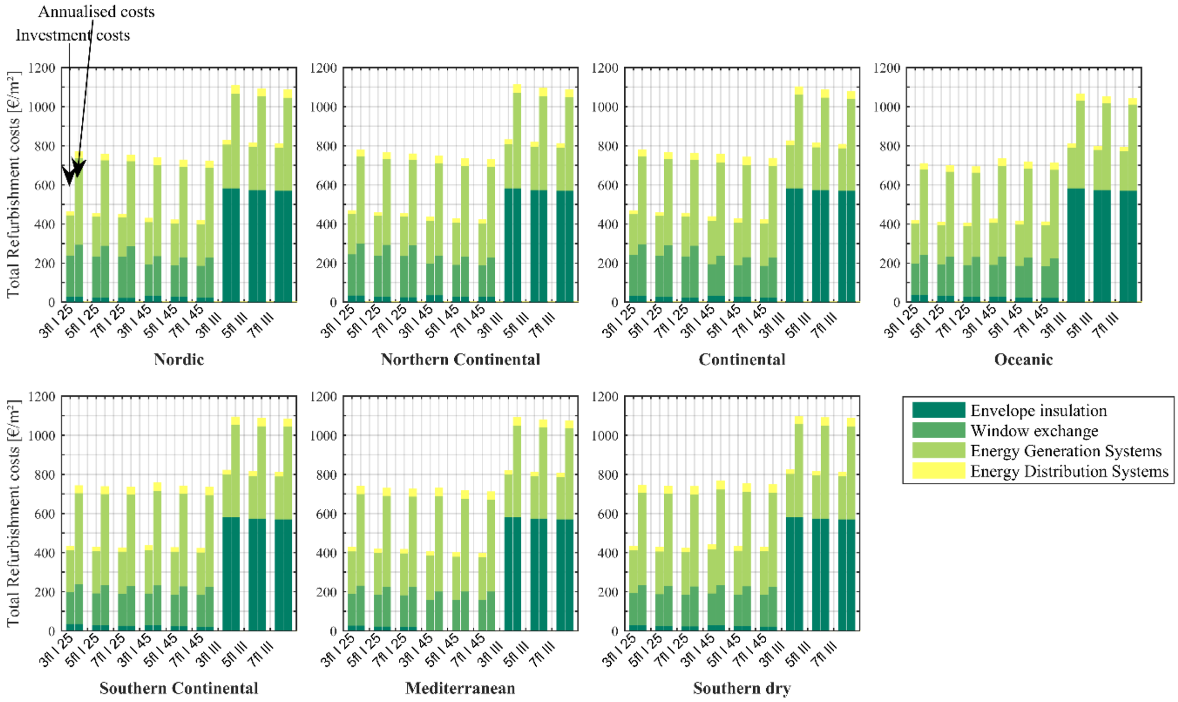


Figure 20 – Investment costs distribution (first year investment and annualised costs over 30 years) for ASHP with fan coils without solar PV systems, for office buildings with a floor area of 162 m² per storey

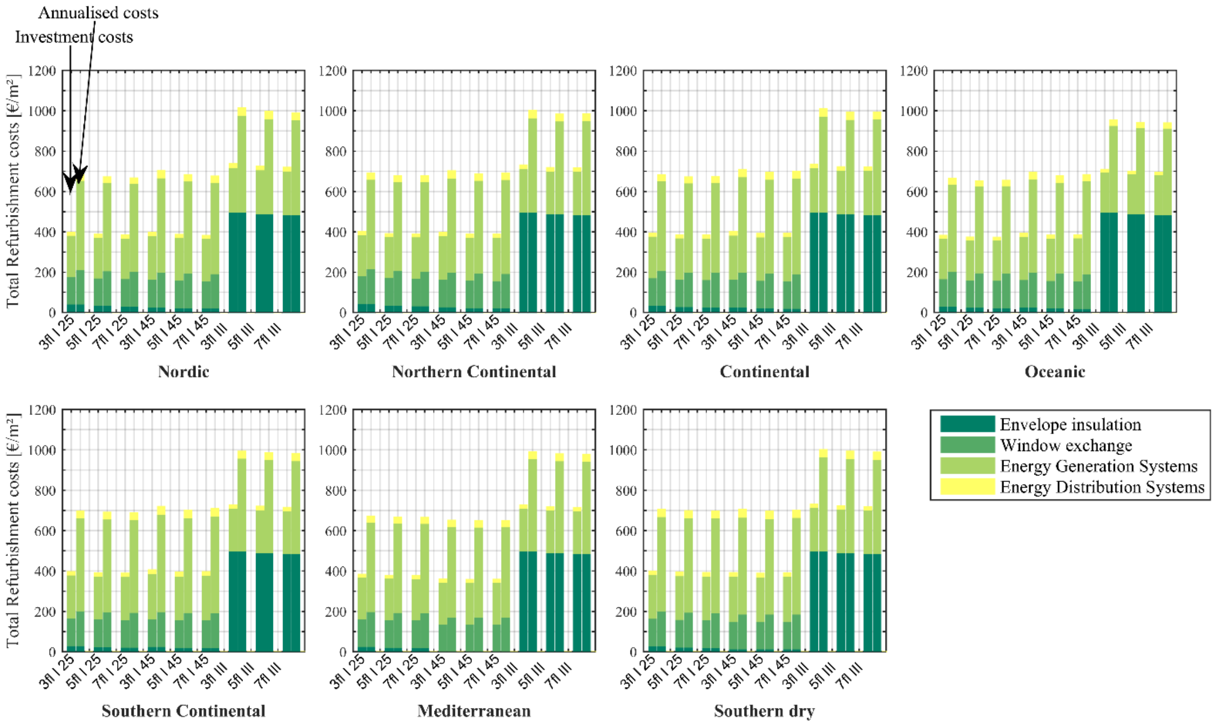


Figure 21 – Investment costs distribution (first year investment and annualised costs over 30 years) for ASHP with fan coils without solar PV systems, for office buildings with a floor area of 324 m² per storey

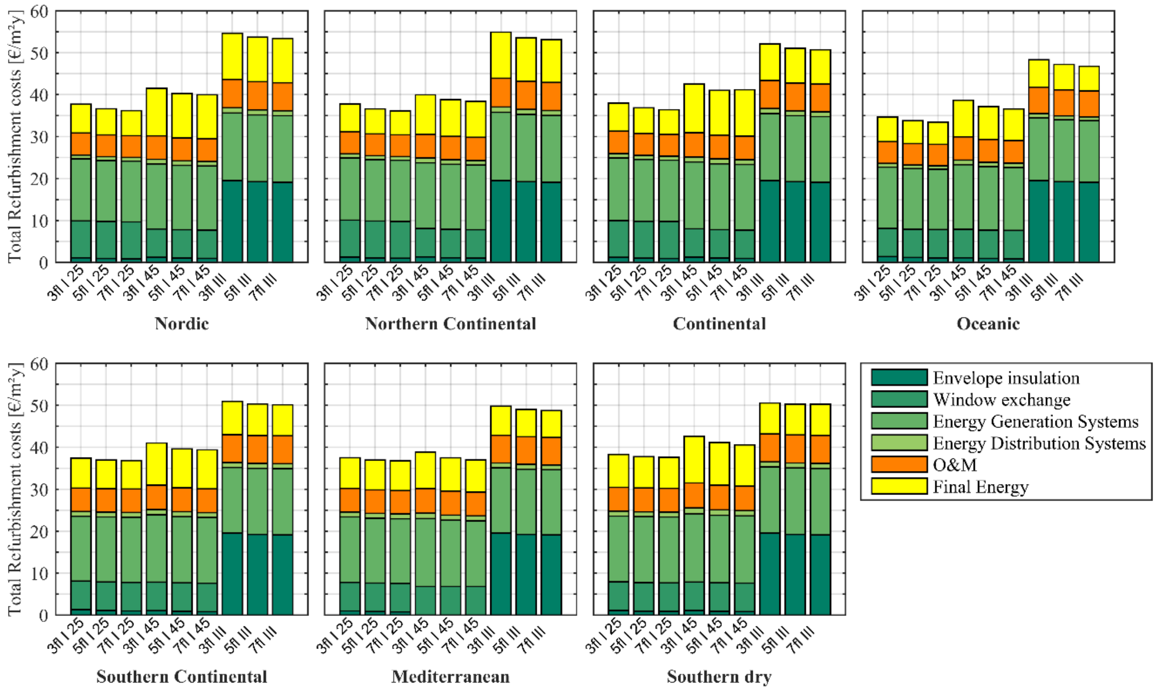


Figure 22 – Distribution of yearly annualised costs for ASHP with fan coils for office buildings with a floor area of 162 m2 per storey without solar PV systems

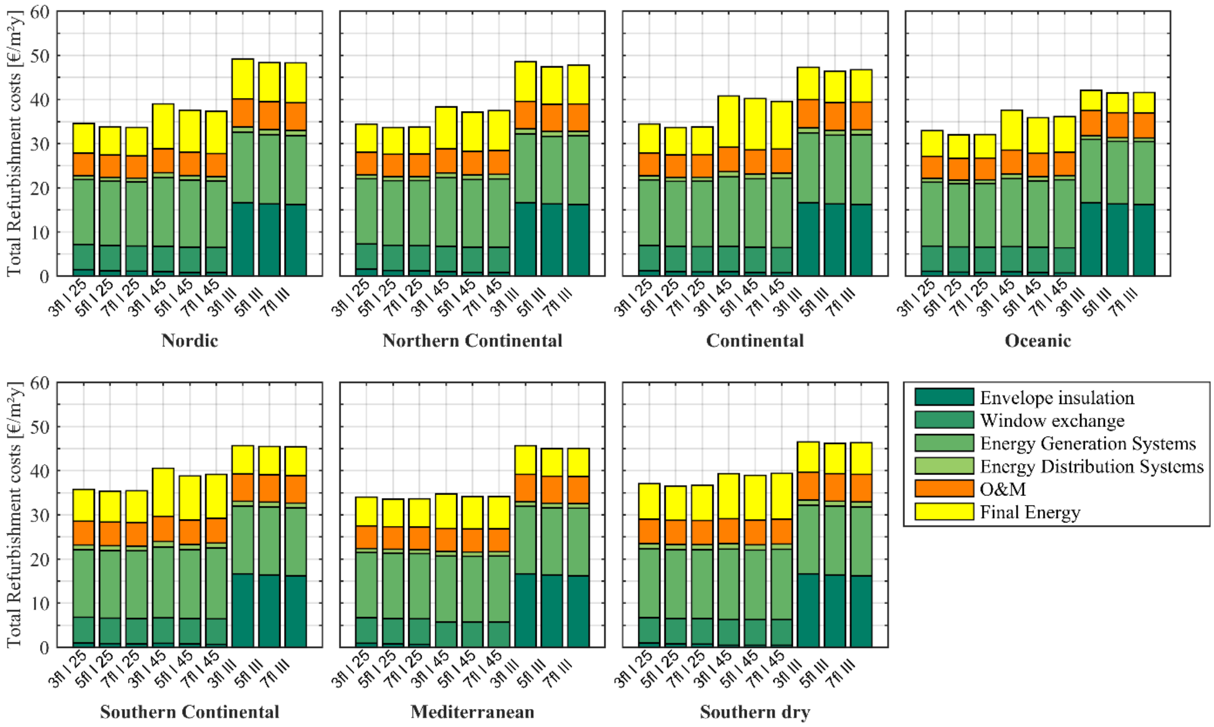


Figure 23 – Distribution of yearly annualised costs for ASHP with fan coils for office buildings with a floor area of 324 m^2 per storey without solar PV systems

4 Gas/Pellet Boiler with Radiant Ceilings

Gas and pellet boilers are reported in the same chapter as they are similar in terms of system design and were simulated with the same model. Final and primary energy consumption was then calculated in post-processing, taking into account different thermal efficiencies primary energy factors for the two systems. Thus, results regarding used energy and thermal comfort are only reported once, while differences between the two boiler types can be seen in terms of final and primary energy consumption and costs for the energy system and the purchased energy.

4.1 Used energy and thermal comfort

As the same distribution system for heating is used, the used energy and thermal comfort with gas/pellet boiler and radiant ceiling is almost exactly the same as with ASHP and radiant ceiling during the heating season. Some differences are observed for cooling though, since the boiler systems use split units to provide this service, whereas in the ASHP systems the heat pump generates both heating and cooling and distributes it via the radiant ceiling panels.

Figure 24 shows the used energy for heating and cooling for buildings with 5 floors and with 162 m^2/storey and 324 m^2/storey, respectively (for buildings with 3 and 7 floors, see Annex I – Simulation results, section 6.3.1). The used energy for heating is, in all cases, on the same level as with ASHP and radiant ceiling, while the used energy for cooling is lower with the current system.

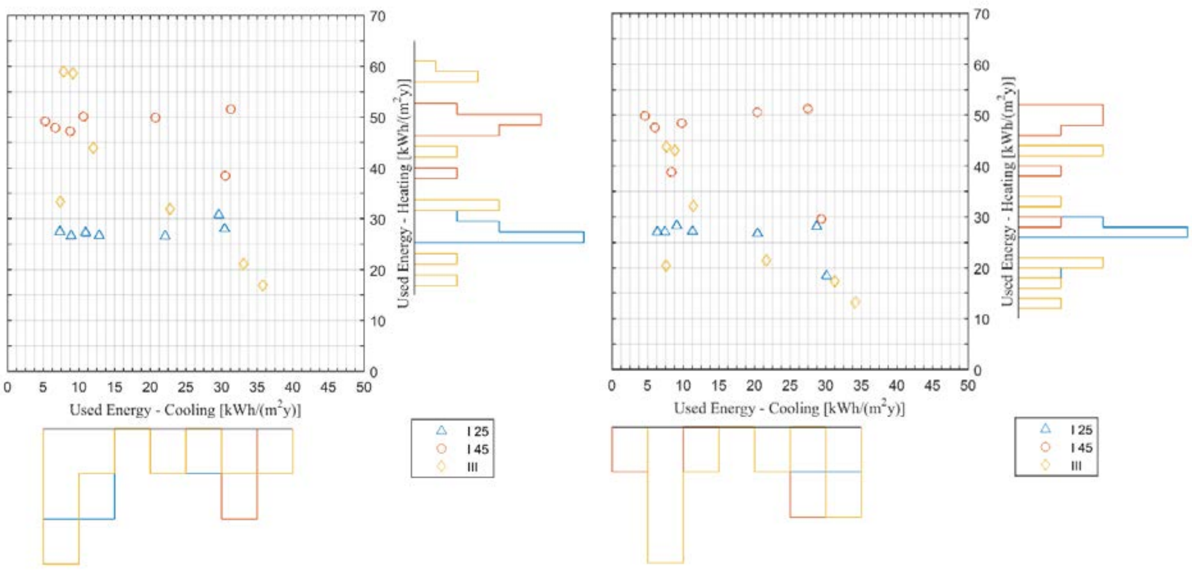


Figure 24 – Used energy for heating and cooling for office buildings with 162 m^2 per storey and 5 floors (left) and for heating and cooling for office buildings with 324 m^2 per storey and 5 floors (right)

The changes and trends in used energy for heating compared to the existing buildings were the same as with ASHP and radiant ceilings. The used energy for cooling was reduced by 4% - 192% after renovation, or in absolute numbers from 0.1 - 41 kWh/m²y. The largest reductions of used energy for cooling were seen for the Nordic and Northern Continental climates. Increases in used energy occurred for the Oceanic climate.

The temperature and humidity in the buildings is essentially the same as already shown for ASHP with radiant ceiling panels (section 2.2). While the convective temperature is effectively maintained within the set limits, the absence of air humidity control allows the humidity in the offices to exceed the recommended range during some periods of the year.

4.2 Final energy and primary energy

Due to the lower system efficiency of boilers compared to heat pumps, the final energy consumption of these systems is in all cases higher than for the heat pump systems. The primary energy target of 50 kWh/m^{2}y cannot be obtained for many cases with gas boiler, while with pellet boiler the primary energy consumption is below this level in all cases, even without solar PV production.

As the boiler is providing the heating, while a split unit is providing the cooling, the final energy comprises different energy carriers. The final energy use is in all cases much higher than for the systems with heat pumps, due to the lower system efficiency with gas or pellets compared to heat pumps. Figure 25 through Figure 28 show that in all cases the final energy for heating is dominant. The final energy for mechanical ventilation is higher than that for cooling in all cases apart from those with the largest cooling demands (Mediterranean and Southern Dry climates).

The impact on the primary energy of using small PV sizes is higher for this system with gas boiler than for systems with heat pumps, but increasing the size of the PV has less impact, as the electrical load is smaller.

In all climates, and both the smaller and larger office, the final energy decreases with increasing number of floors. This is in contrast to the case with reversible heat pumps, where the final energy, especially for the larger office, was often greater for the 7 floor building than the 5 floor. This is because the heating load dominates (gas), and this decreases with number of floors, while the smaller cooling load increases with number of floors.

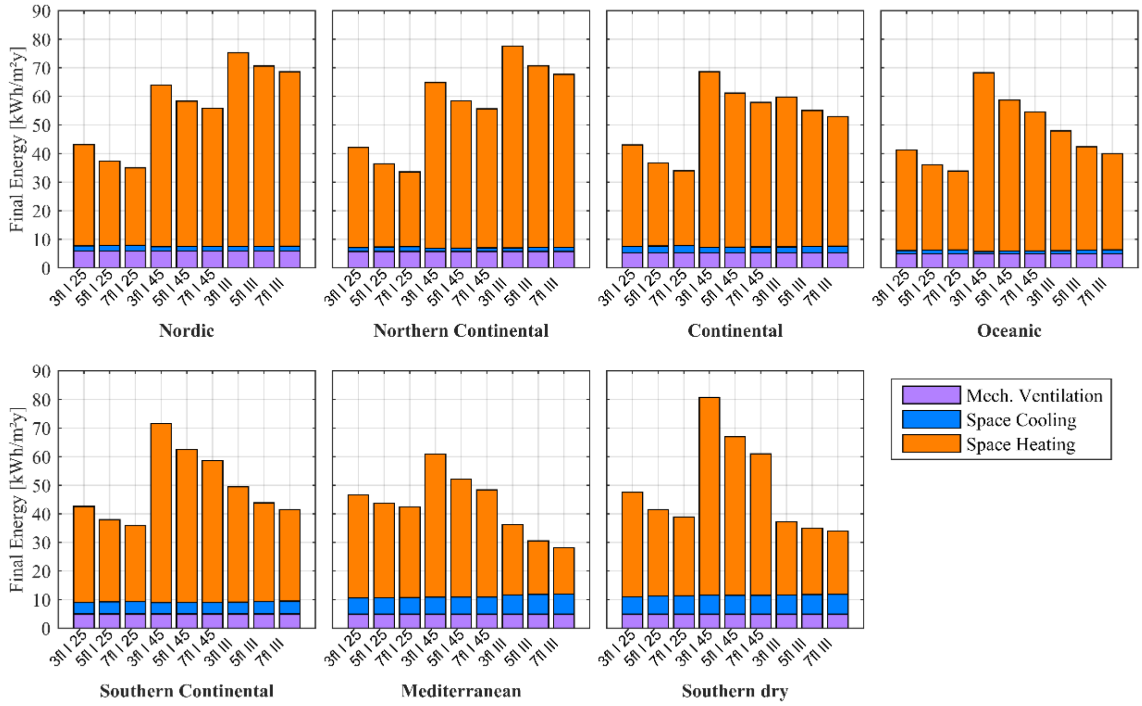


Figure 25 – Final energy consumption for gas boiler for office buildings with 162 m² per storey, split into three different categories: space heating (gas); Space cooling (electricity); Mechanical ventilation (electricity)

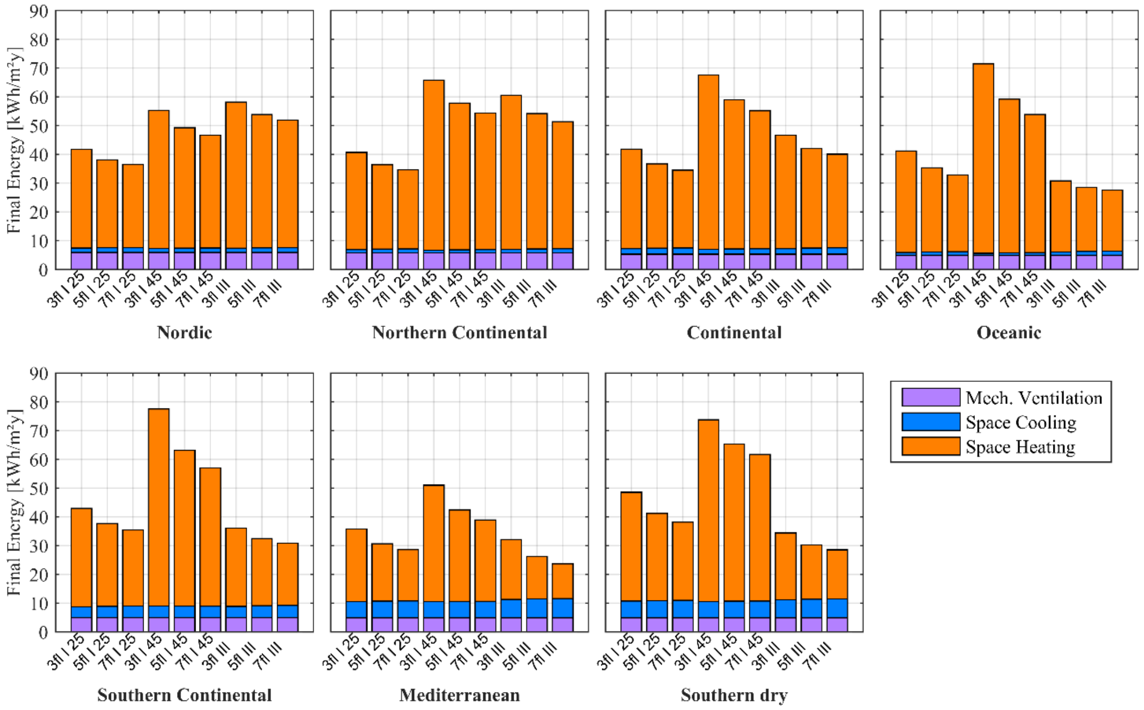


Figure 26 – Final energy consumption for gas boiler for office buildings with 324 m² per storey, split into three different categories: space heating (gas); Space cooling (electricity); Mechanical ventilation (electricity)

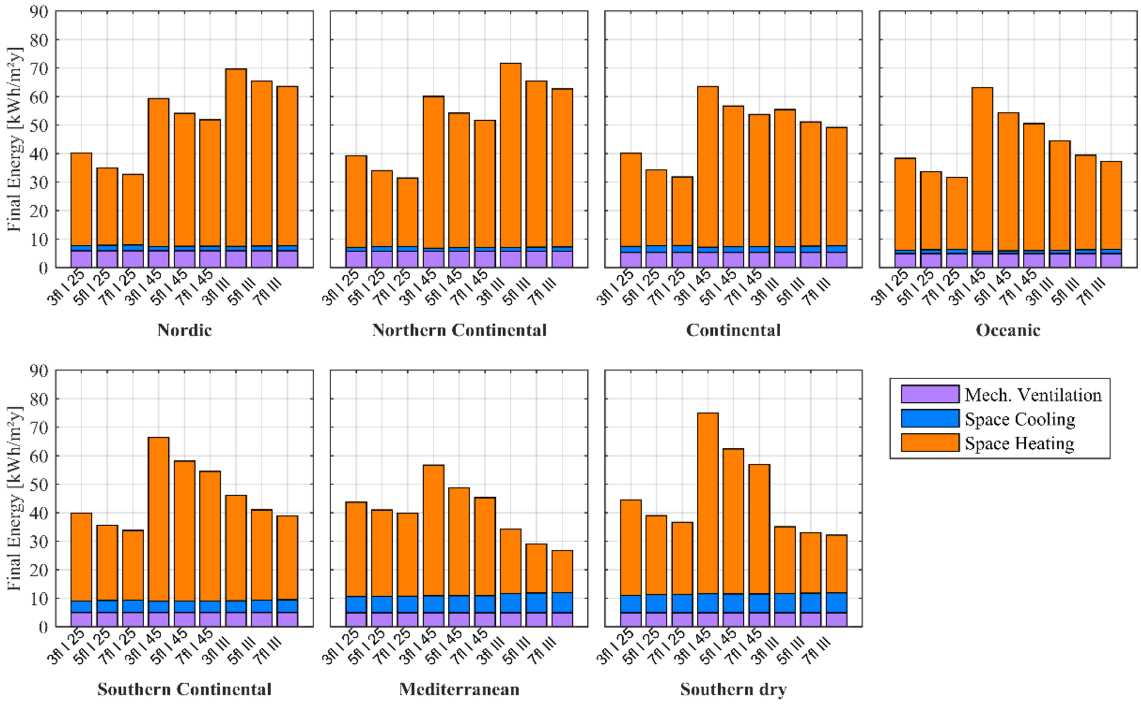


Figure 27 – Final energy consumption for pellet boiler for office buildings with 162 m² per storey, split into three different categories: space heating (pellets); Space cooling (electricity); Mechanical ventilation (electricity)

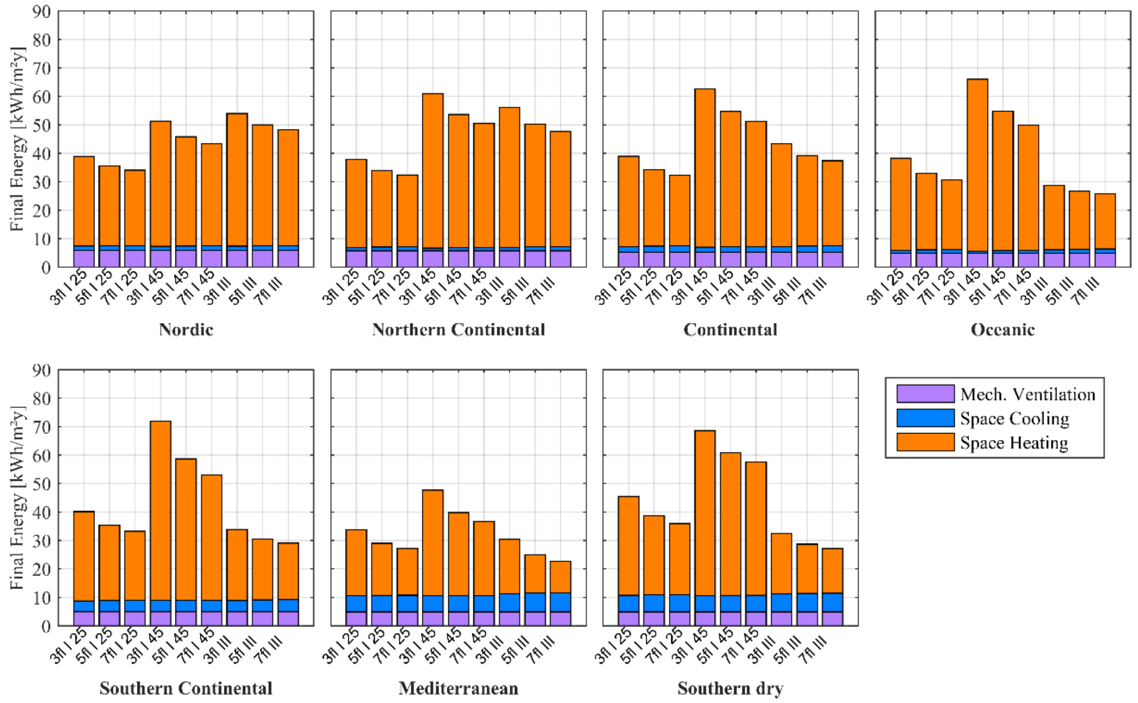


Figure 28 – Final energy consumption for pellet boiler for office buildings with 324 m² per storey, split into three different categories: space heating (pellets); Space cooling (electricity); Mechanical ventilation (electricity)

With gas boiler, the primary energy consumption (Figure 29 and Figure 30) for the three coldest climates (Nordic, Northern Continental and Continental) is above the target value of 50 kWh/m^{2}y for all cases apart from for EL25 in all three climates and for the curtain wall building in the Continental climate, where the use of PV is required for all cases to achieve this level. For the other cases, it is not even possible to get close for the smaller office, with the lowest values being ~65 kWh/m^{2}y with the largest PV fields. For the larger office size, it can nearly be reached with the largest PV areas, with slightly lower values in the Nordic than Northern Continental and Continental climates.

For the Oceanic and Southern Continental climates, target value of 50 kWh/m^{2}y can be achieved in all cases of EL25 and with the curtain wall construction if PV is used. Again, only small sizes are generally required to come down to this level, and larger sizes do not give very large decreases. For EL45, it is not possible to get below 60 kWh/m^{2}y even with the largest PV fields.

For the two hottest climates, Mediterranean and Southern Dry, the primary energy use without PV is relatively high, being above 60 kWh/m^{2}y for all cases apart from for the curtain wall in the Mediterranean climate. With PV it is possible to reach the target value of 50 kWh/m^{2}y for EL25 and the curtain wall. It is also possible for EL45 in the Mediterranean climate, but not Southern Dry as the heat demand in Mediterranean climate is actually lower than of 45 kWh/m^{2}y without added insulation. The use of even relatively small PV fields makes a large impact on primary energy consumption for these two climates, but increasing the size has lower impact.

With pellet boiler, the primary energy consumption is below the 50 kWh/m^{2}y target for all cases, even without PV. The highest primary energy consumption, 49 kWh/m^{2}y, is seen for OFF1 with 3 floors, EL45 in the Southern Dry climate. With PV it is possible to come down below 10 kWh/m^{2}y in many cases, and for the renovated period III buildings in the Mediterranean and Southern Dry climates even as low as 5 – 7 kWh/m^{2}y. The primary energy factor for pellets was set to 0.19 kWh/kWh, while for gas it was 1.19 kWh/kWh. With pellet boiler, most of the primary energy consumption is due to electricity (with a primary energy factor of 2.88) for cooling and ventilation.

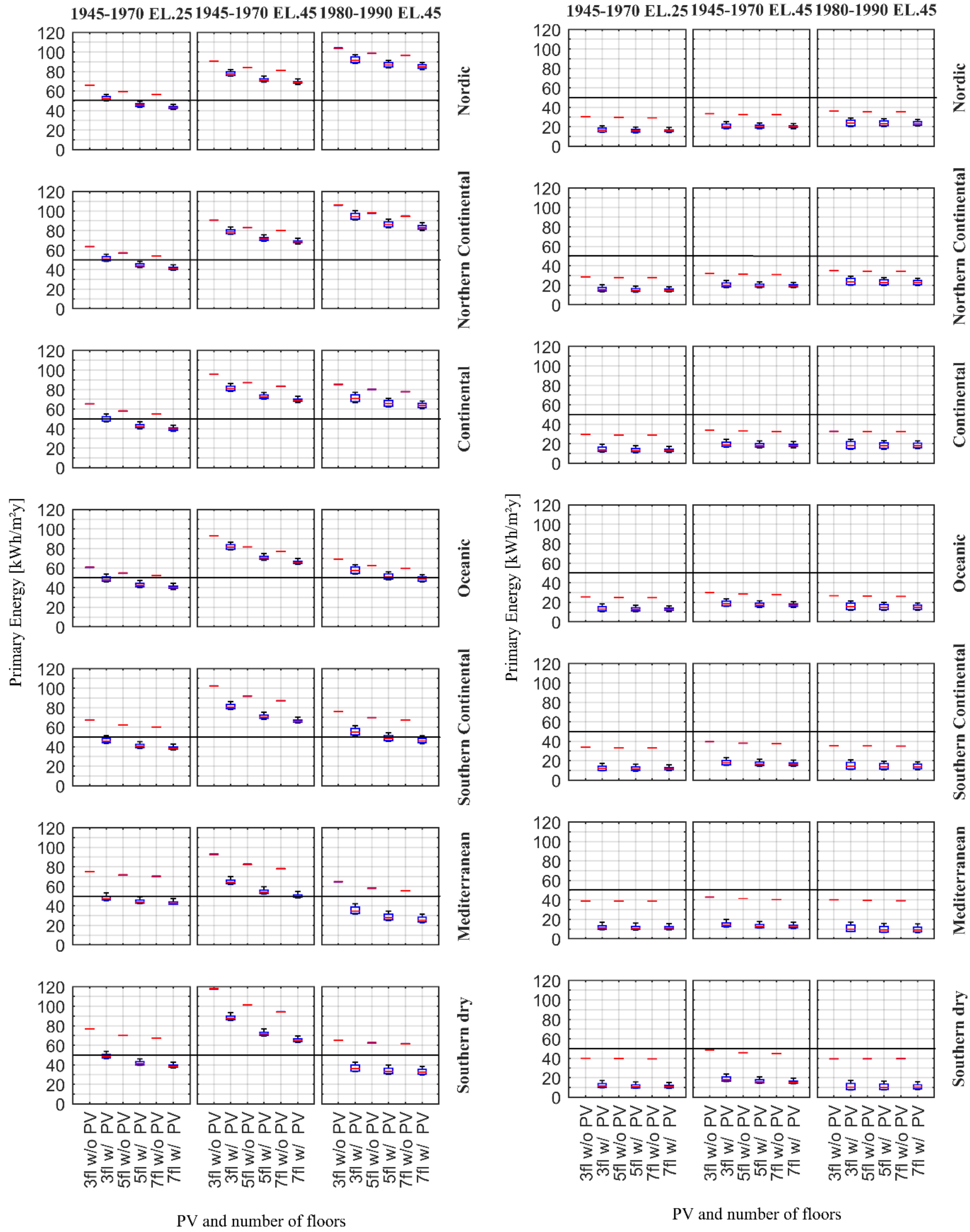


Figure 29 – Primary energy consumption for the renovated office buildings with 162 m^2 per storey with gas (left) and pellet boiler (right)

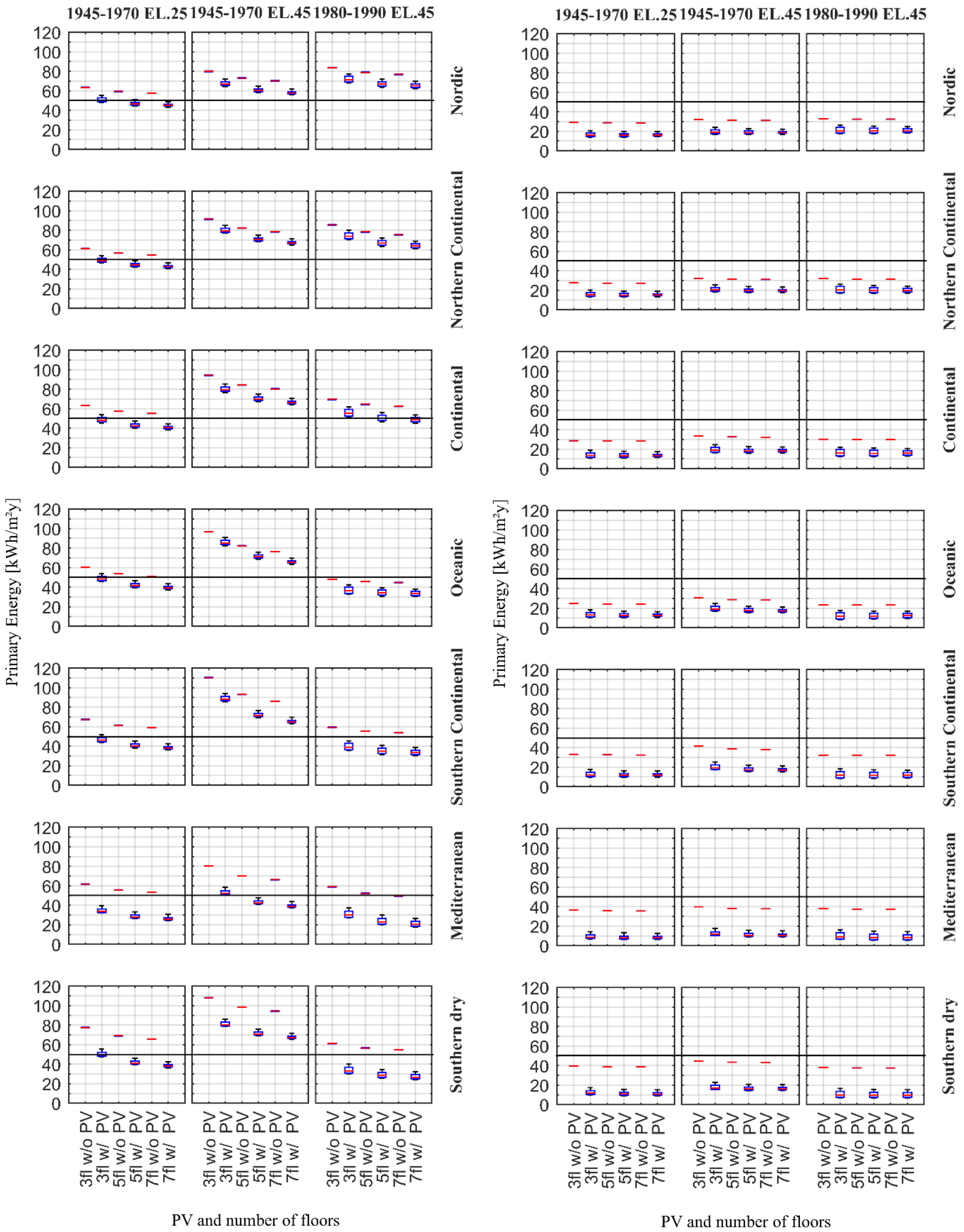


Figure 30 – Primary energy consumption for the renovated office buildings with 324 m² per storey with gas (left) and pellet boiler (right)

4.3 Solar PV energy utilisation

The total electricity production from PV panels is the same for the boiler systems as for the heat pump systems. The self-consumption is also very similar, as the boiler systems use electricity for cooling via split units in the summer and the demand is in all cases higher than the PV production.

The production and utilisation of electricity from solar PV panels are shown in Figure 31 for office buildings with 5 floors (for buildings with 3 and 7 floors, see Annex I – Simulation results, section 6.3.2). The figures show the use of PV electricity to drive the HVAC system (red), lighting and appliances (orange), and the surplus production fed to the grid (yellow).

The PV production in total is of course the same as that shown for the heat pump systems. The self-consumption is also very similar as the demand is much larger than the PV production even for the largest fields. Note that the self-consumption is calculated first for the HVAC system, and remaining (excess) PV production can be used for the other loads. The electricity demand does not have any electricity demand for heating, which limits the self-consumption for HVAC for the largest fields that are located on the facade. This is most obvious in the colder climates where the cooling demand is lower, with the self-consumption nearly at its maximum even at the smallest size for the façade. For the hotter climates this maximum is reached for the middle sized field. However, for these cases the other electrical loads are large enough so that the total self-consumption is practically the same for the boiler systems as for the systems with heat pumps. The results for the boiler systems (also pellet) with radiant ceilings and fan-coils are essentially the same, but the systems with fan-coils have a marginally higher self-consumption.

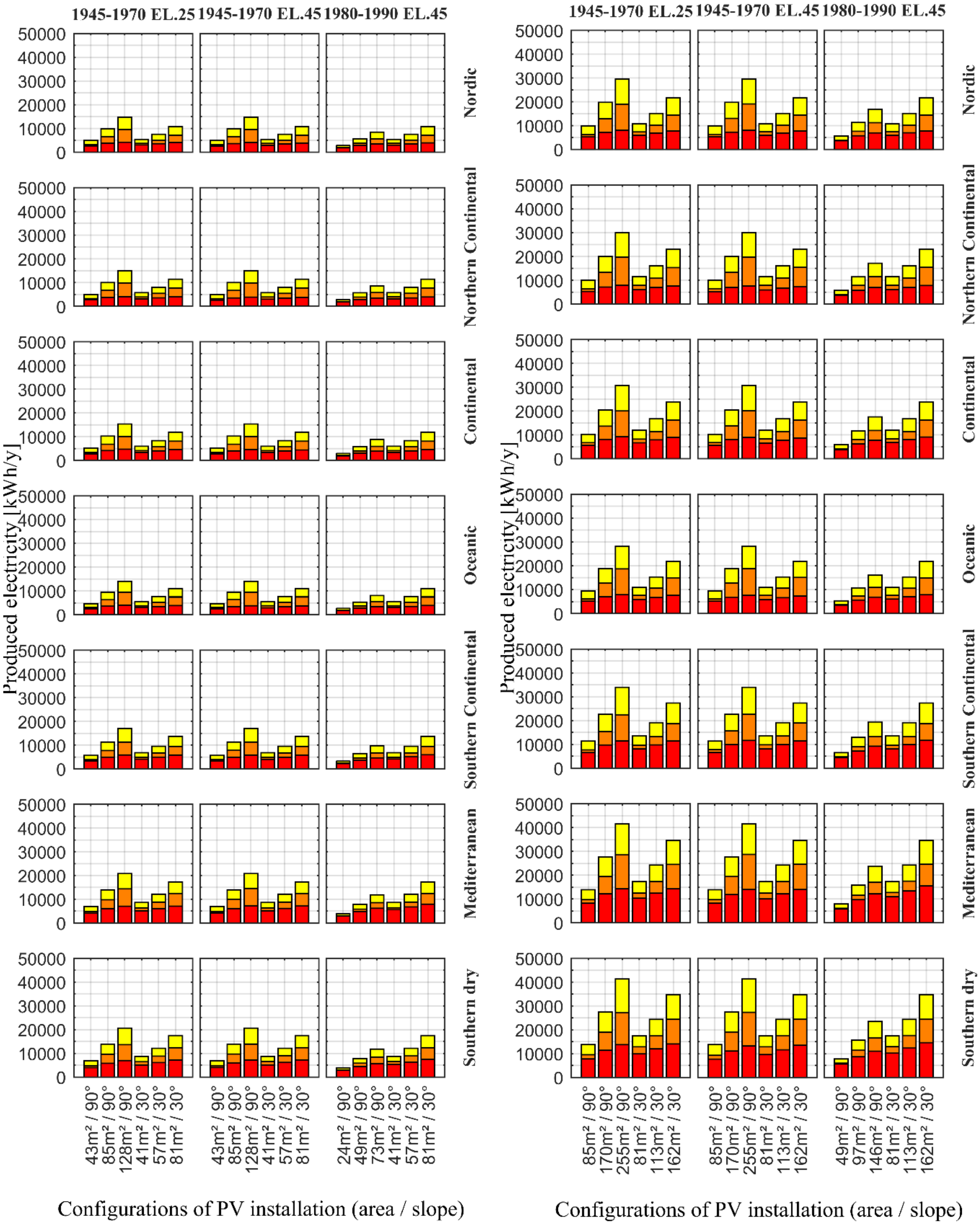


Figure 31 – Self-consumption and PV electricity to grid for office buildings with 5 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

4.4 Economic evaluations

To a large extent, the same considerations regarding initial investment costs as for the case air source heat pump with radiant ceilings (see section 2.6) are valid also here, only with a different investment cost for the boiler compared to the heat pump.

The initial and the annualised investment costs per m^2 with gas boiler are shown in Figure 32 and Figure 33. The initial investment costs range from 360 to 840 €/m^2, resulting in annualised costs between 650 and 1100 €/m^2y. For the period I buildings, the annualised costs for the 25 kWh/m^2y heating demand level were in most cases equally high or higher than the costs for the 45 kWh/m^2y level. With solar PV panels, the investment costs increase by up to 27 – 51 €/m^2 (maximum increase for each case), or 3 – 13%. The annualised costs increase by up to 44 – 82 €/m^2y, or 4 – 12%.

The initial and the annualised investment costs with pellet boiler are shown in Figure 34 and Figure 35. The initial investment costs range from 380 to 860 €/m^2, resulting in annualised costs between 680 and 1150 €/m^2y. For the period I buildings, the annualised costs for the 25 kWh/m^2y heating demand level were in most cases equally high or higher than the costs for the 45 kWh/m^2y level. With solar PV panels, the investment costs increase by up to 27 – 51 €/m^2 (maximum increase for each case), or 3 – 13%. The annualised costs increase by up to 44 – 82 €/m^2y, or 4 – 12%.

Figure 36 and Figure 37 show the total annualised costs for the gas boiler system over 30 years, divided by the floor area. The total costs for the buildings from period I are, in all cases, the lowest for the ones renovated to the 25 kWh/m^2y level. The total yearly costs amount to 31 – 40 €/m^2y for the 25 kWh/m^2y level and 32 – 43 €/m^2y for the 45 kWh/m^2y level. The total costs for the period III buildings varied within the range 42 – 53 €/m^2y. As with the ASHP systems, adding PV to the energy generation system increases the annualised investment costs by 1.5 €/m^2y, on average, and reduces the final energy costs by approximately the same amount.

The total annualised costs for the pellet boiler system are shown in Figure 41 and Figure 42. The total costs for the buildings from period I are the lowest for the ones renovated to the 25 kWh/m^2y level. The total yearly costs amount to 31 – 40 €/m^2y for EL25 and 32 – 42 €/m^2y for EL45. The total costs for the period III buildings varied within the range 43 – 52 €/m^2y. Adding PV to the energy generation system increases the annualised investment costs by 1.5 €/m^2y, on average, and reduces the final energy costs by approximately the same amount.

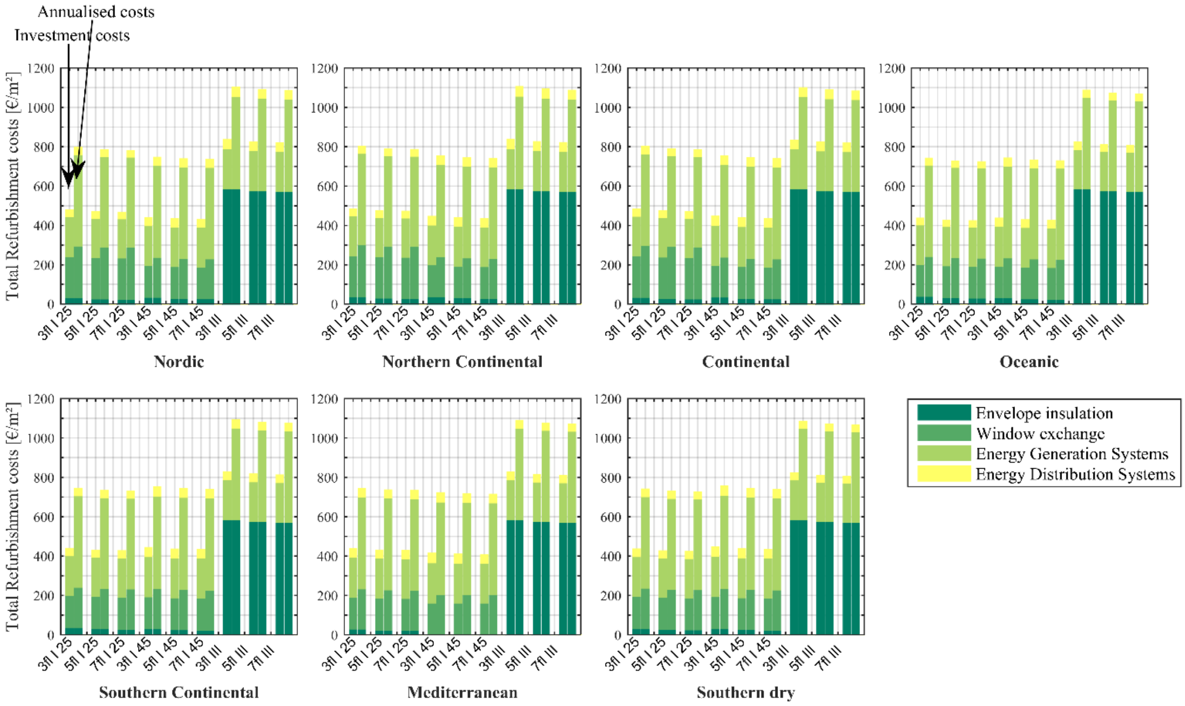


Figure 32 – Investment costs distribution (first year investment and annualised costs over 30 years) for gas boiler system with radiant ceilings without solar PV, for office buildings with a floor area of 162 m² per storey

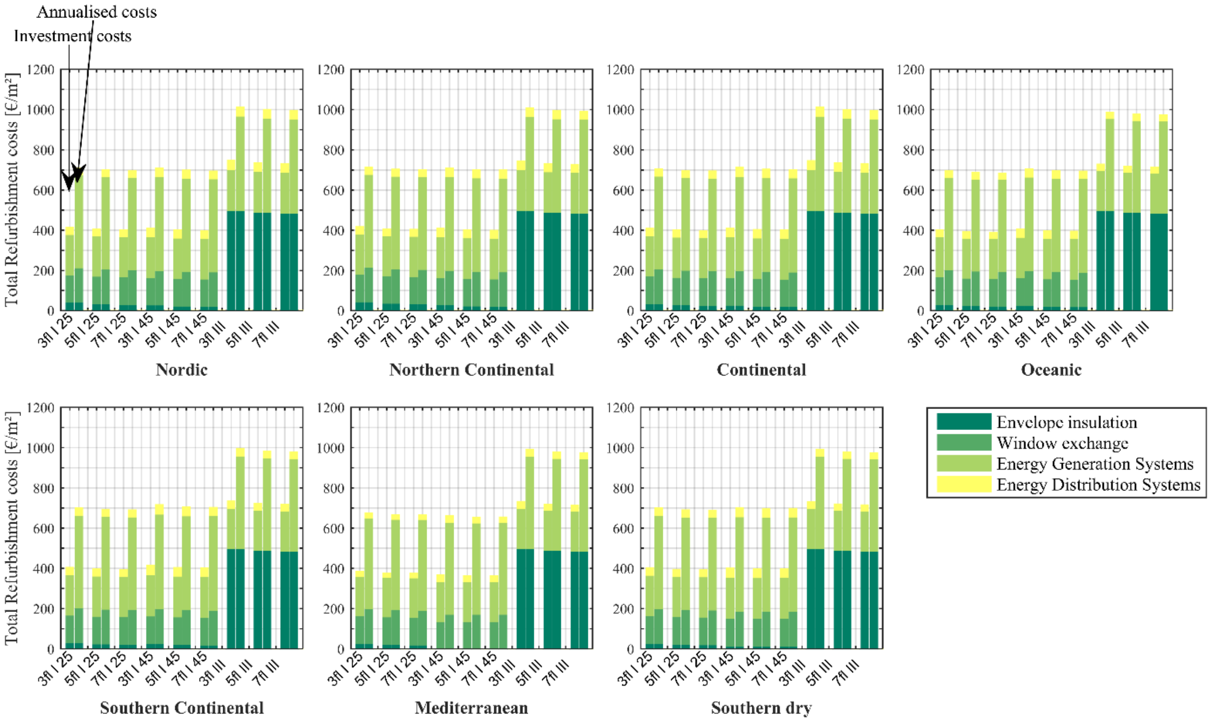


Figure 33 – Investment costs distribution (first year investment and annualised costs over 30 years) for gas boiler system with radiant ceilings without solar PV, for office buildings with a floor area of 324 m² per storey

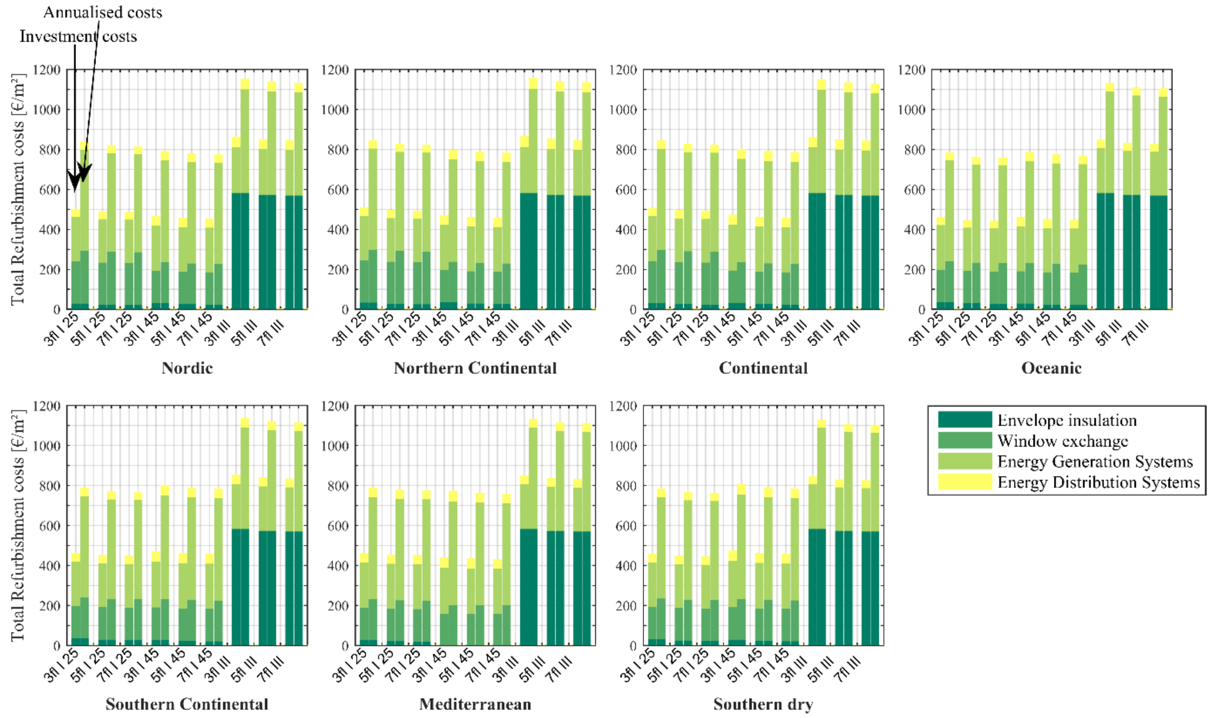


Figure 34 – Investment costs distribution (first year investment and annualised costs over 30 years) for pellet boiler system with radiant ceilings without solar PV, for office buildings with a floor area of 162 m^2 per storey

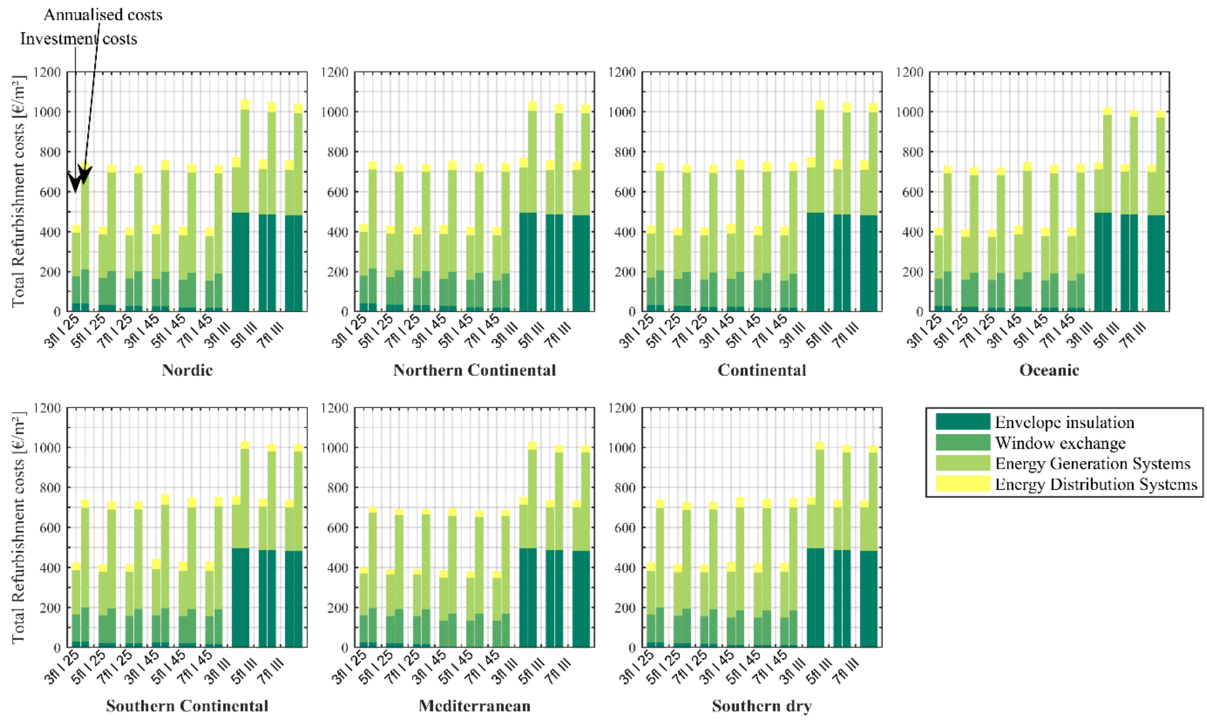


Figure 35 – Investment costs distribution (first year investment and annualised costs over 30 years) for pellet boiler system with radiant ceilings without solar PV, for office buildings with a floor area of 324 m^2 per storey

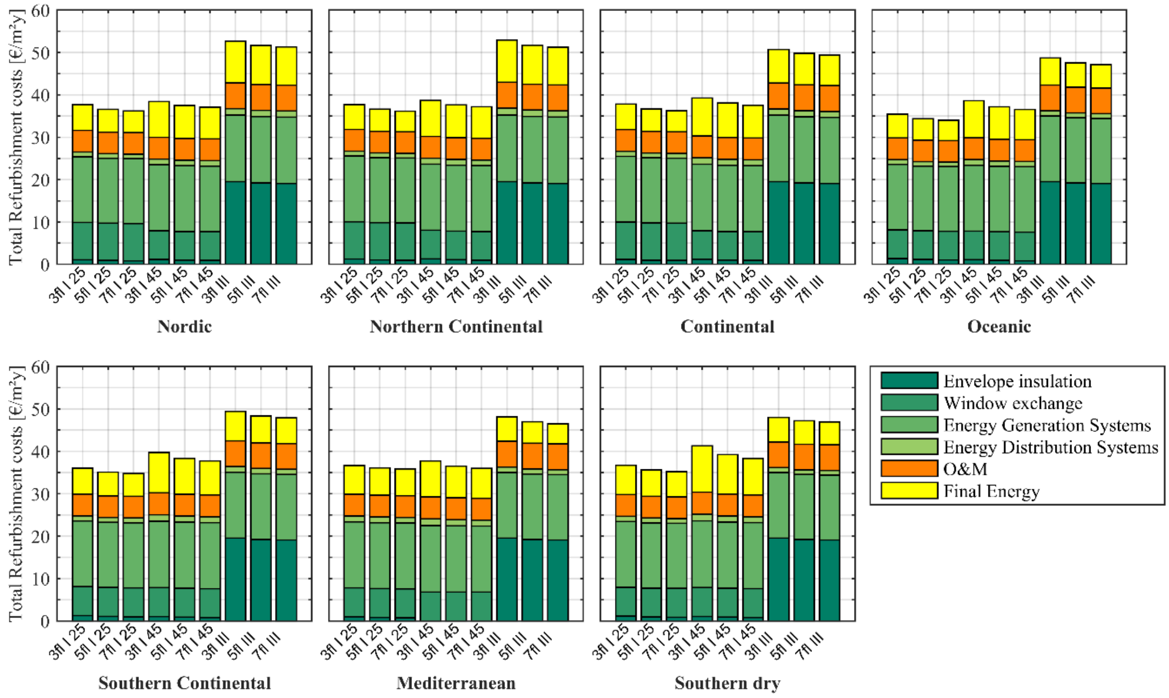


Figure 36 – Distribution of yearly annualised costs for gas boiler system with radiant ceilings for office buildings with a floor area of 162 m² per storey without solar PV systems

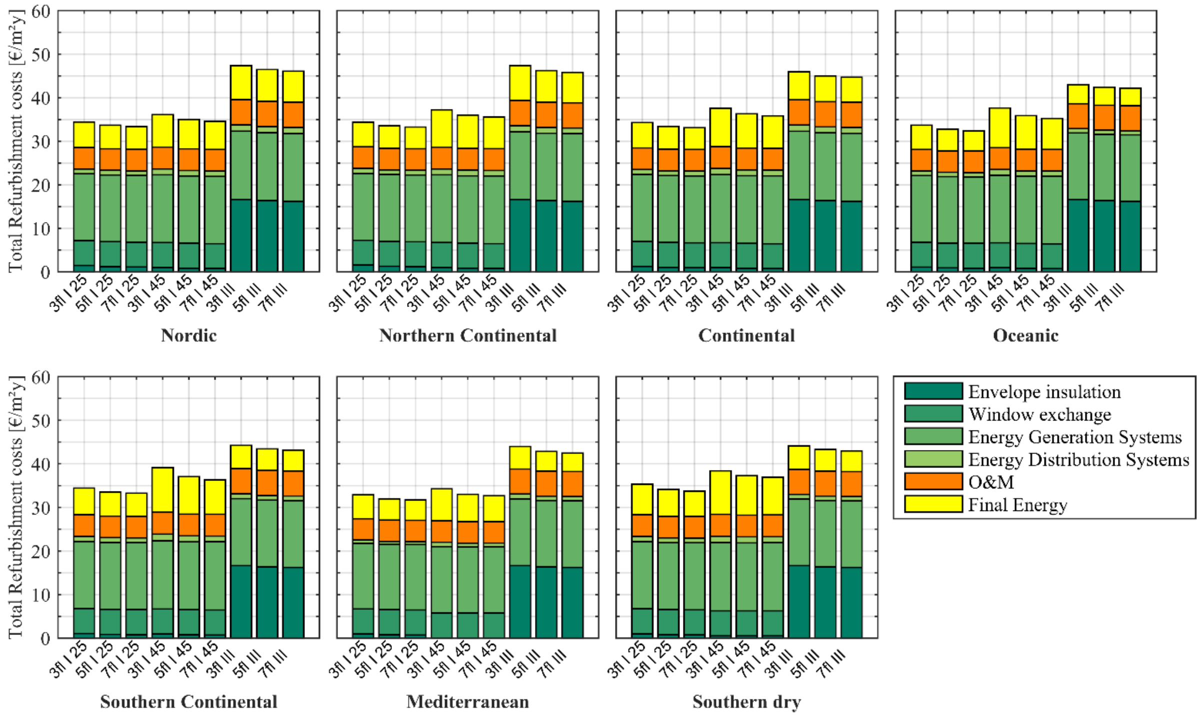


Figure 37 – Distribution of yearly annualised costs for gas boiler system with radiant ceilings for office buildings with a floor area of 324 m² per storey without solar PV systems

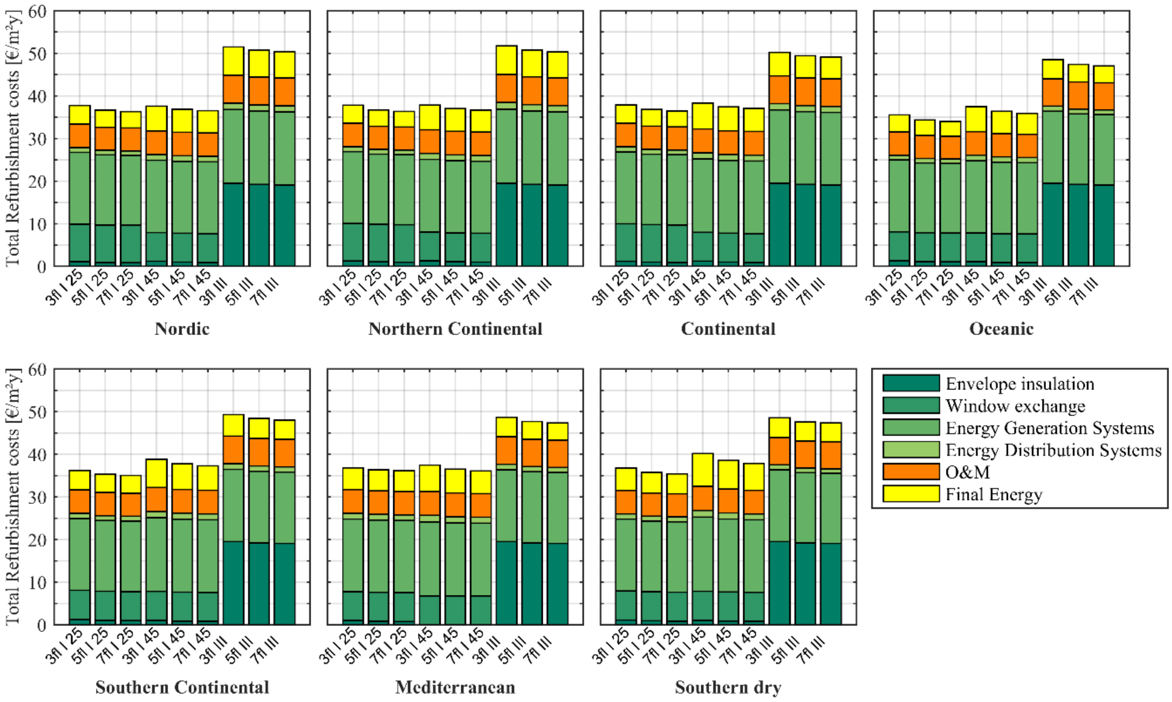


Figure 38 – Distribution of yearly annualised costs for pellet boiler system with radiant ceilings for office buildings with a floor area of 162 m² per storey without solar PV systems

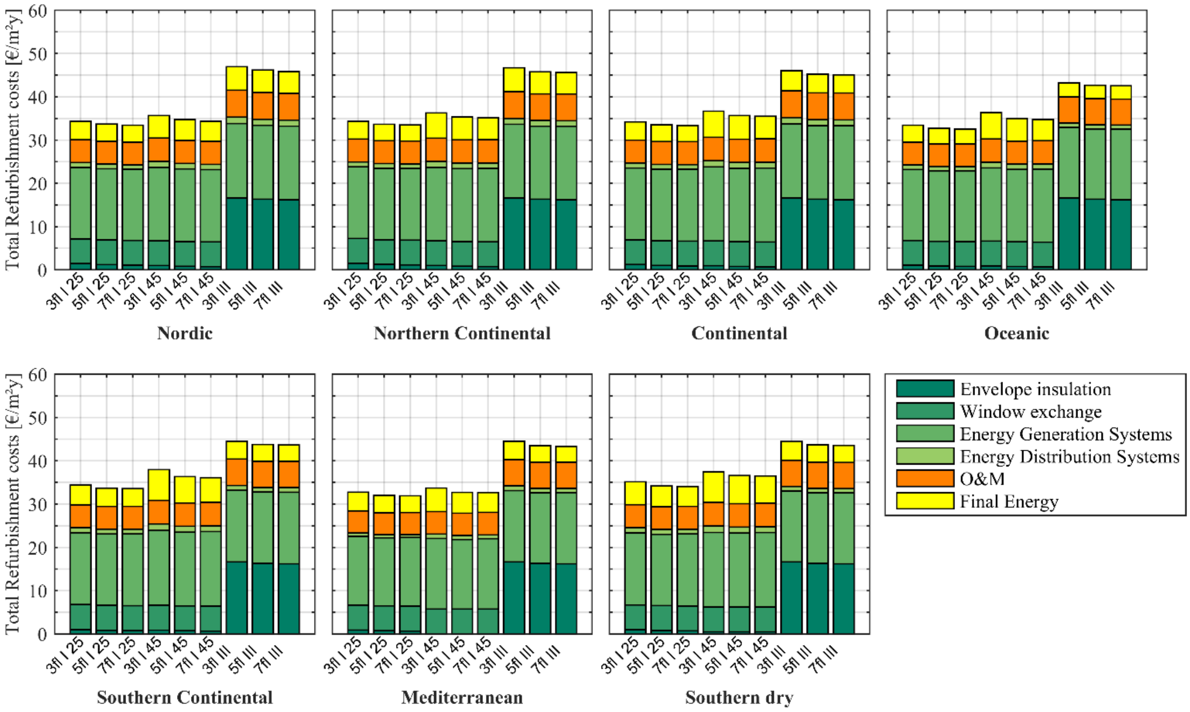


Figure 39 – Distribution of yearly annualised costs for pellet boiler system with radiant ceilings for office buildings with a floor area of 324 m² per storey without solar PV systems

5 Gas/Pellet Boiler with Fan Coils

Just as for gas/pellet boiler with radiant ceilings, the results for gas/pellet boiler with fan coils are reported in one section, highlighting the differences in primary energy consumption and costs with the two types of boiler.

The results regarding PV utilisation for the boiler systems (also pellet) with radiant ceilings and fan-coils are essentially the same, but the systems with fan-coils have a marginally higher self-consumption. Graphs for solar PV utilisation are found in Annex I – Simulation results, section 6.4.2.

5.1 Used energy and thermal comfort

As the same distribution system for heating is used, the used energy and thermal comfort with gas/pellet boiler and fan coil is almost exactly the same as with ASHP and fan coil during the heating season. Some differences are observed for cooling though, since the boiler systems use split units to provide this service, whereas in the ASHP systems the heat pump generates both heating and cooling and distributes it via the fan coils. Compared to the system with boiler and radiant ceiling panels, the used energy with fan coils is slightly lower.

Figure 40 shows the used energy for heating and cooling for buildings with 5 floors and with 162 m^2/storey and 324 m^2/storey, respectively (for buildings with 3 and 7 floors, see Annex I – Simulation results, section 6.4.1). As already stated in section 3, the used energy is lower with fan coils than with radiant ceilings solutions, for heating as well as for cooling. The used heat for energy is often 5 to 10 kWh/m^{2}y lower if fan coils are used as distribution units. A smaller difference would probably result if the operative temperature were to be controlled instead of the convective.

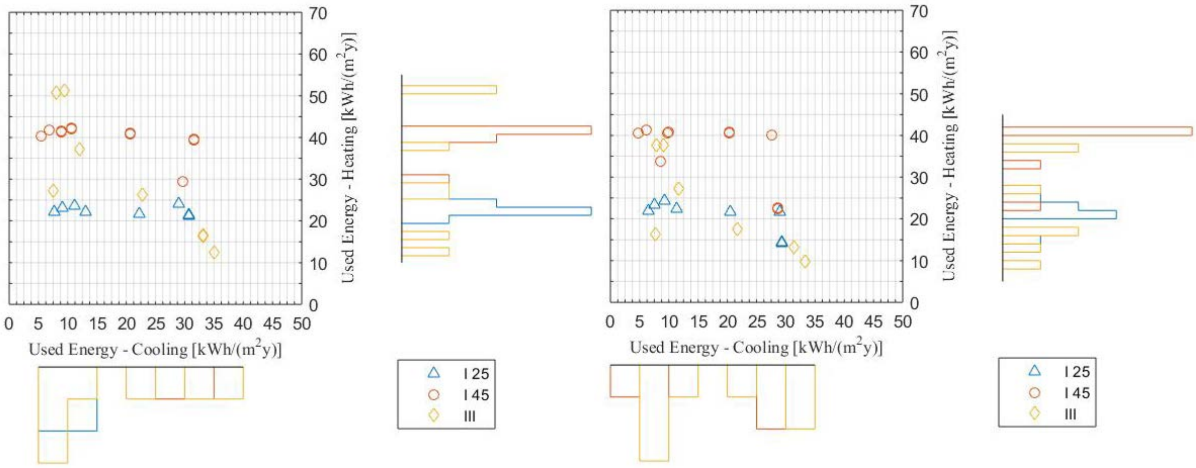


Figure 40 – Used energy for heating and cooling for office buildings with 162 m^2 per storey and 5 floors (left) and for heating and cooling for office buildings with 324 m^2 per storey and 5 floors (right)

The temperature and humidity in the buildings is essentially the same as already shown for ASHP with fan coils (section 3.2). While the convective temperature is effectively maintained within the set limits, the absence of air humidity control allows the humidity in the offices to exceed the recommended range during some periods of the year.

5.2 Final energy and primary energy

Due to the lower system efficiency of boilers compared to heat pumps, the final energy consumption of these systems is in all cases higher than for the heat pump systems. The primary energy target of 50 kWh/m^{2}y cannot be obtained for many cases with gas boiler, while with pellet boiler the primary energy consumption is below this level in nearly all cases, even without solar PV production. Compared to the system with boiler and radiant ceiling, the primary energy consumption with fan coils is slightly higher, due to the higher use of electricity.

Figure 41 through Figure 44 show the final energy consumption with gas/pellet boiler and fan coils, divided into energy for heating, cooling and ventilation. While the final energy consumption for heating is slightly lower, on average 1 kWh/m^{2}y, compared to the system with boiler and radiant ceilings, the final electric energy consumption (cooling and ventilation) is higher, almost 2 kWh/m^{2}y on average. This is due to the use of electricity to run the fans in the fan coils. However, with the lower primary energy factors of gas and pellets (1.19 and 0.19, respectively) compared to electricity (2.88), the primary energy consumption is still lower with fan coils.

The trends in primary energy (Figure 45 and Figure 46) are the same as for the systems with boiler and radiant ceilings. The values with fan coils are only slightly higher, due to the lower use of gas/pellets and the higher use of electricity. With pellet boiler, the primary energy consumption is below the 50 kWh/m^{2}y in all cases except for the smaller office building at energy level 45 in the Southern Dry climate. With PV panels, it is possible in some cases to obtain a primary energy consumption lower than 10 kWh/m^{2}y. For the system with gas boiler and fan coils the 50 kWh/m^{2}y target is in some cases not achievable even with the largest PV systems.

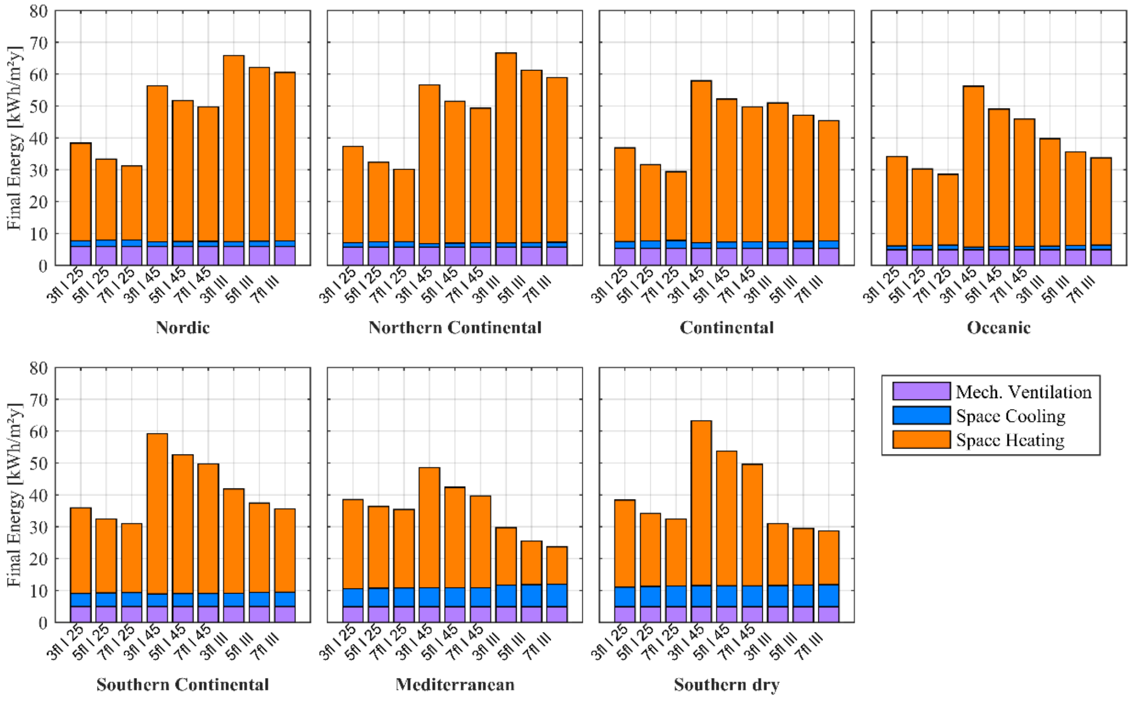


Figure 41 – Final energy consumption for gas boiler for office buildings with 162 m^2 per storey, split into three different categories: space heating (gas); Space cooling (electricity); Mechanical ventilation (electricity)

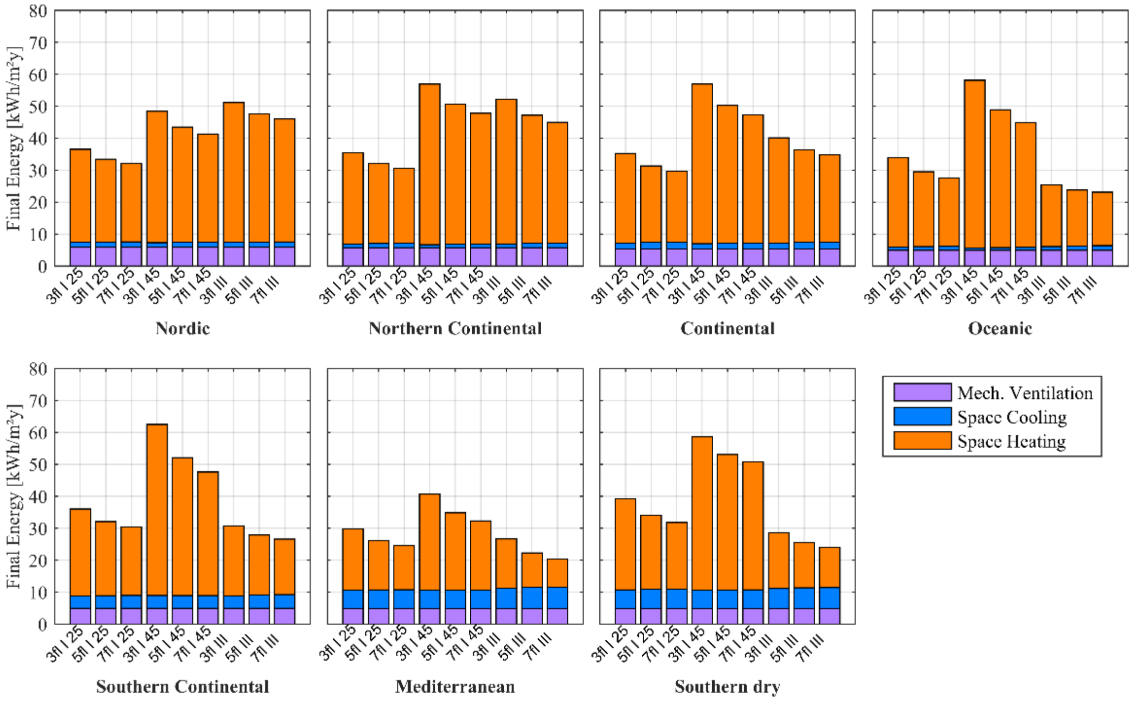


Figure 42 – Final energy consumption for gas boiler for office buildings with 162 m^2 per storey, split into three different categories: space heating (gas); Space cooling (electricity); Mechanical ventilation (electricity)

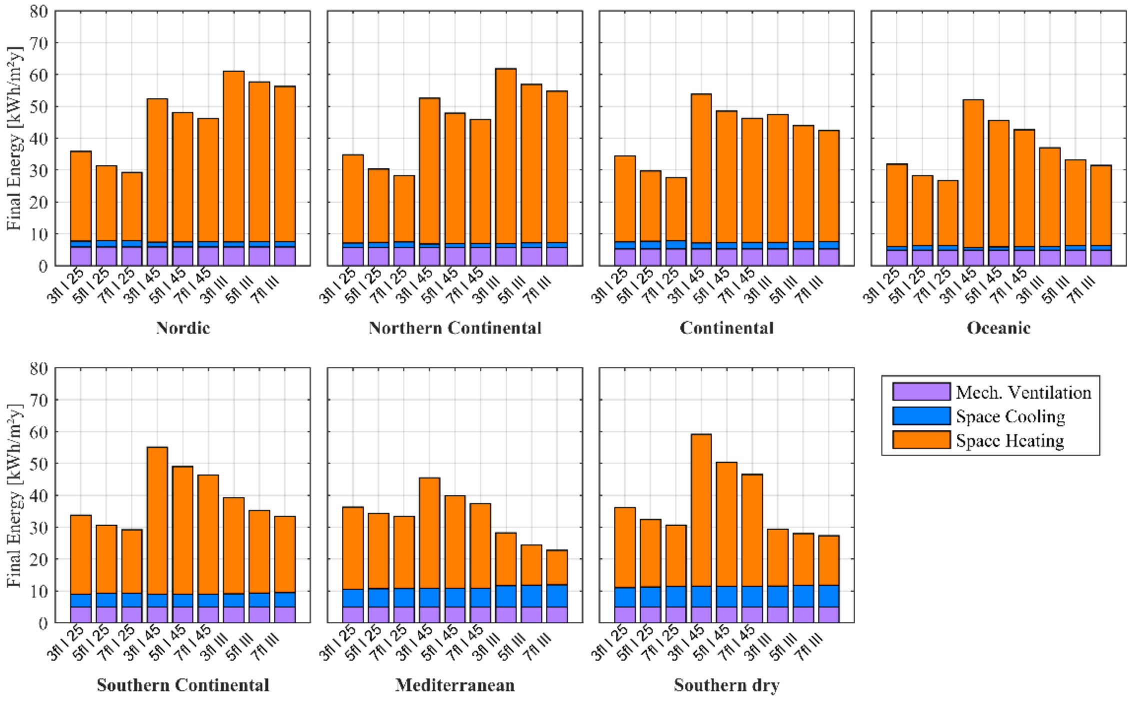


Figure 43 – Final energy consumption for pellet boiler for office buildings with 162 m² per storey, split into three different categories: space heating (gas); Space cooling (electricity); Mechanical ventilation (electricity)

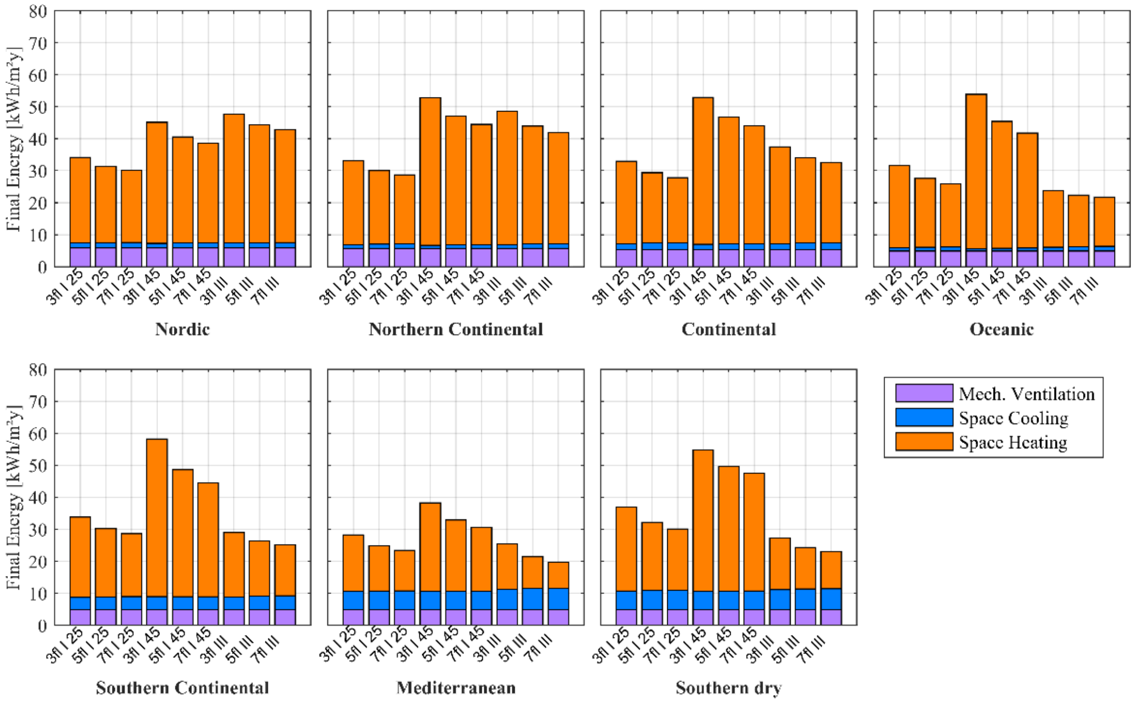


Figure 44 – Final energy consumption for pellet boiler for office buildings with 324 m² per storey, split into three different categories: space heating (gas); Space cooling (electricity); Mechanical ventilation (electricity)

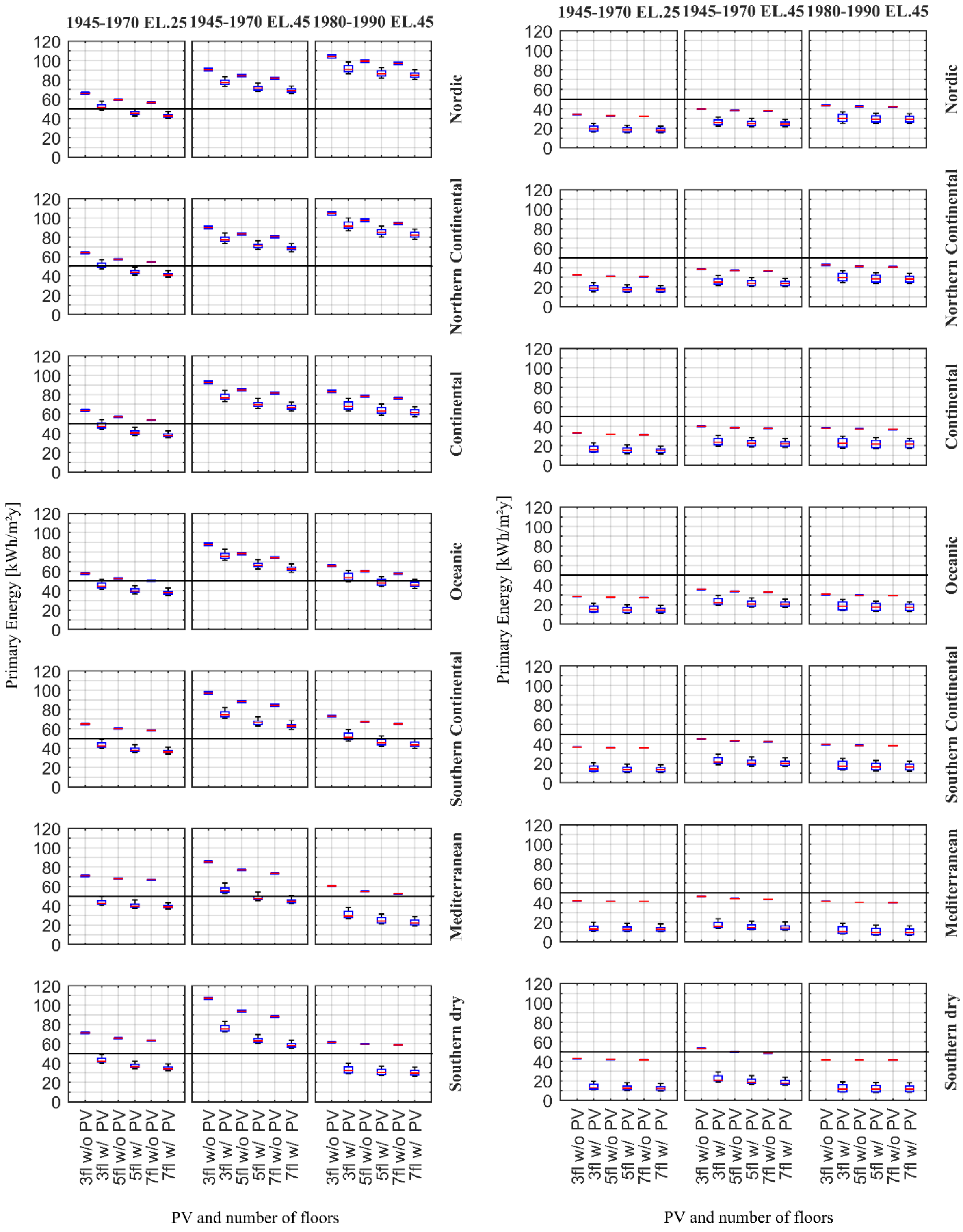


Figure 45 – Primary energy consumption for the renovated office buildings with 162 m² per storey with gas (left) and pellet boiler (right)

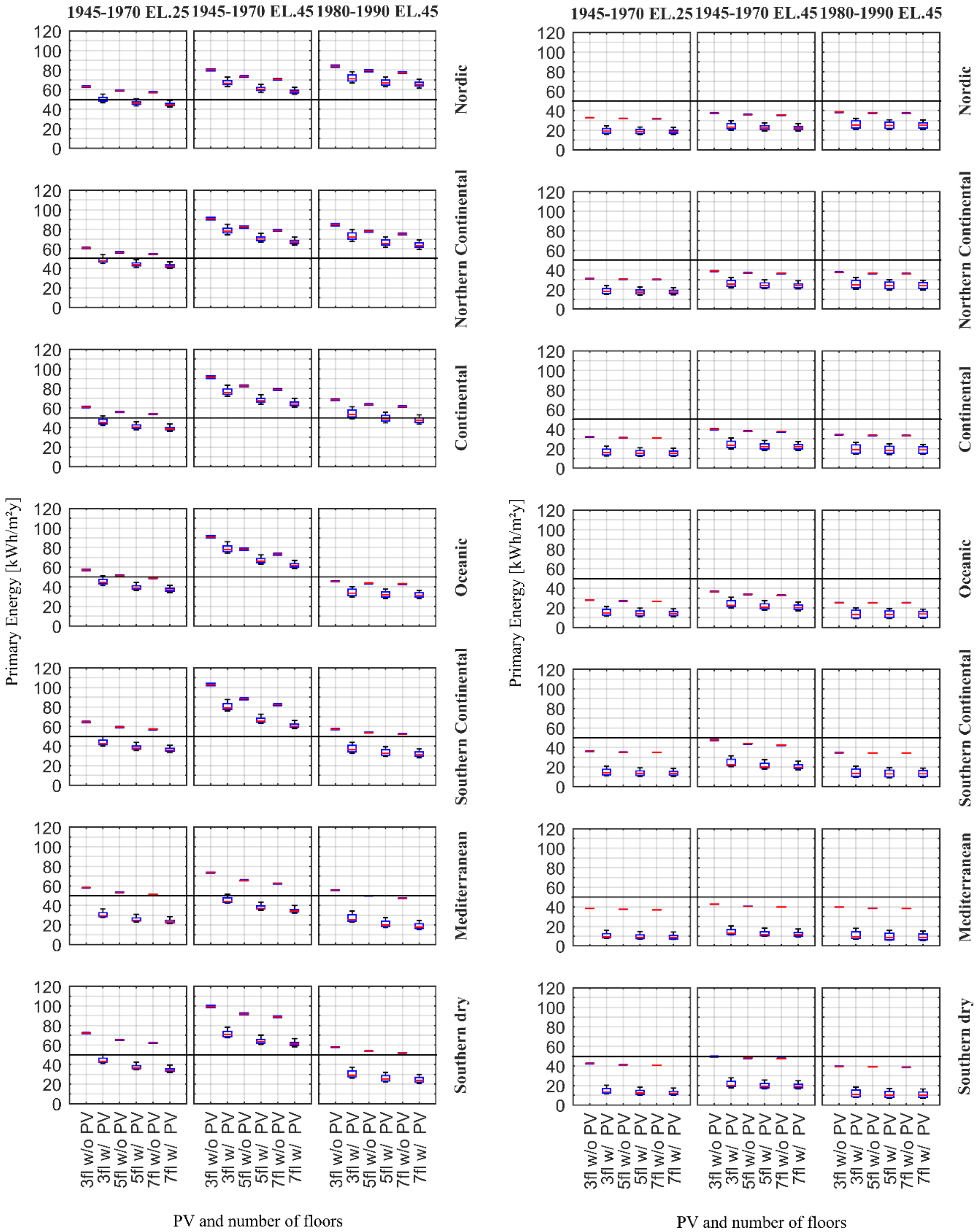


Figure 46 – Primary energy consumption for the renovated office buildings with 324 m² per storey with gas (left) and pellet boiler (right)

5.3 Economic evaluations

To a large extent, the same considerations regarding initial investment costs as for the case air source heat pump with fan coils (see section 3.4) are valid also here, only with a different investment cost for the boiler compared to the heat pump.

As expected, the initial and the annualised investment costs of pellet boilers are higher than gas boilers, mainly due to the significant difference in investment costs (€/kW) between the two systems.

The initial and the annualised investment costs per m^2 for the system with gas boiler are shown in Figure 47 and Figure 48. The initial investment costs range from 350 to 810 €/m^2, resulting in annualised costs between 650 and 1100 €/m^2y. For the period I buildings, the annualised costs for the 25 kWh/m^2y heating demand level were in most cases equally high or higher than the costs for the 45 kWh/m^2y level. With solar PV panels, the investment costs increase by up to 27 – 51 €/m^2y (maximum increase for each case), or 3 – 15%. The annualised costs increase by up to 44 – 82 €/m^2y, or 4 – 12%.

For pellet boilers (Figure 49 and Figure 50) the initial investment costs range from 360 to 830 €/m^2, resulting in annualised costs between 680 and 1150 €/m^2y. For the period I buildings, the costs for the 25 kWh/m^2y heating demand level were in all cases higher than the costs for the 45 kWh/m^2y level. With solar PV panels, the investment costs increase by up to 27 – 51 €/m^2y (maximum increase for each case), or 3 – 14%. The annualised costs increase by up to 44 – 82 €/m^2y, or 4 – 12%.

Figure 51 and Figure 52 show the total annualised costs over 30 years for the gas boiler system, divided by the floor area. The total costs are in all cases the lowest for the buildings from period I renovated to the 25 kWh/m^2y level. The total yearly costs amount to 31 – 41 €/m^2y for EL25 and 32 – 42 €/m^2y for EL45. The total costs for the period III buildings varied within the range 42 – 53 €/m^2y. As with the ASHP systems, adding PV to the energy generation system increases the annualised investment costs by 1.5 €/m^2y, on average, and reduces the final energy costs by approximately the same amount.

Figure 53 and Figure 54 show the total annualised costs over 30 years for the pellet boiler system, divided by the floor area. The total costs are in all cases the lowest for the buildings from period I renovated to the 25 kWh/m^2y level. The total yearly costs amount to 32 – 41 €/m^2y for the 25 kWh/m^2y level and 32 – 42 €/m^2y for the 45 kWh/m^2y level. The total costs for the period III buildings varied within the range 43 – 53 €/m^2y. As with the ASHP systems, adding PV to the energy generation system increases the annualised investment costs by 1.5 €/m^2y, on average, and reduces the final energy costs by approximately the same amount.

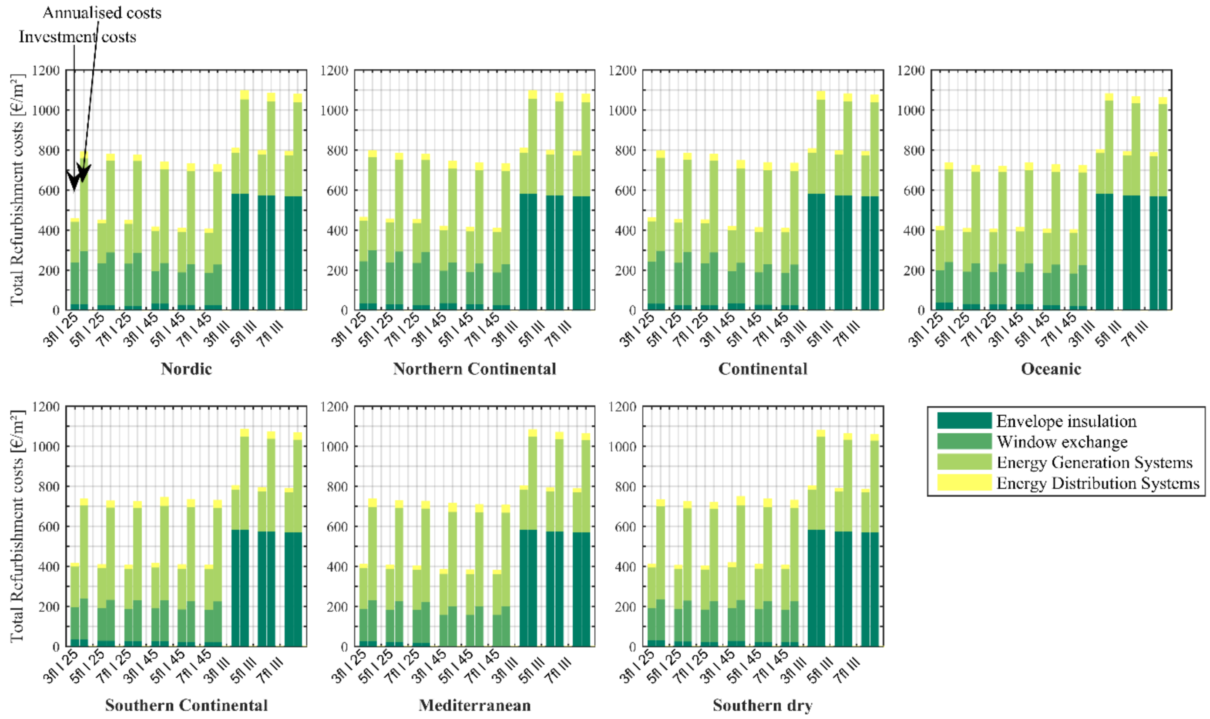


Figure 47 – Investment costs distribution (first year investment and annualised costs over 30 years) for gas boiler system with fan coils without solar PV, for office buildings with a floor area of 162 m² per storey

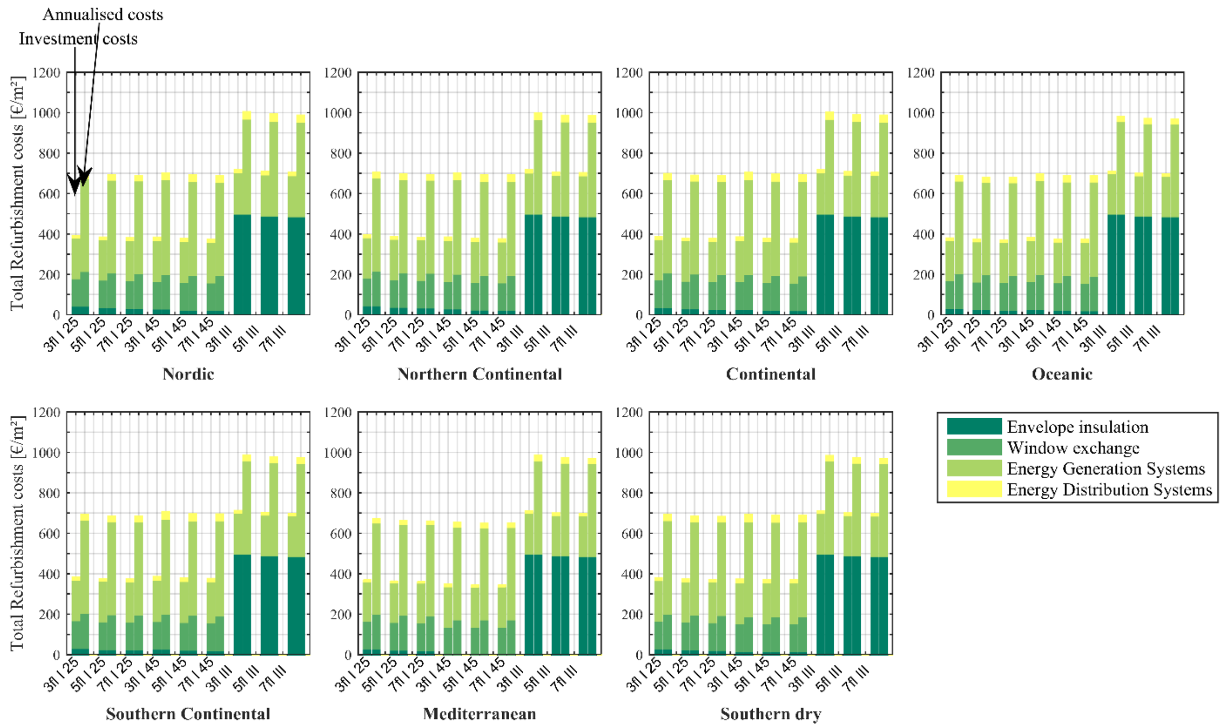


Figure 48 – Investment costs distribution (first year investment and annualised costs over 30 years) for gas boiler system with fan coils without solar PV, for office buildings with a floor area of 324 m² per storey

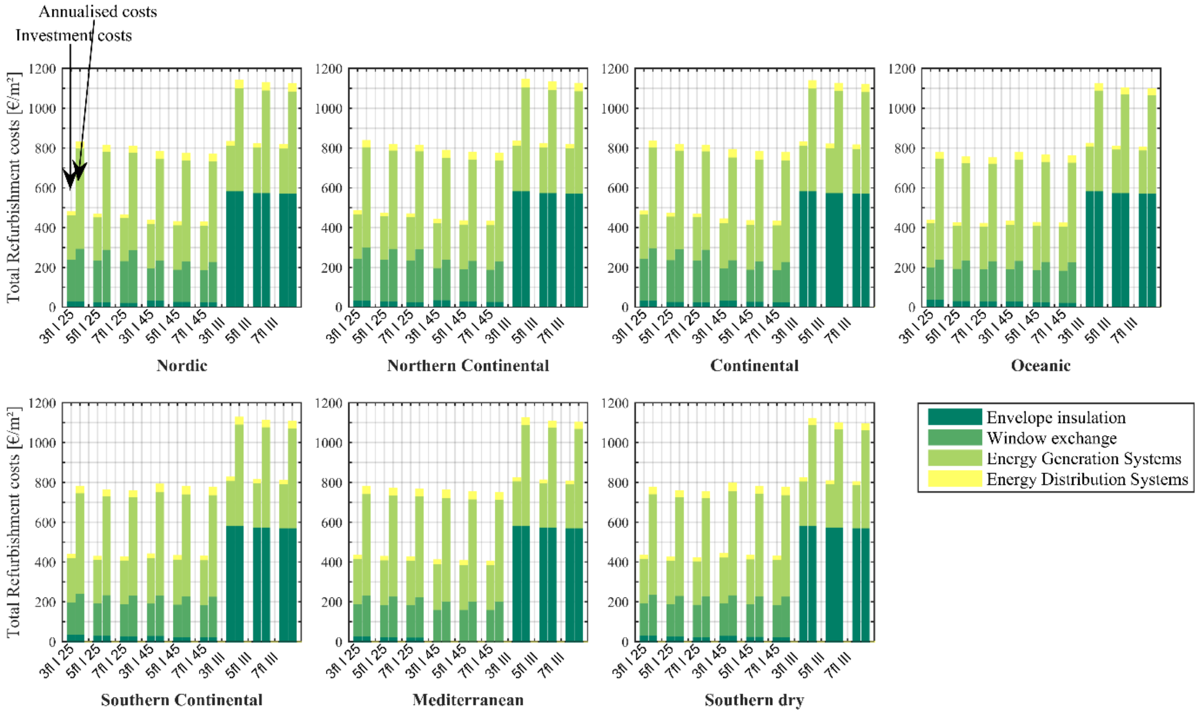


Figure 49 – Investment costs distribution (first year investment and annualised costs over 30 years) for pellet boiler system with fan coils without solar PV, for office buildings with a floor area of 162 m^2 per storey

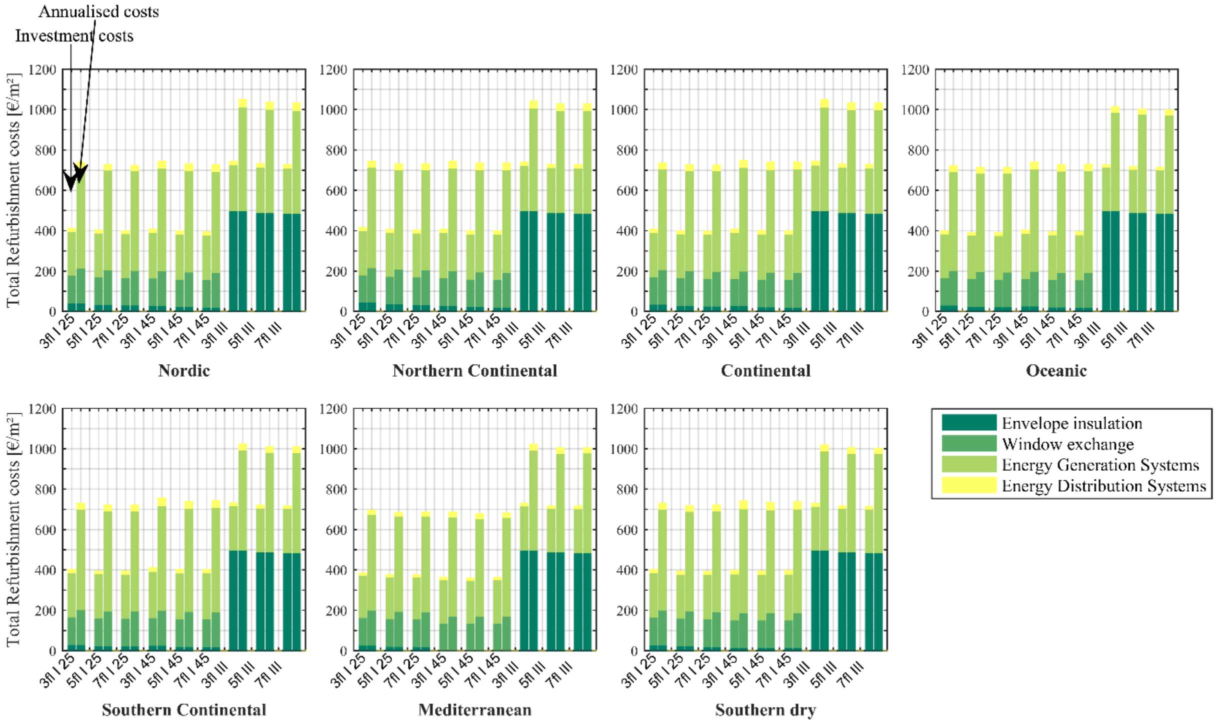


Figure 50 – Investment costs distribution (first year investment and annualised costs over 30 years) for pellet boiler system with fan coils without solar PV, for office buildings with a floor area of 324 m^2 per storey

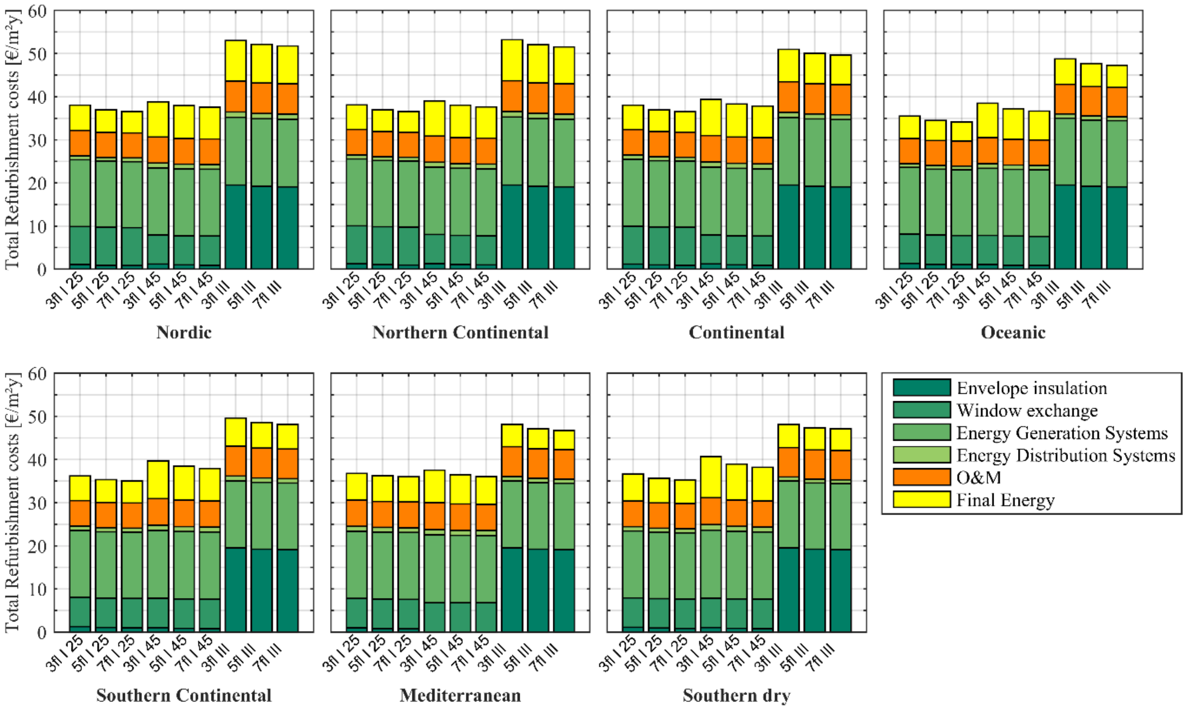


Figure 51 – Distribution of yearly annualised costs for gas boiler system with fan coils for office buildings with a floor area of 162 m² per storey without solar PV systems

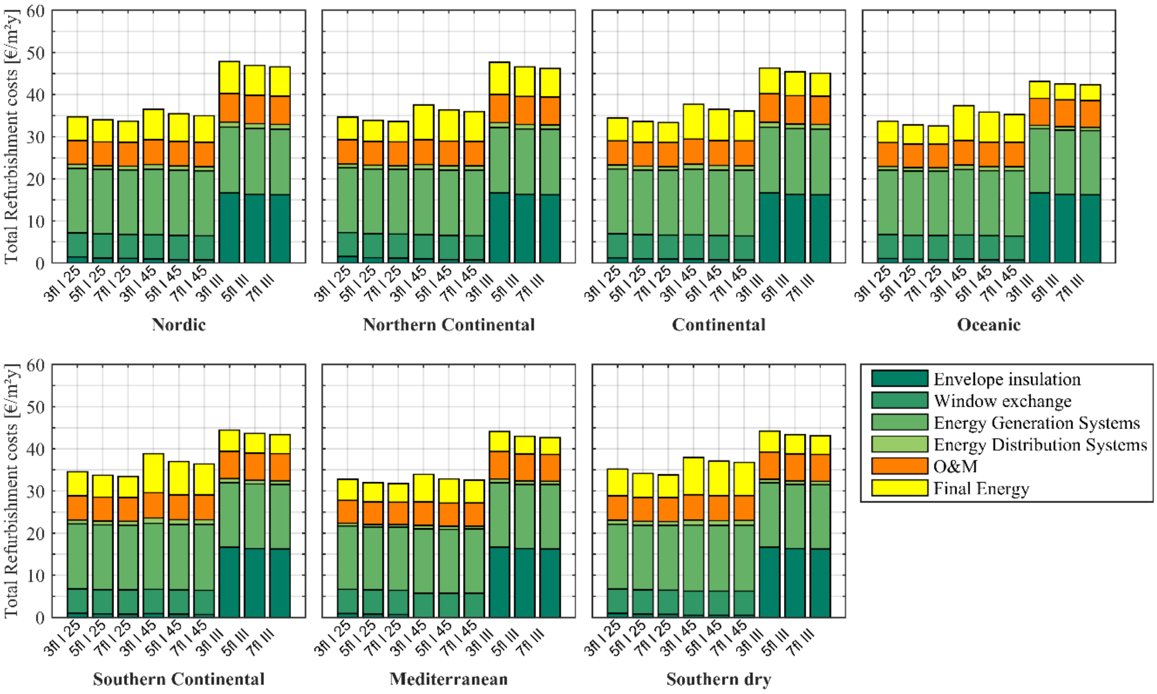


Figure 52 – Distribution of yearly annualised costs for gas boiler system f with fan coils or office buildings with a floor area of 324 m² per storey without solar PV systems

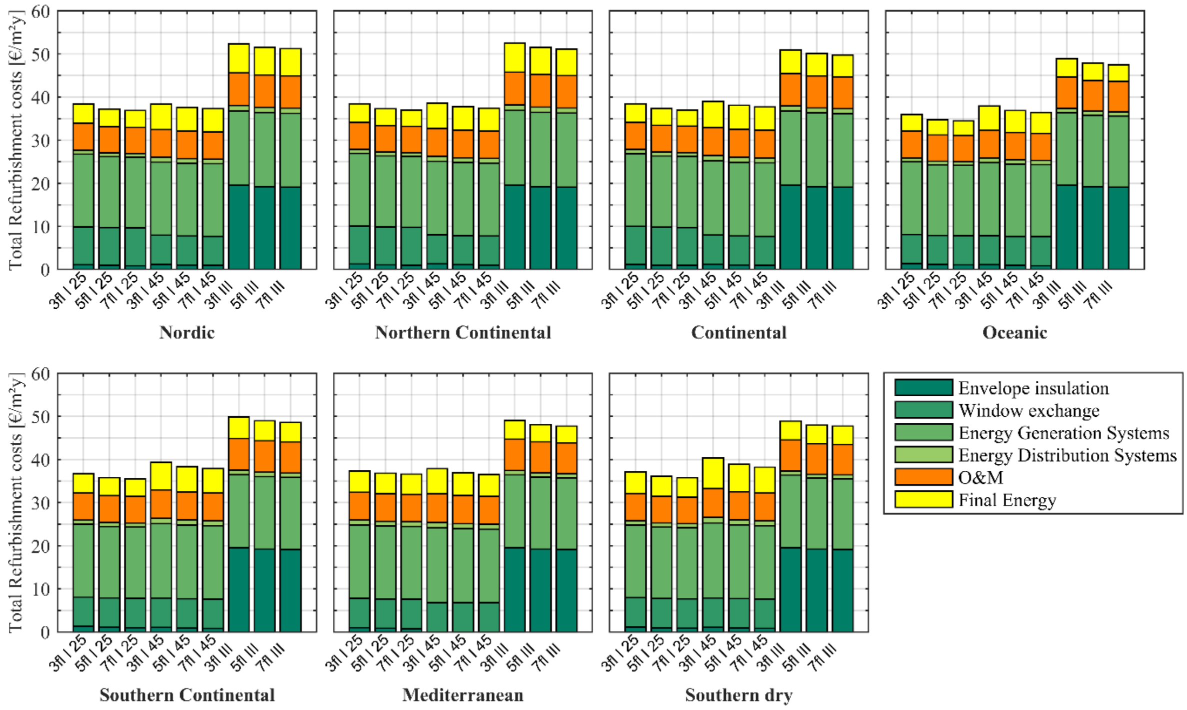


Figure 53 – Distribution of yearly annualised costs for pellet boiler system with fan coils for office buildings with a floor area of 162 m² per storey without solar PV systems

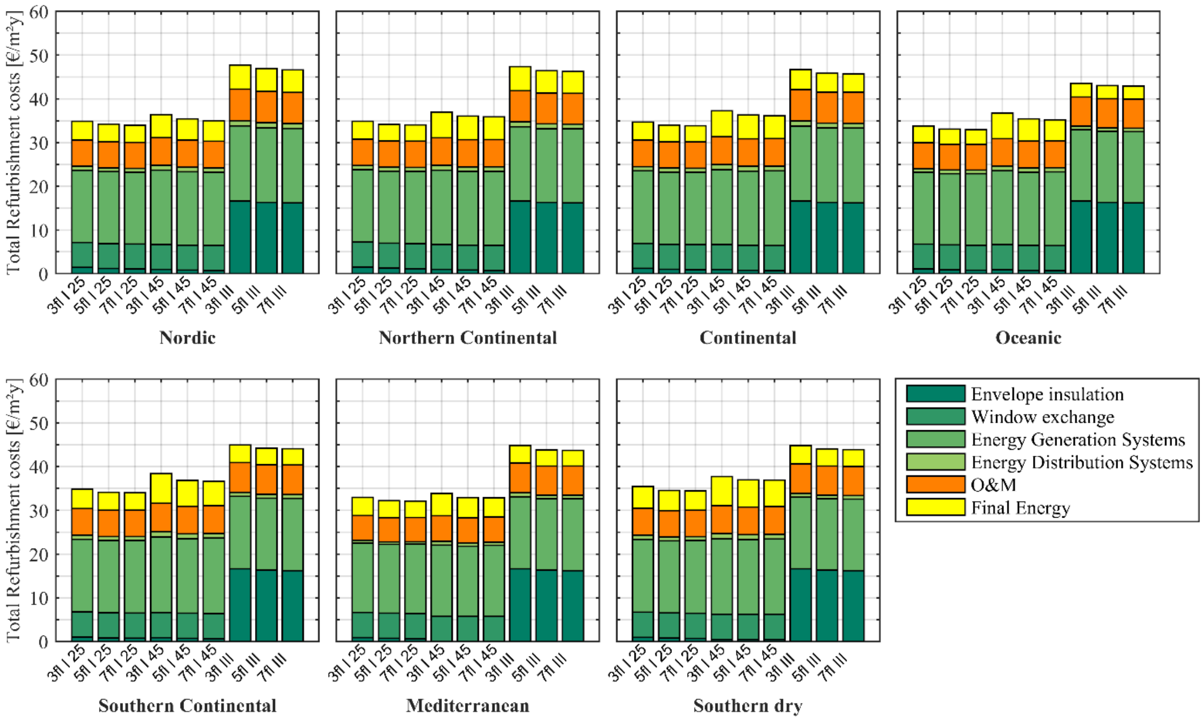


Figure 54 – Distribution of yearly annualised costs for pellet boiler system with fan coils for office buildings with a floor area of 324 m² per storey without solar PV systems

6 Annex I - Simulation results

6.1 Air Source Heat Pump with Radiant Ceilings

6.1.1 Used energy

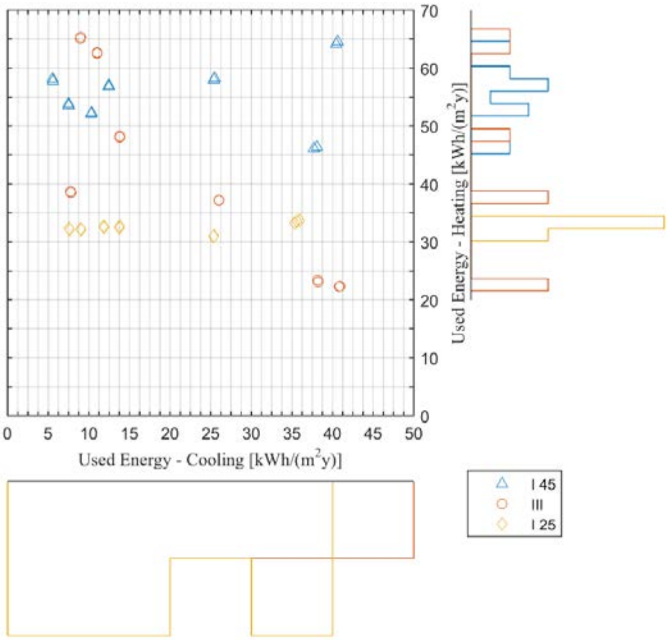


Figure 55 – Used energy for heating and cooling for office buildings with 162 m² per storey and 3 floors

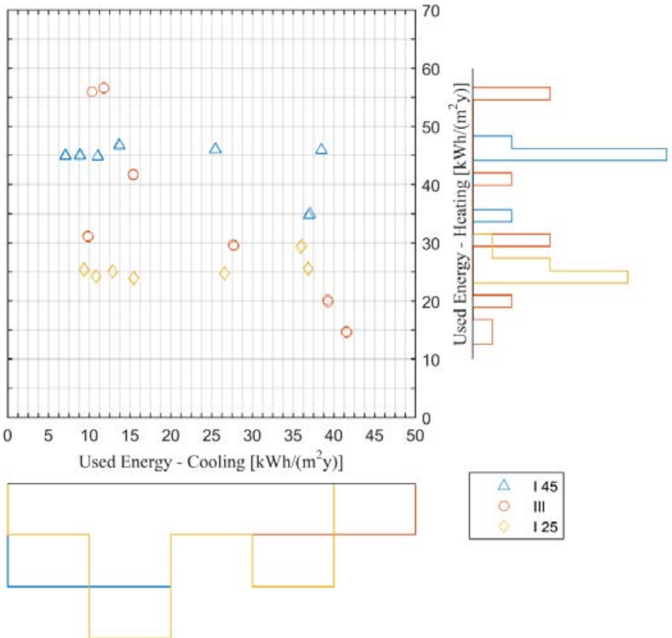


Figure 56 – Used energy for heating and cooling for office buildings with 162 m² per storey and 7 floors

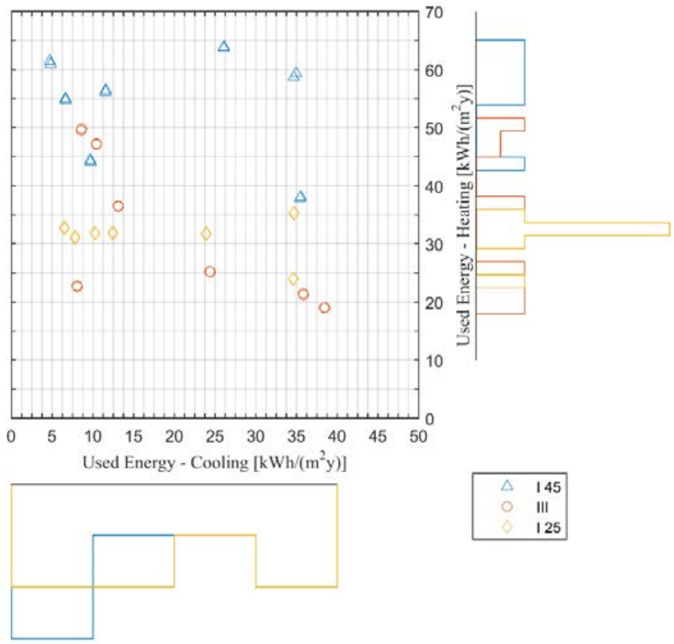


Figure 57 – Used energy for heating and cooling for office buildings with 324 m² per storey and 3 floors

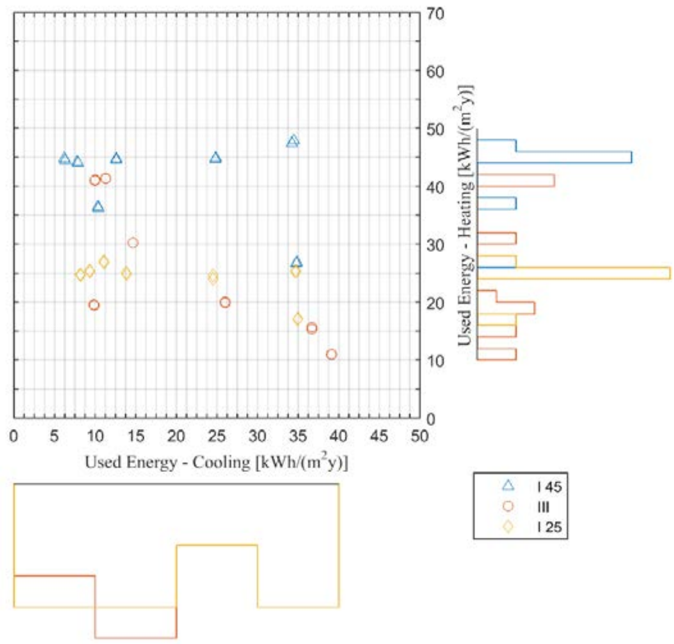


Figure 58 – Used energy for heating and cooling for office buildings with 324 m² per storey and 7 floors

6.1.2 SPF

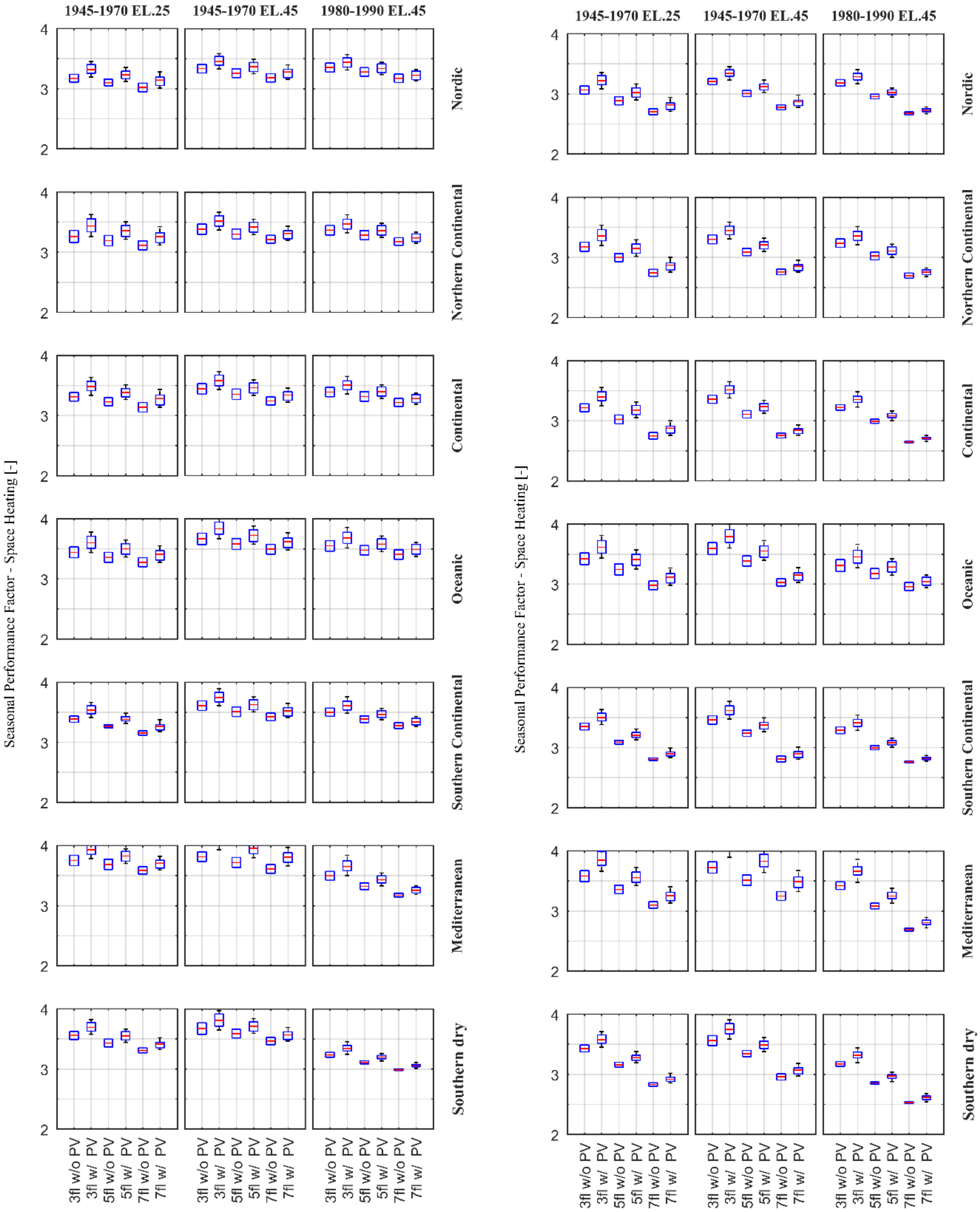


Figure 59 – SPF for heating for office buildings with 162 m² per storey (left) and 324 m² per storey (right)

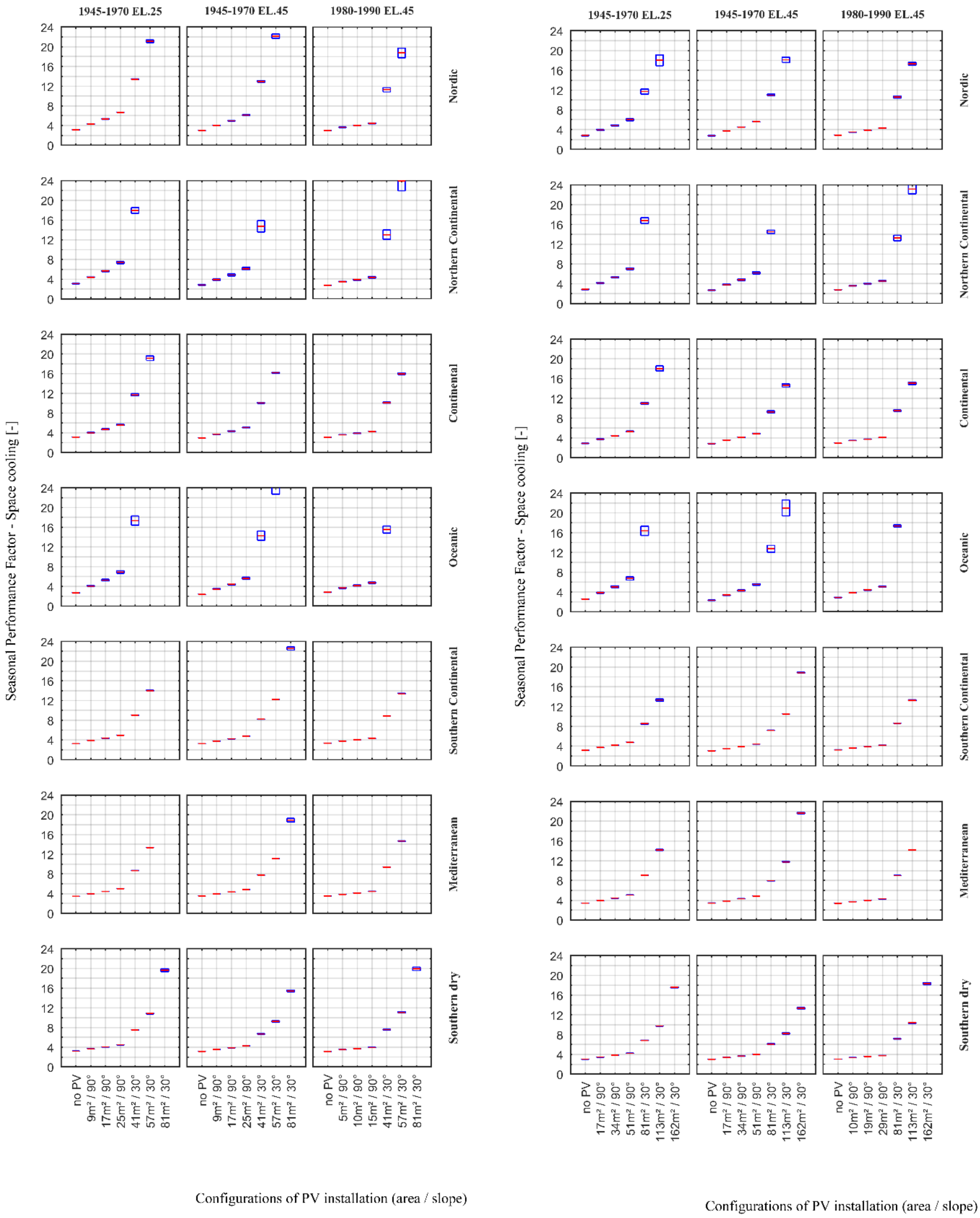


Figure 60 – SPF for cooling for office buildings with 3 floors: 162 m² per storey (left) and 324 m² per storey (right)

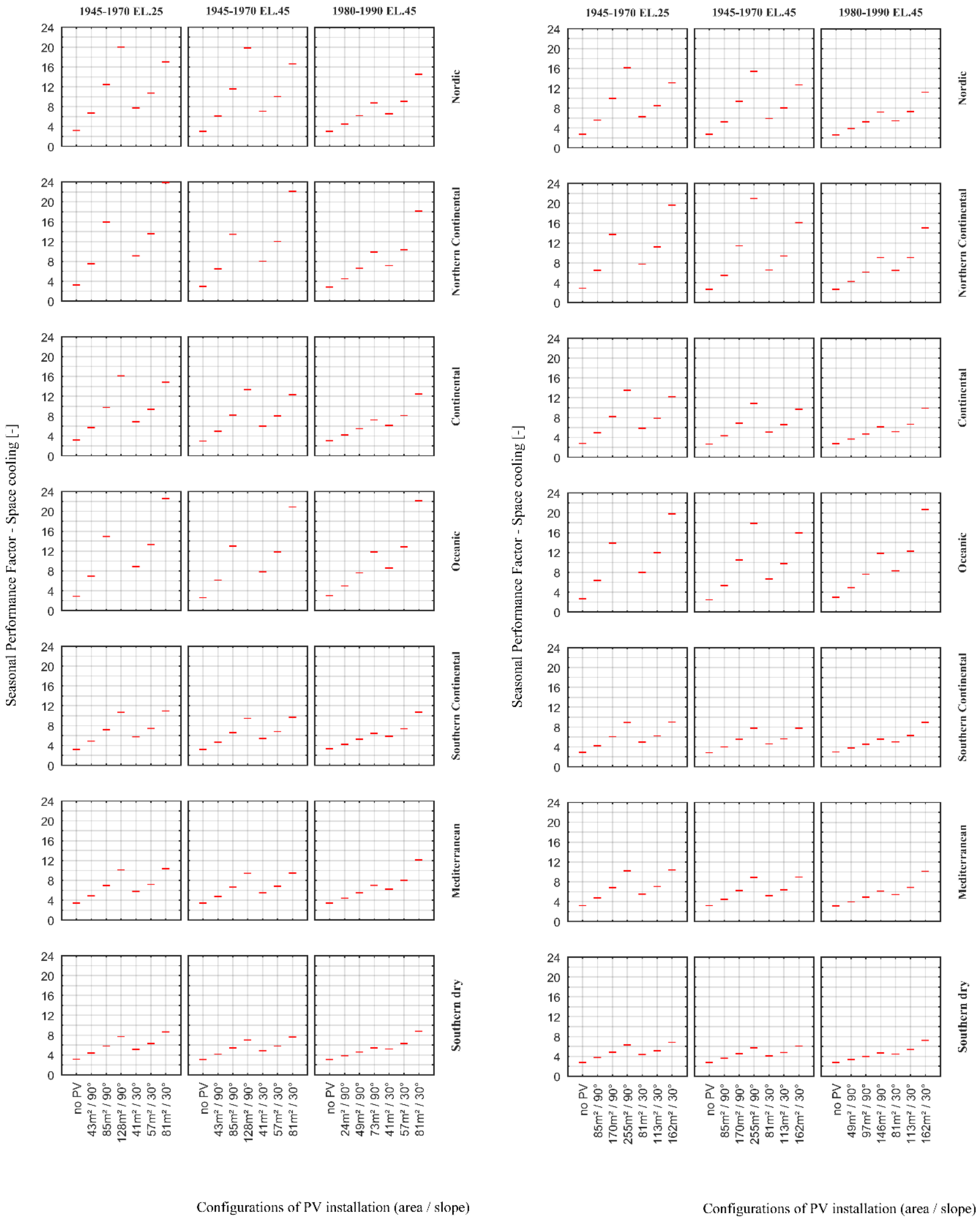


Figure 61 – SPF for cooling for office buildings with 5 floors: 162 m² per storey (left) and 324 m² per storey (right)

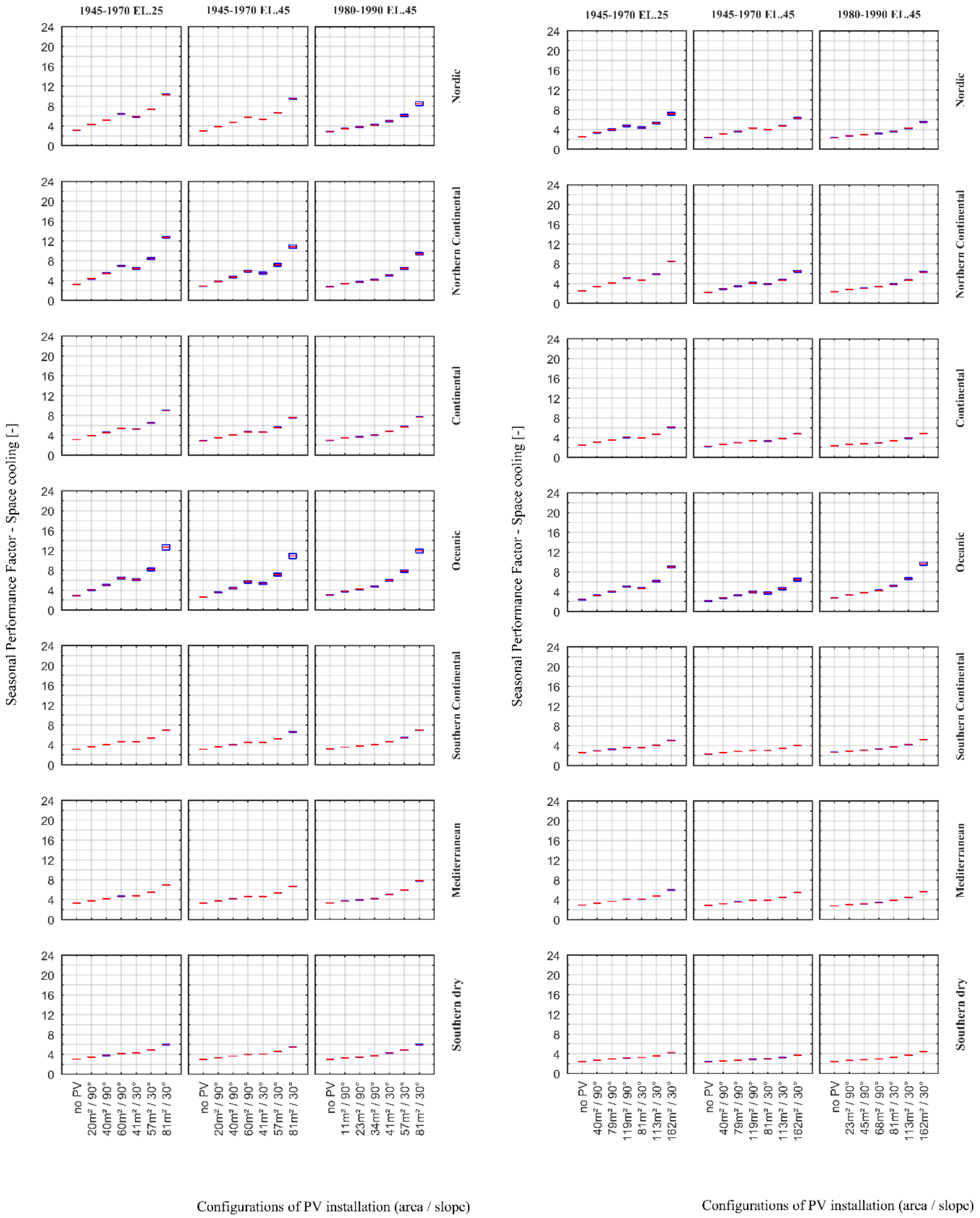


Figure 62 – SPF for cooling for office buildings with 7 floors: 162 m² per storey (left) and 324 m² per storey (right)

6.1.3 Solar PV energy utilisation

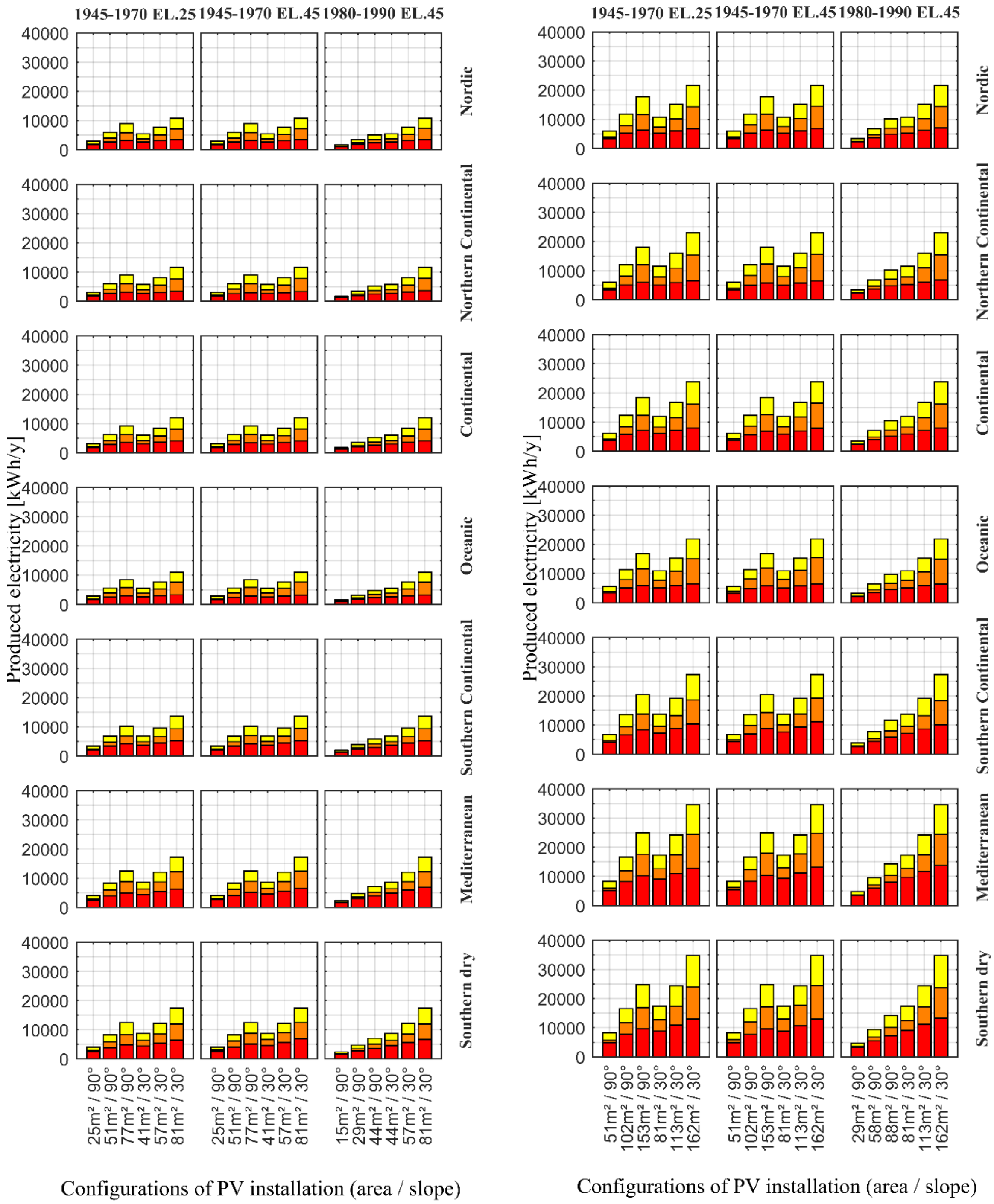


Figure 63 - Self-consumption and PV electricity to grid for office buildings with 3 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

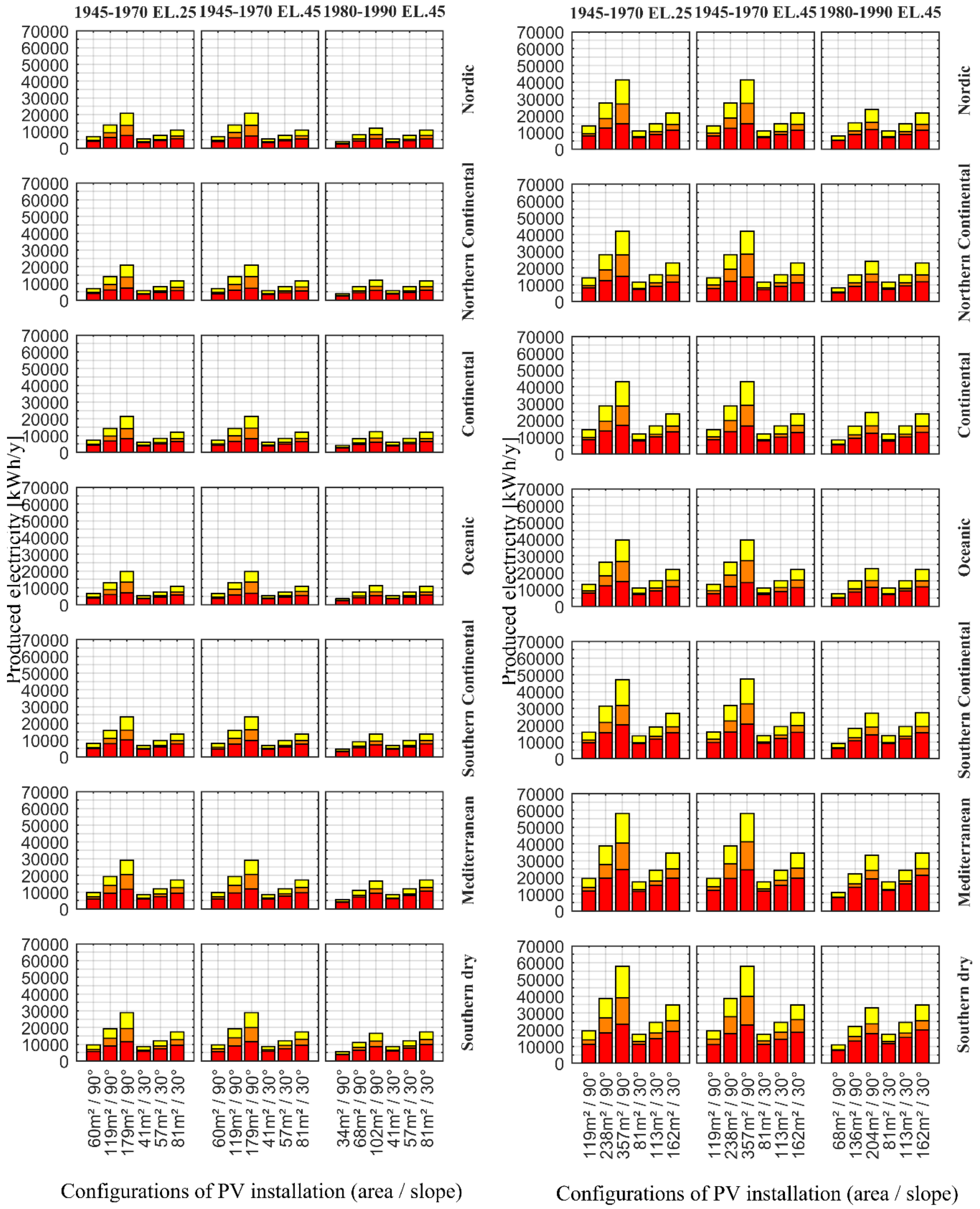


Figure 64 – Self-consumption and PV electricity to grid for office buildings with 7 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

6.2 Air Source Heat Pump with Fan Coils

6.2.1 Used energy

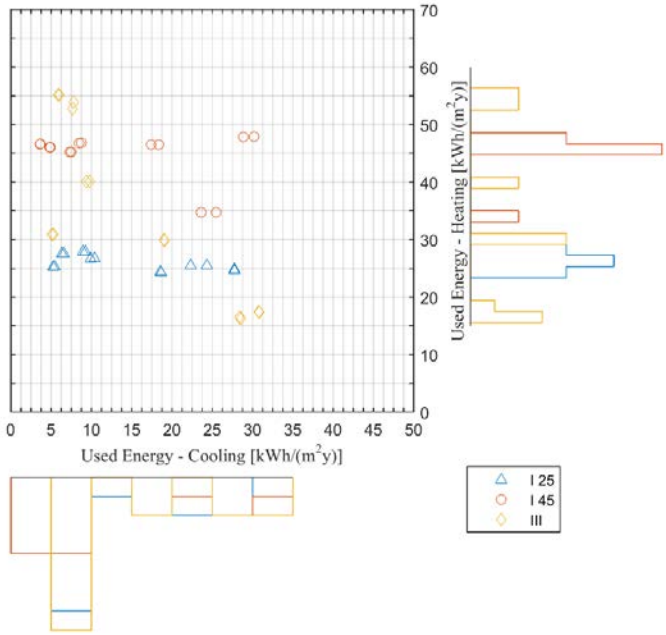


Figure 65 - Used energy for heating and cooling for office buildings with 162 m² per storey and 3 floors

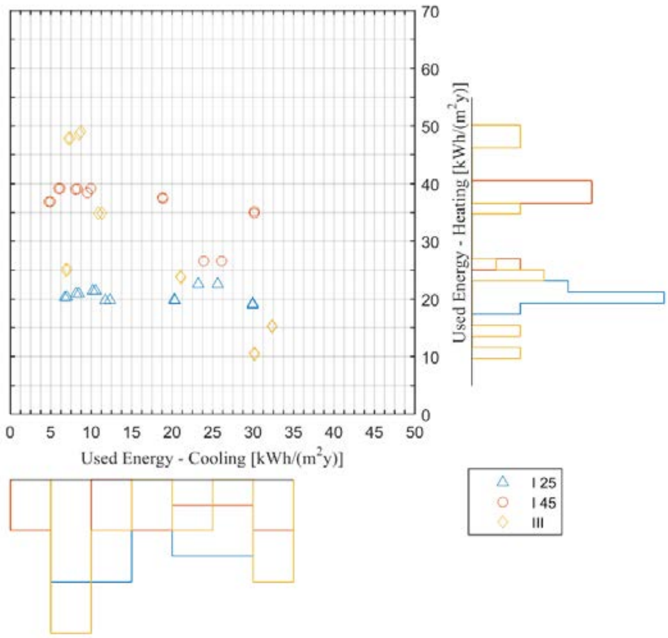


Figure 66 – Used energy for heating and cooling for office buildings with 162 m² per storey and 7 floors

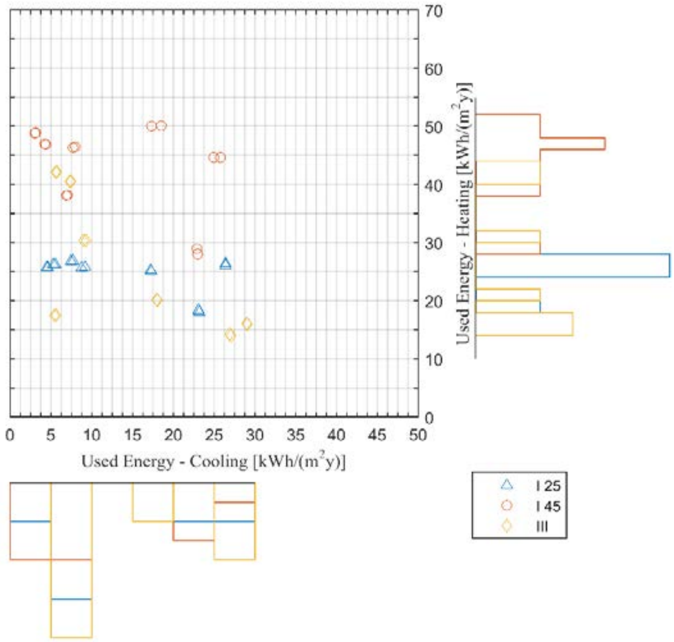


Figure 67 – Used energy for heating and cooling for office buildings with 324 m^2 per storey and 3 floors

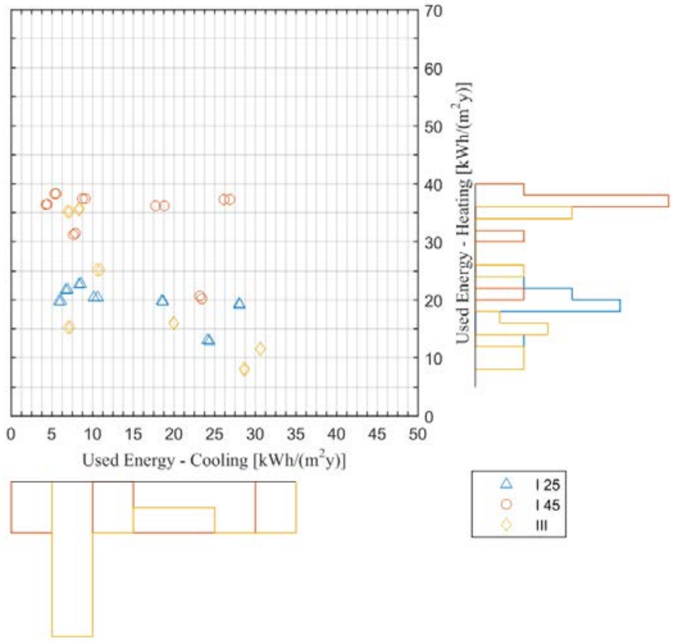


Figure 68 – Used energy for heating and cooling for office buildings with 324 m^2 per storey and 7 floors

6.2.2 SPF

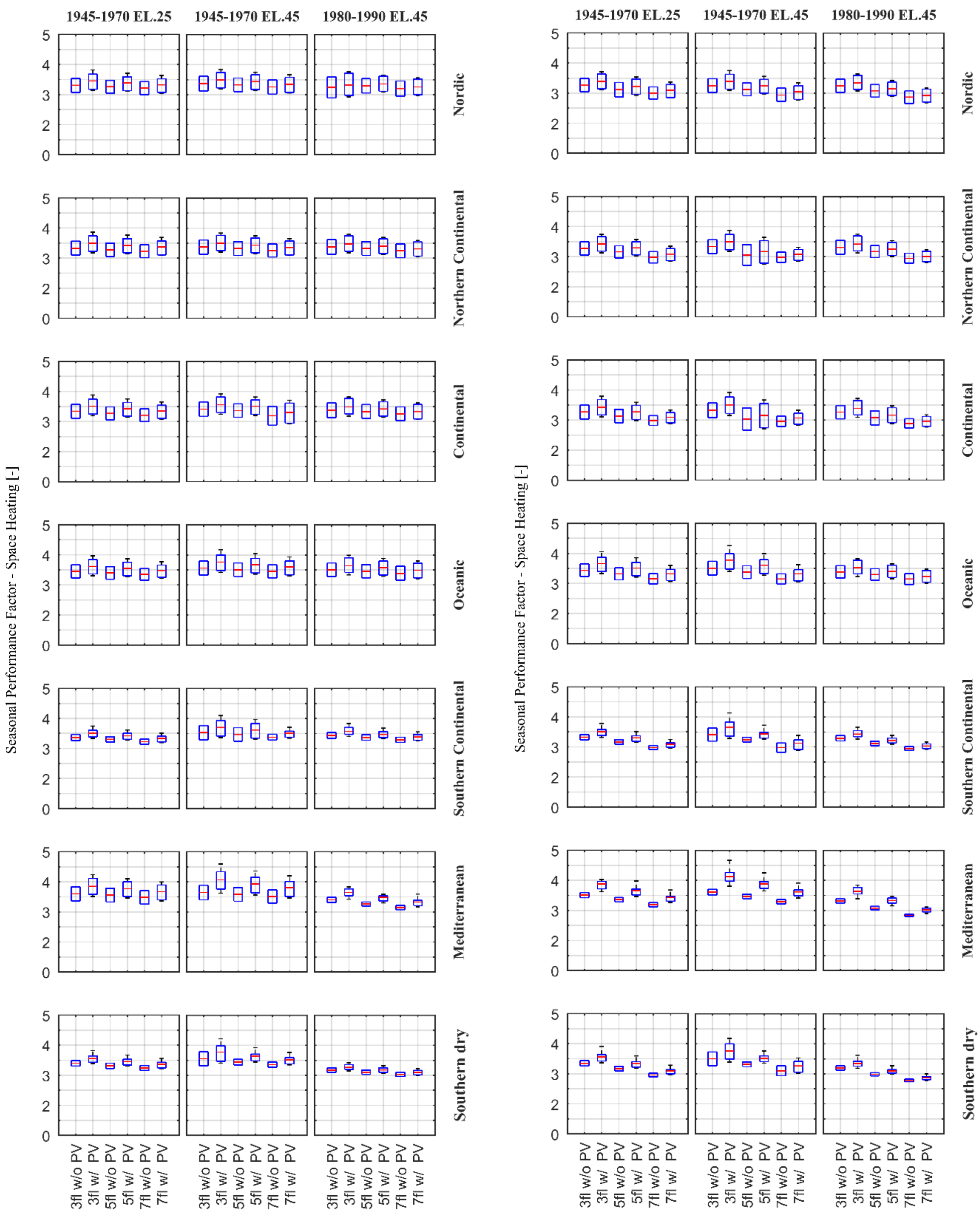


Figure 69 – SPF for heating for office buildings with 162 m^2 per storey (left) and 324 m^2 per storey (right)

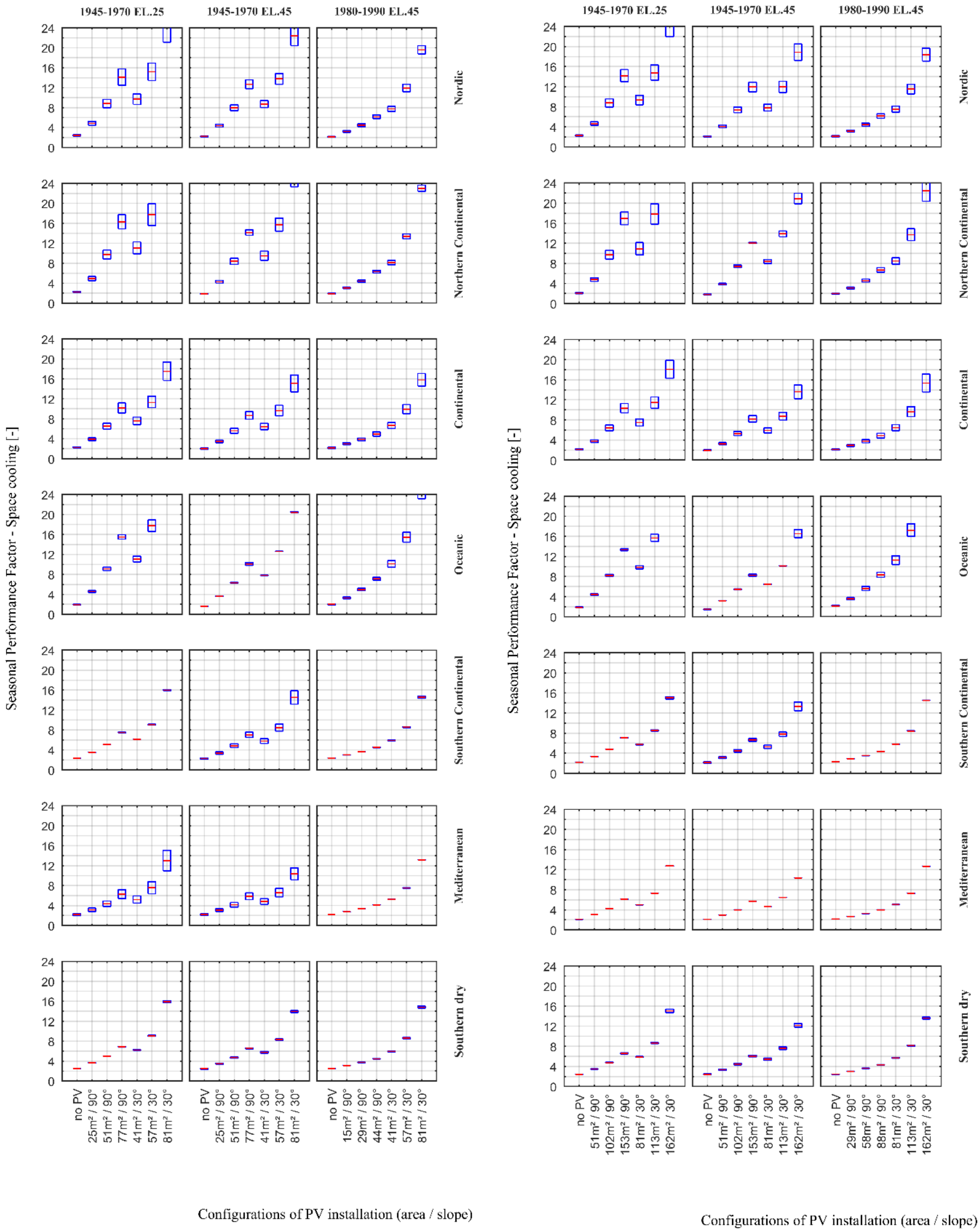


Figure 70 – SPF for cooling for office buildings with 3 floors: 162 m² per storey (left) and 324 m² per storey (right)

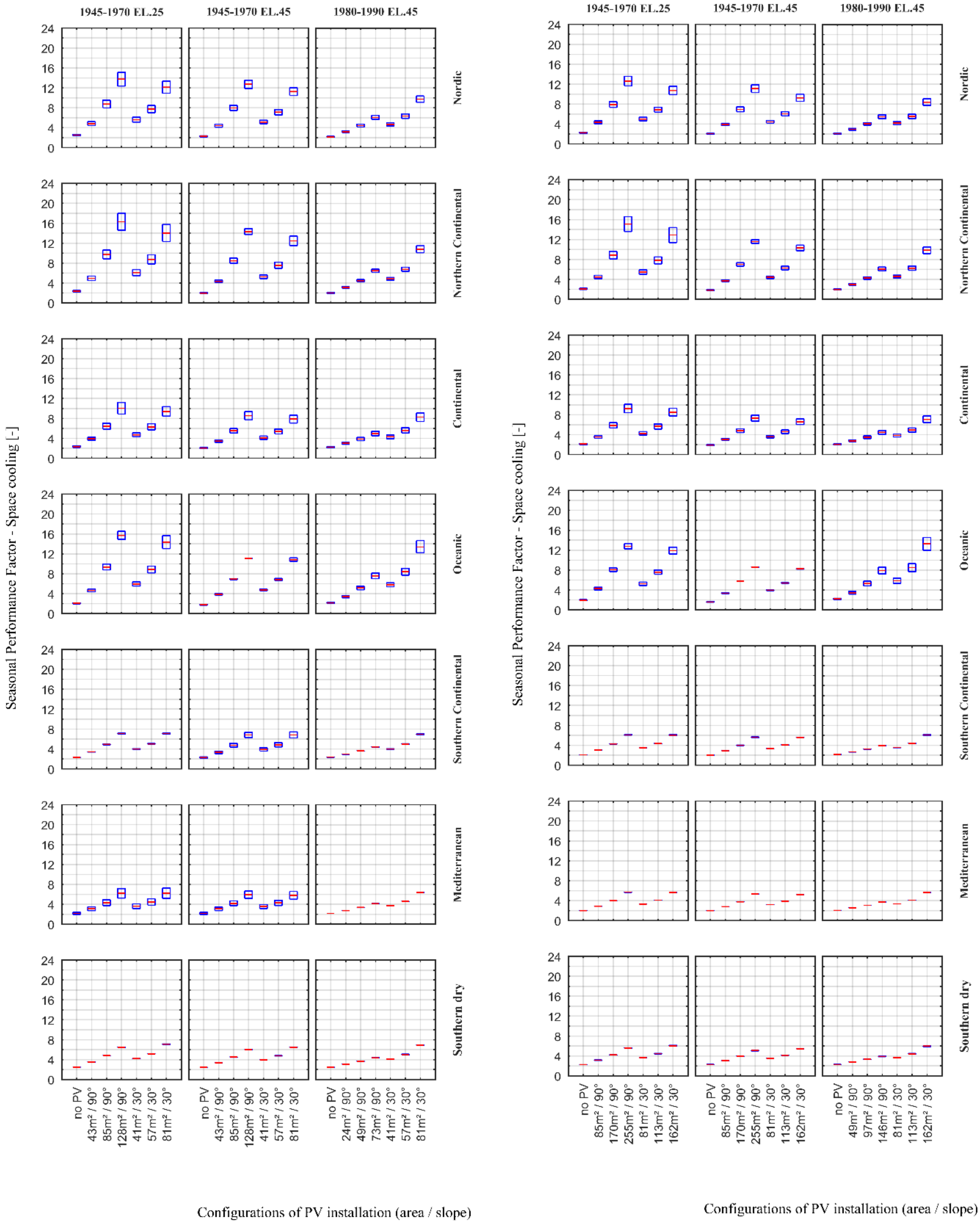


Figure 71 – SPF for cooling for office buildings with 5 floors: 162 m² per storey (left) and 324 m² per storey (right)

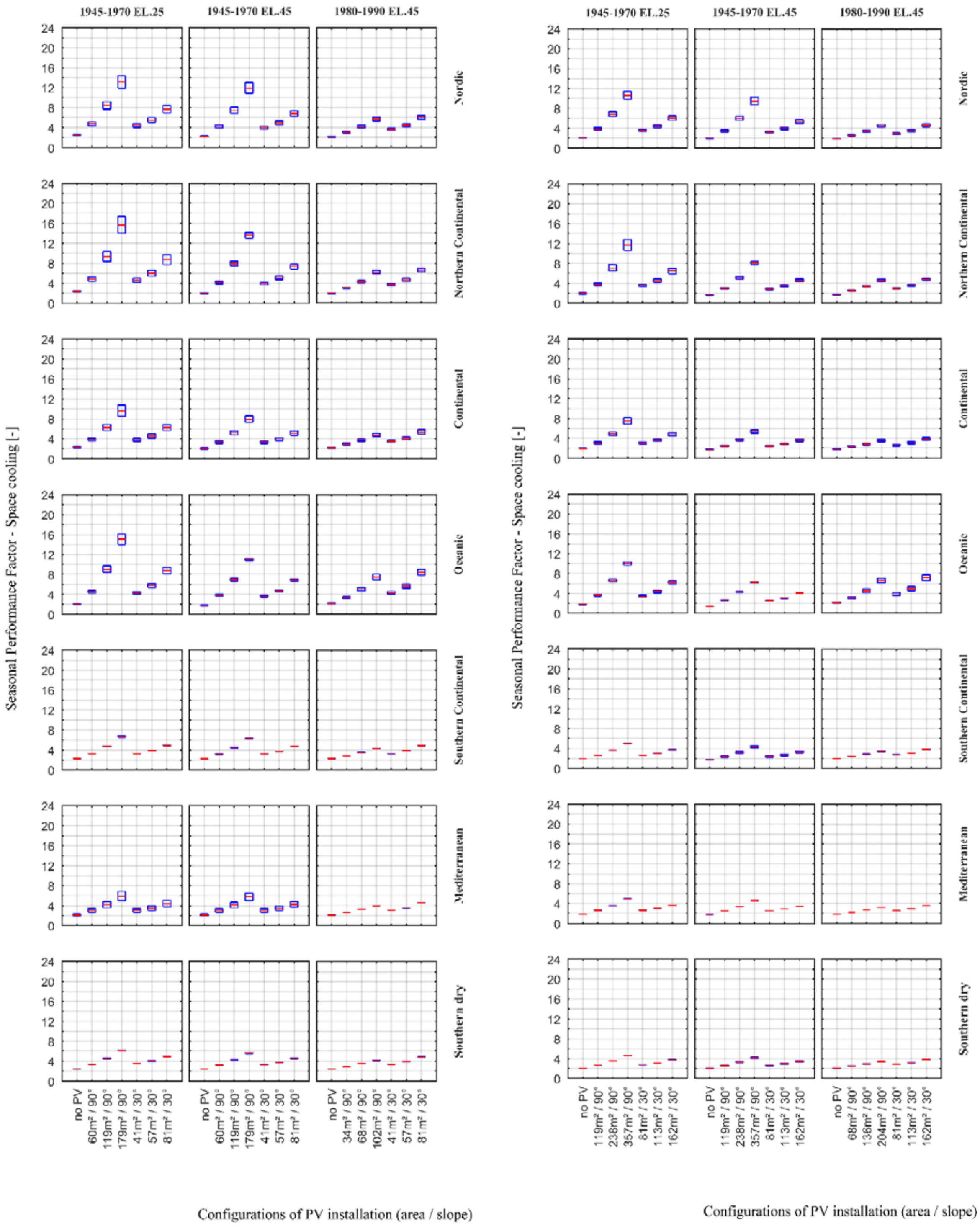
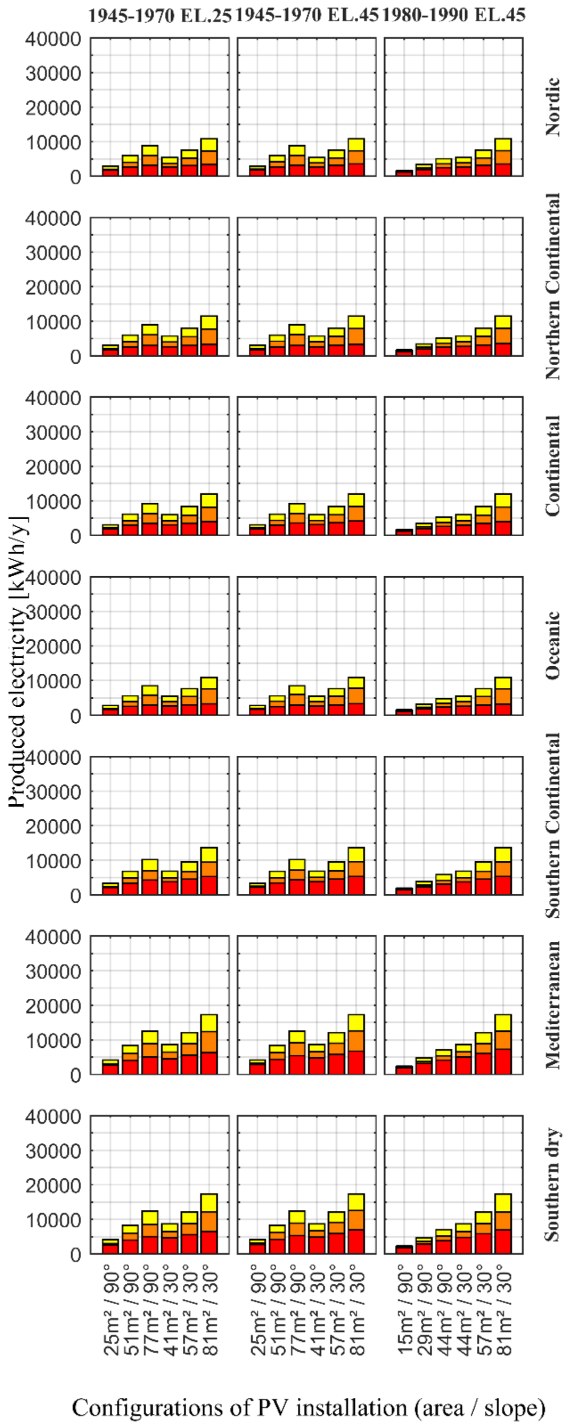


Figure 72 – SPF for cooling for office buildings with 7 floors: 162 m² per storey (left) and 324 m² per storey (right)

6.2.3 Solar PV energy utilisation



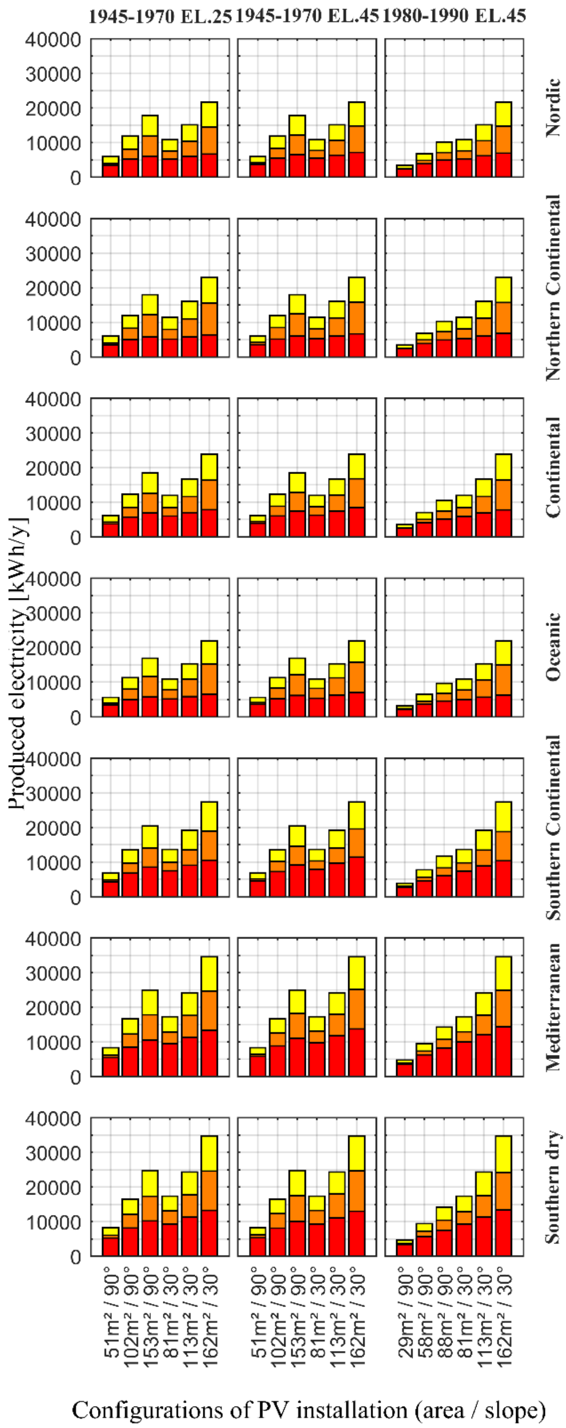


Figure 73 - Self-consumption and PV electricity to grid for office buildings with 3 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

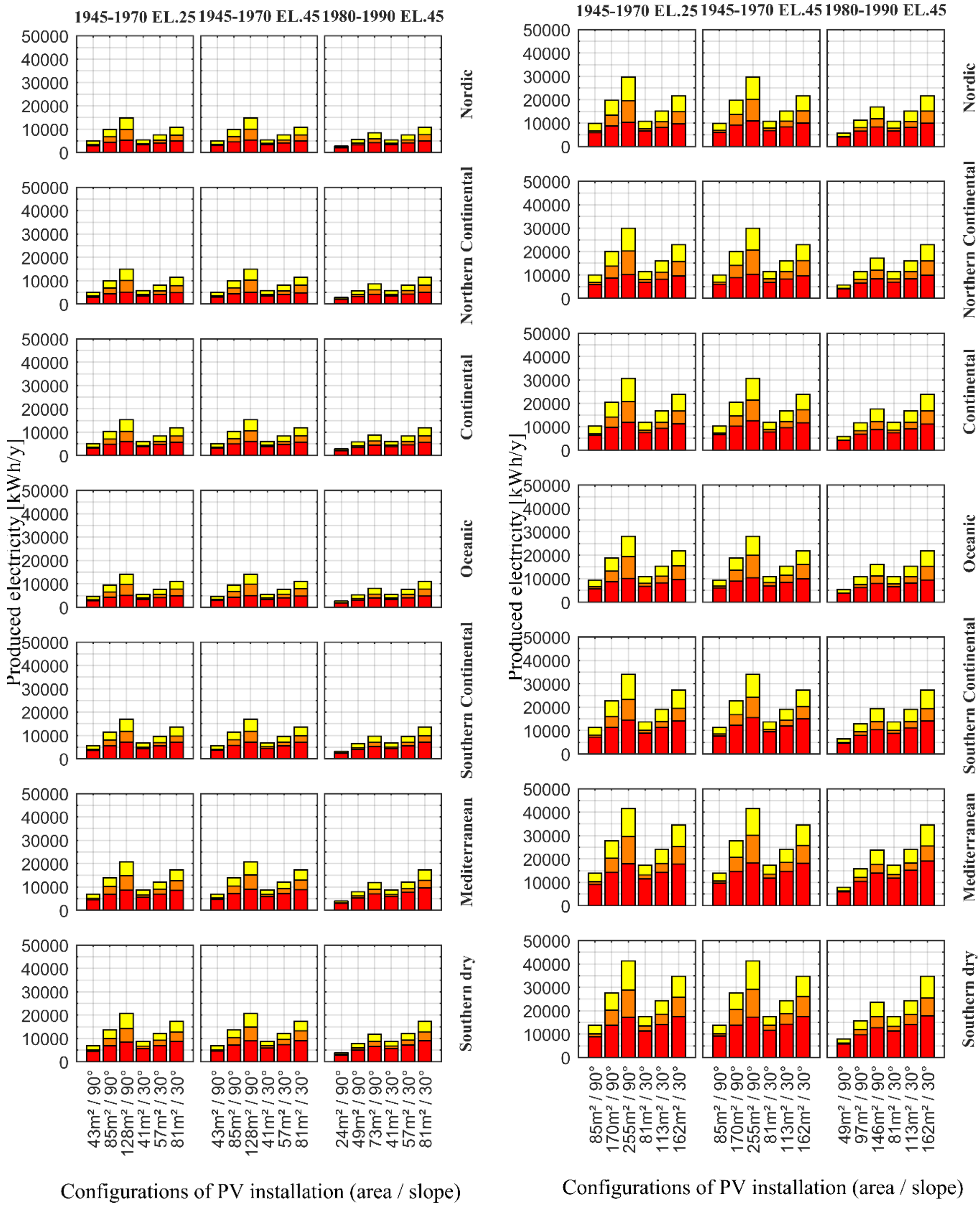


Figure 74 - Self-consumption and PV electricity to grid for office buildings with 5 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

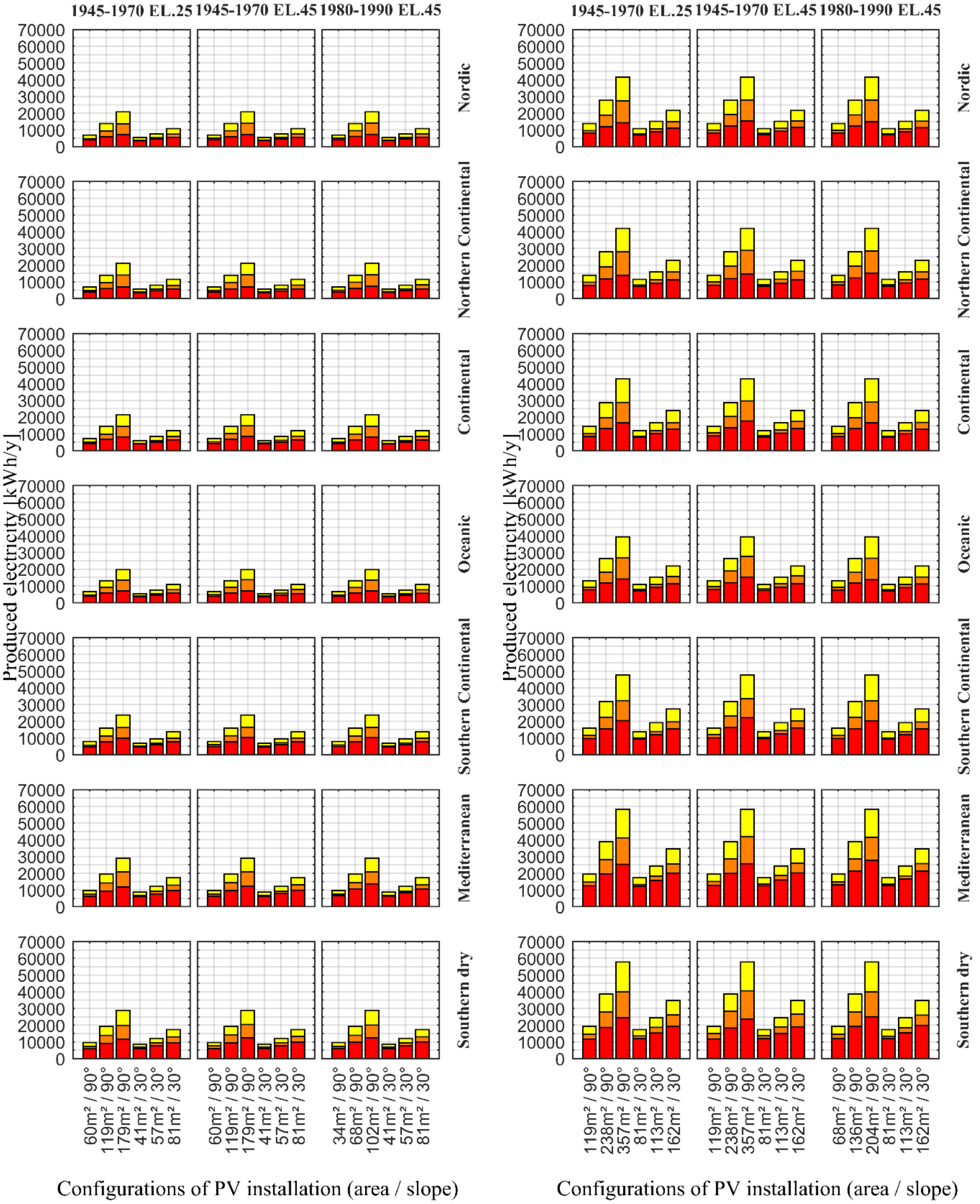


Figure 75 – Self-consumption and PV electricity to grid for office buildings with 7 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

6.3 Gas/Pellet Boiler with Radiant Ceiling Panels

6.3.1 Used energy

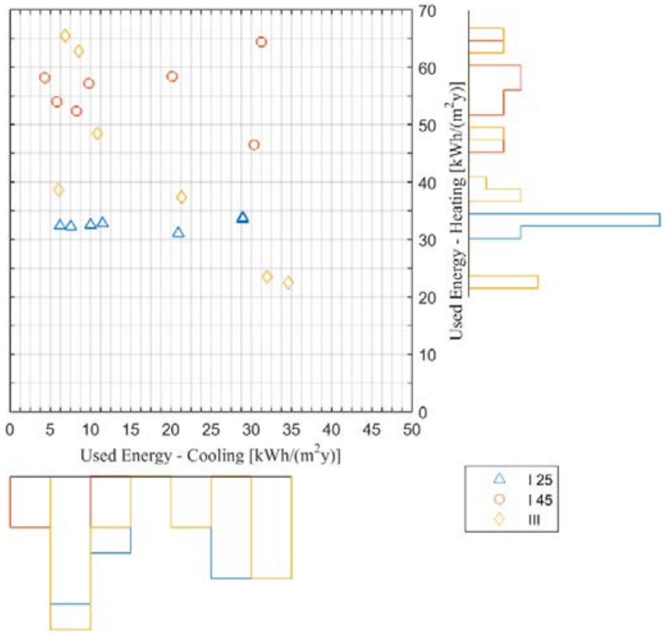


Figure 76 - Used energy for heating and cooling for office buildings with 162 m² per storey and 3 floors

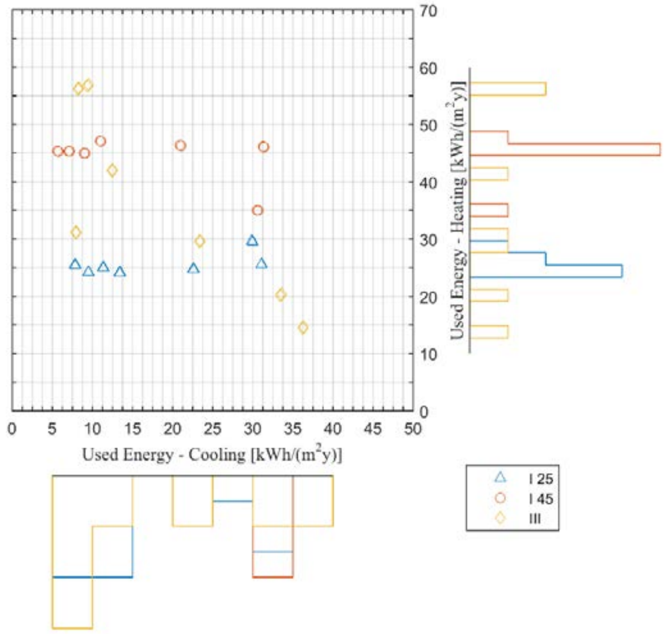


Figure 77 - Used energy for heating and cooling for office buildings with 162 m² per storey and 7 floors

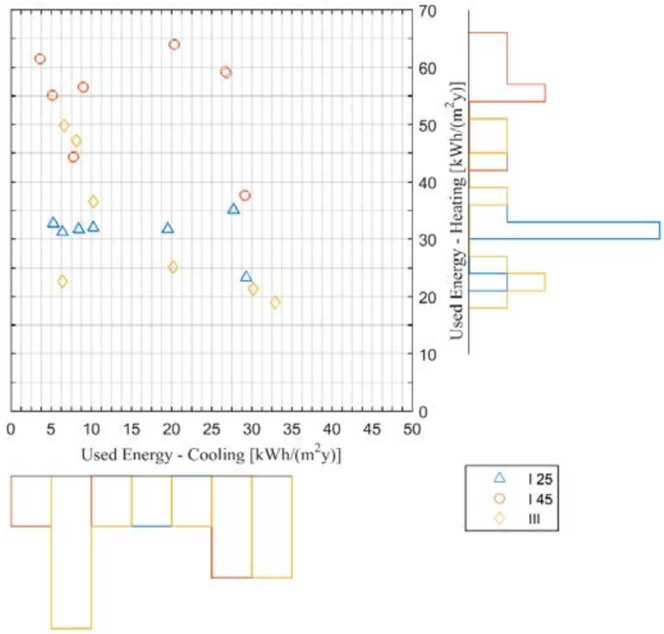


Figure 78 - Used energy for heating and cooling for office buildings with 324 m² per storey and 3 floors

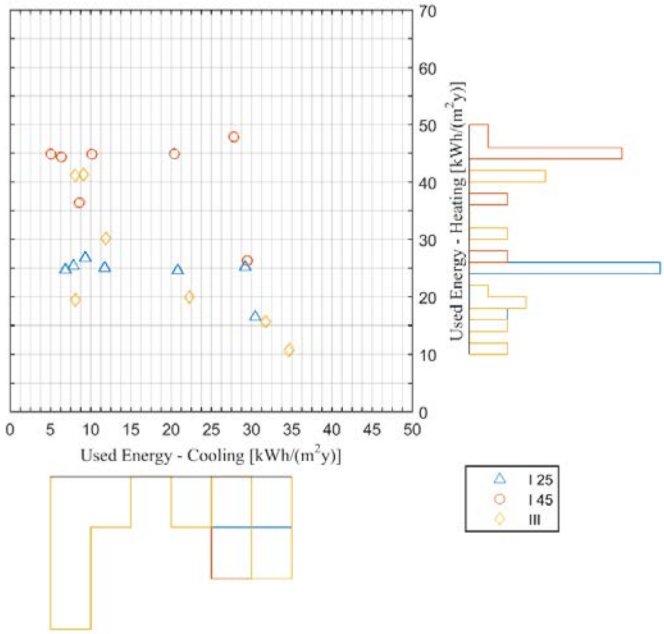


Figure 79 - Used energy for heating and cooling for office buildings with 162 m² per storey and 3 floors

6.3.2 Solar PV energy utilisation

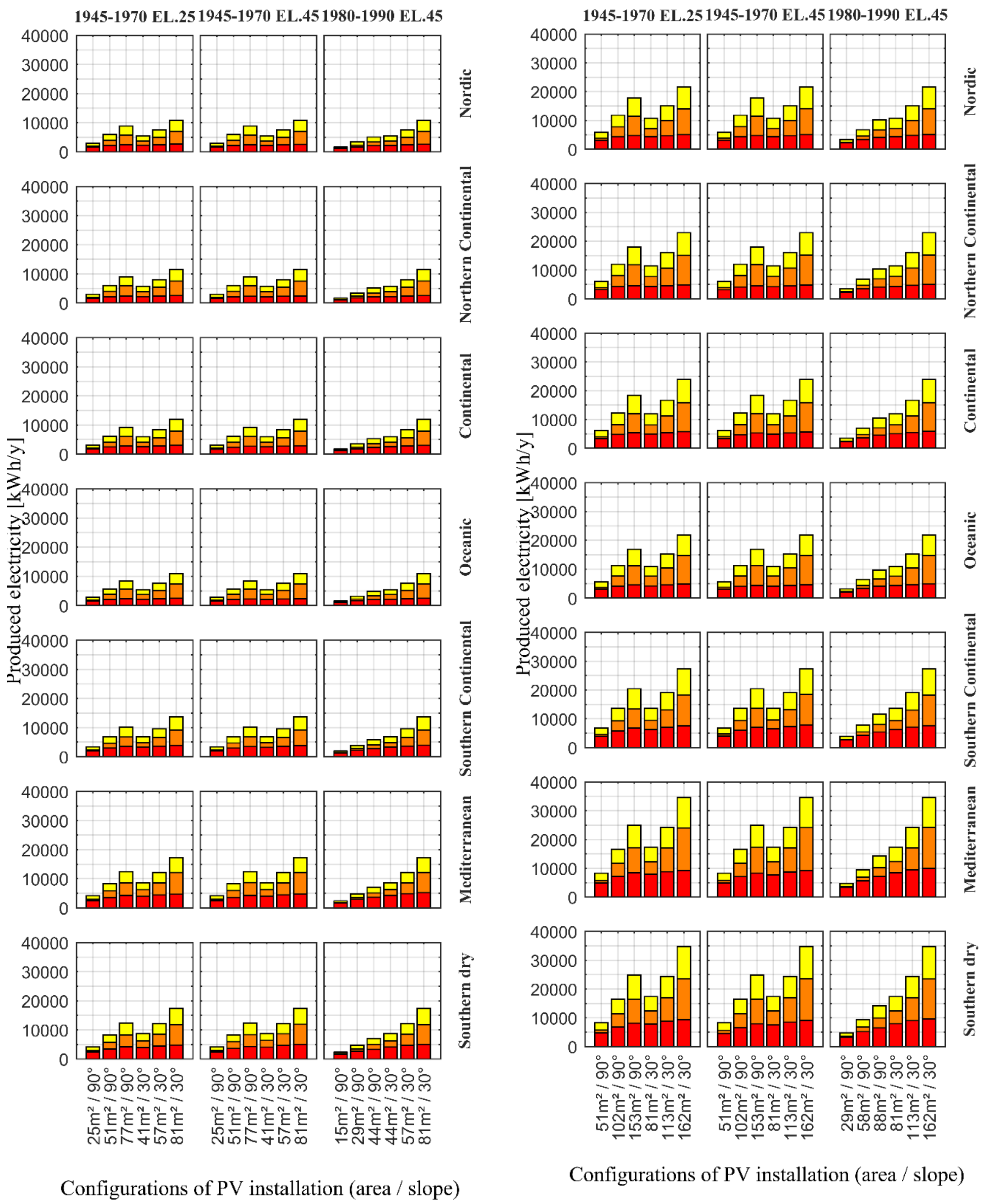


Figure 80 – Self-consumption and PV electricity to grid for office buildings with 3 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

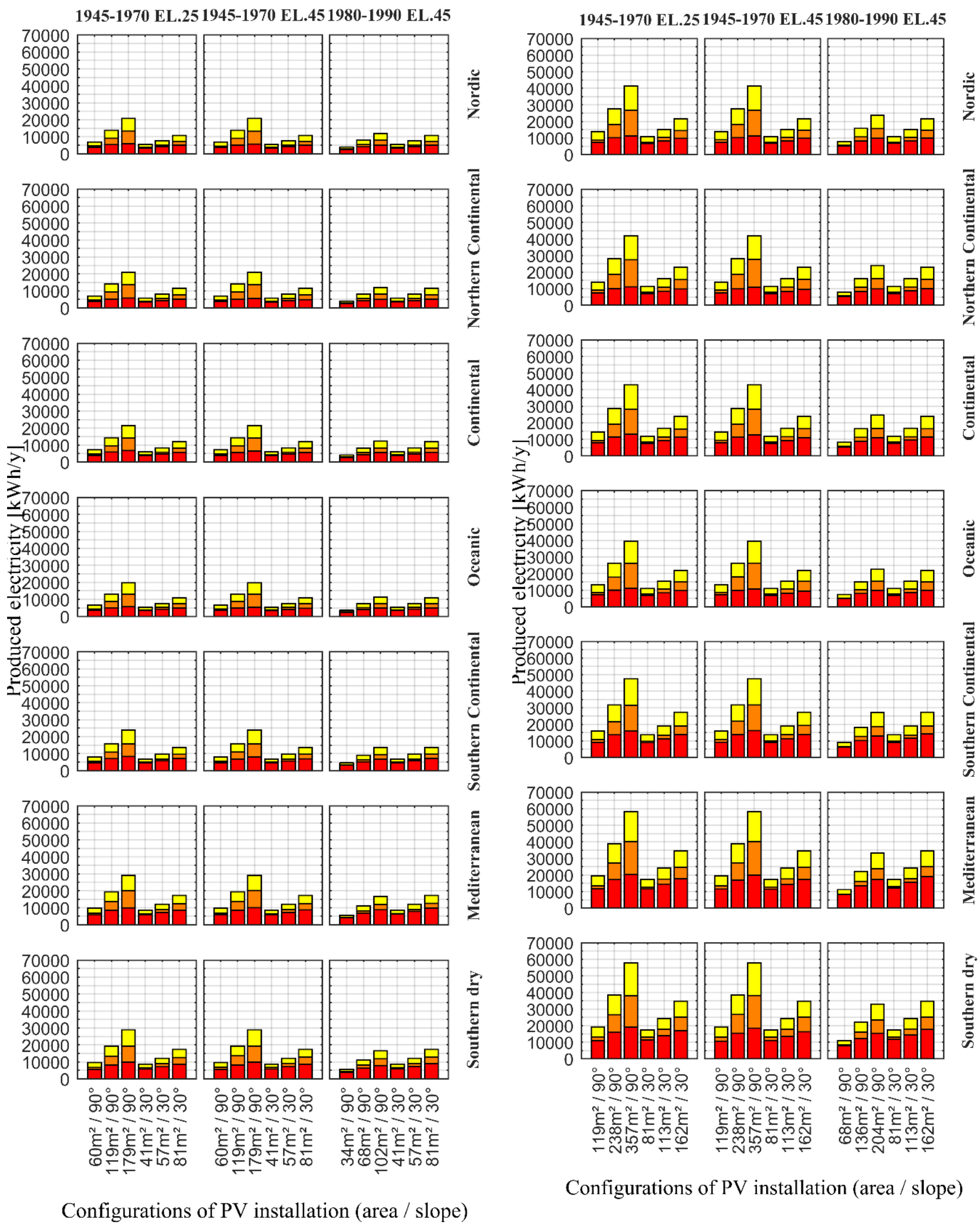


Figure 81 – Self-consumption and PV electricity to grid for office buildings with 7 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

6.4 Gas/Pellet Boiler with Fan Coils

6.4.1 Used energy

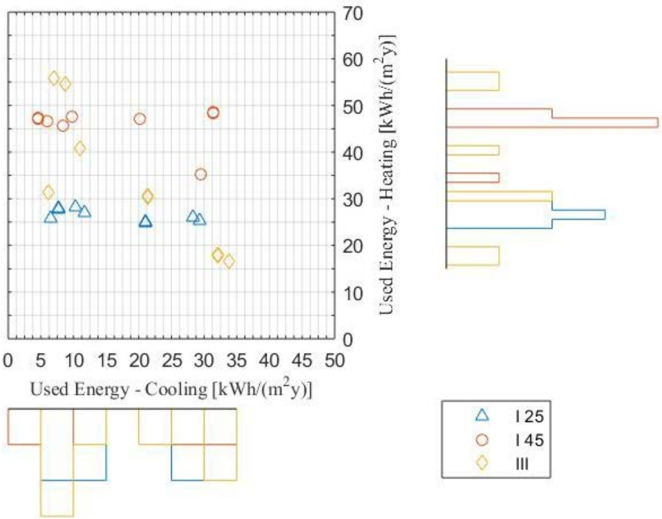


Figure 82 - Used energy for heating and cooling for office buildings with 162 m² per storey and 3 floors

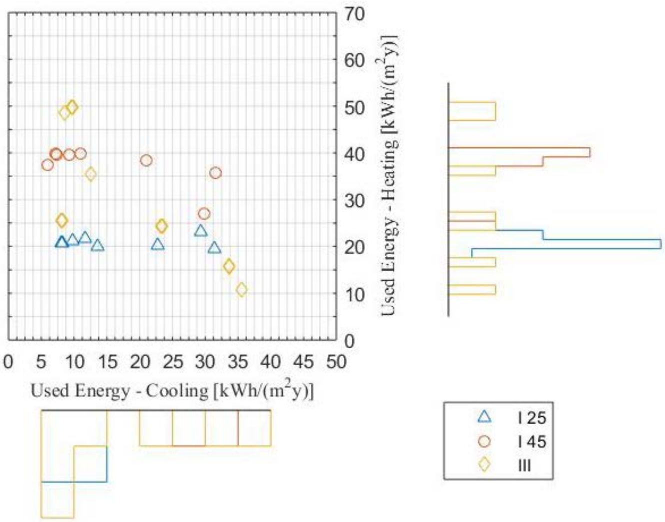


Figure 83 - Used energy for heating and cooling for office buildings with 162 m² per storey and 7 floors

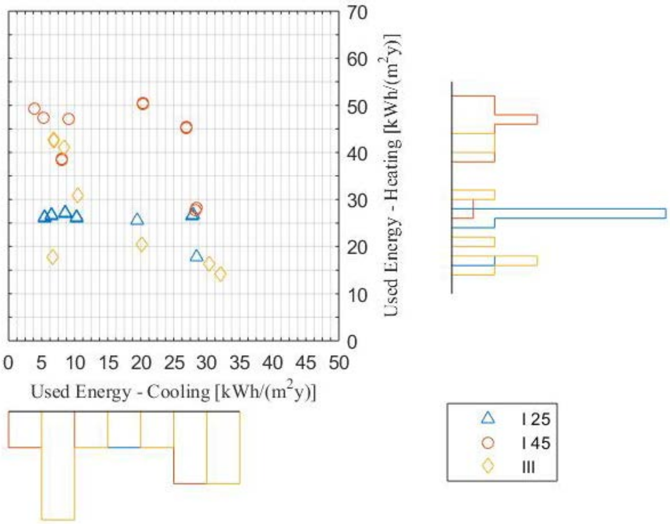


Figure 84 - Used energy for heating and cooling for office buildings with 324 m² per storey and 3 floors

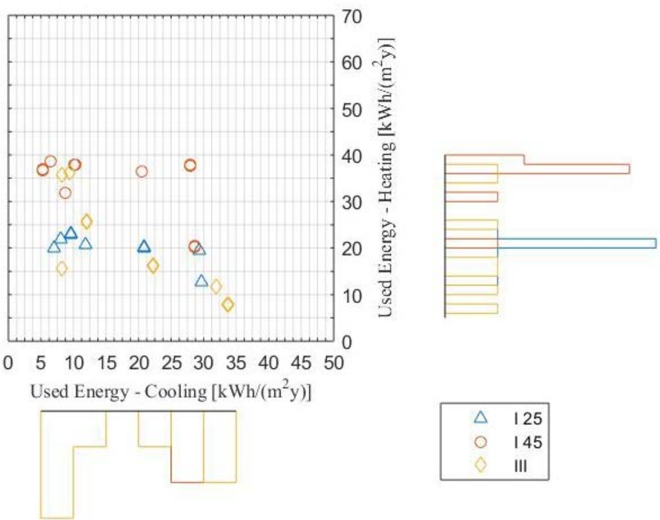


Figure 85 - Used energy for heating and cooling for office buildings with 324 m² per storey and 7 floors

6.4.2 Solar PV energy utilisation

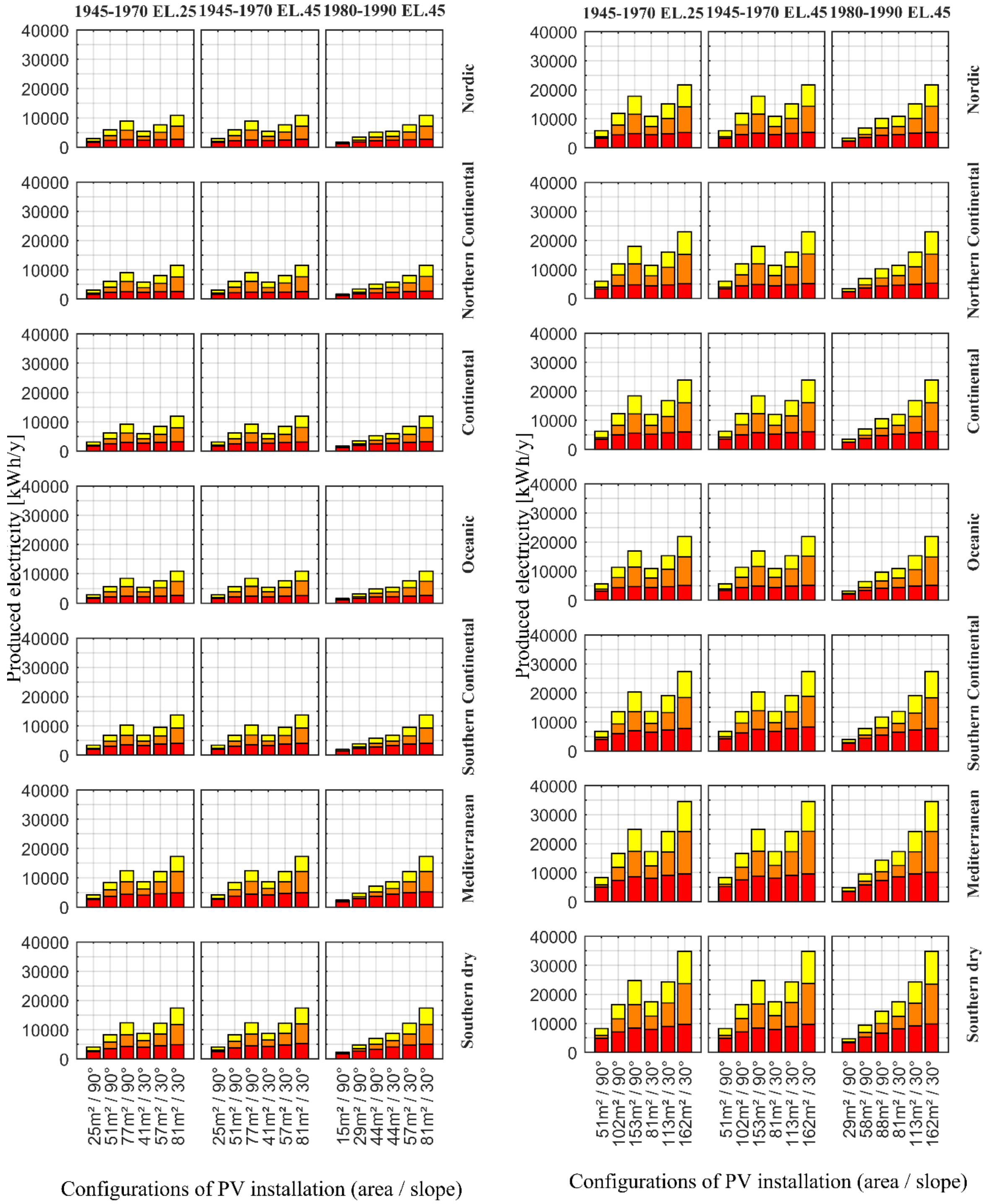


Figure 86 – Self-consumption and PV electricity to grid for office buildings with 3 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

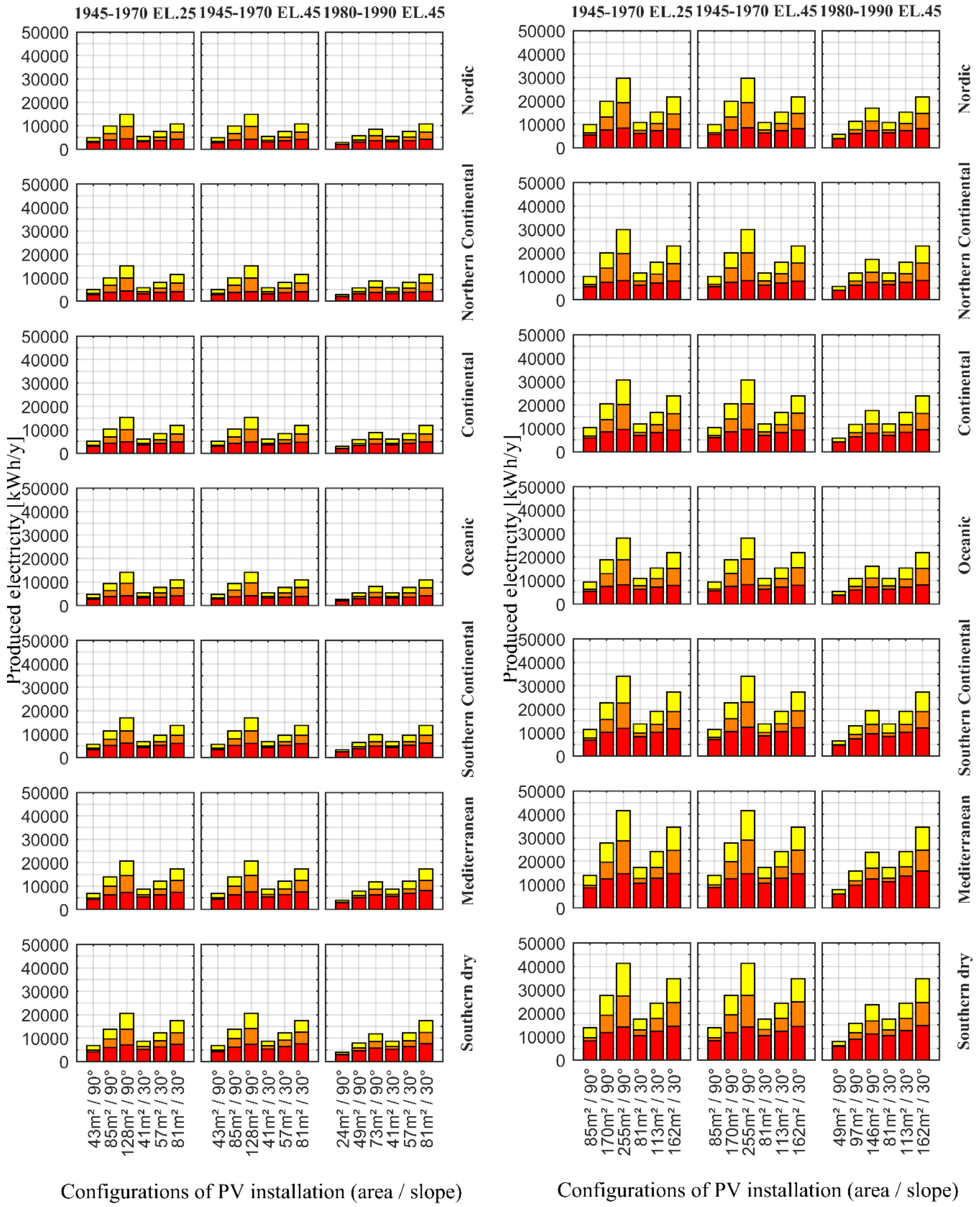


Figure 87 – Self-consumption and PV electricity to grid for office buildings with 5 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

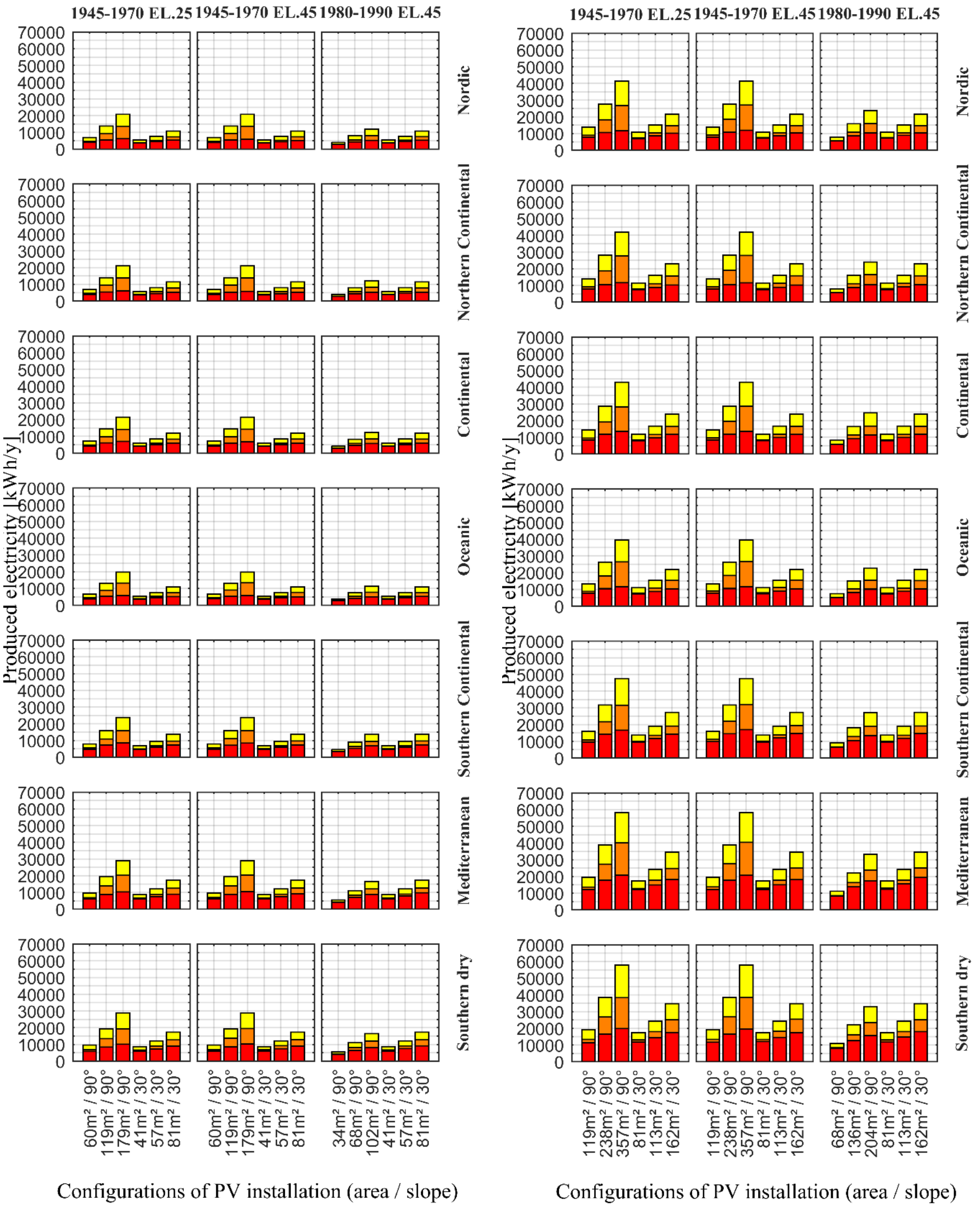


Figure 88 – Self-consumption and PV electricity to grid for office buildings with 7 floors: 162 m² per storey (left) and 324 m² per storey (right). Red: consumed by HVAC system; orange: lighting and ventilation; yellow: surplus fed to grid.

7 Literature references

1. Klein SA, Beckman A, Mitchell W, Duffie A. TRNSYS 17 - A TRansient SYstems Simulation program. Solar Energy Laboratory, University of Wisconsin, Madison; 2011.
2. Fedrizzi R, Dipasquale C, Bellini A, Nouvel R, Cotrado M, Gustafsson M, et al. D6.3a Performance of the Studied Systemic Renovation Packages - Method. iNSPiRe FP7 project, grant agreement no. 314461: 2016.
3. Fedrizzi R, Dipasquale C, Bellini A, Nouvel R, Cotrado M, Gustafsson M, et al. D6.3b Performance of the Studied Systemic Renovation Packages - Single Family Houses. iNSPiRe FP7 project, grant agreement no. 314461: 2016.