D6.3c - Performance of the Studied Systemic Renovation Packages – Multifamily Houses

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

In this report, we comment the results relative to the reference buildings built within the first age (1945-1970), and renovated with 4 generation systems (air to water heat pump, ground water heat pump, gas boiler and biomass boiler) and 3 distribution systems (radiant ceilings, radiators and fan coils).

According to the buildings classification (see D2.1a and D2.1c), two different Multi Family Houses typologies are identified, small Multi Family House (s-MFH) and large Multi Family House (l-MFH). In the published database, only s-MFHs are included, varying the number of floors (3, 5 and 7 floors) and, consequently, the surface over volume (S/V) ratio.

As well as for the SFHs, we adopted a reference S/V ratio as the basis to define insulation, windows and mechanical ventilation measures to match the sought heating demand targets (15, 25, 45, 70 kWh/m^2y), that is 5 floors and 10 apartments.

1.1 Main Results

1.1.1 Thermal comfort

The newly installed insulation and windows allow to reach energy used to cover space heating demand close to the ideal objectives of 15, 25, 40, 70 kWh/m^2y. The solutions are “only” close to the objective since the Used Energy is somehow dependent on the building management strategy, on the heating and cooling distribution system and on a suitable envelope renovation (insulation layer at least 4 cm, two windows typologies, presence of Mechanical Ventilation Heat Recovery – MVHR).

Looking at the cooling demand, despite the attempts to limit solar gains with shading devices, the energy used to cover this load increases significantly after renovation for all climates, from 2 up to 6 times in the northern countries. This effect is more evident in multifamily houses than in the single family houses due to the massive construction. This result shows how cooling loads have to be considered carefully also in the northern climates when sizing distribution systems.

As stated in Deliverable 6.3a, this does not necessarily mean that a cooling system has to be installed, since night ventilation can be effectively used in northern countries.

In this study the distribution systems have been sized based on the heating loads, as done in praxis in European residential buildings. As a consequence, discomfort can eventually be perceived during summertime along a limited number of hours. In the renovations with the highest energy savings in winter, significant cooling load peaks can be encountered that cannot be covered effectively: although average indoor air temperatures vary around 25°C in all cases (set temperature 24.5 °C), this can top to 26.5 °C during summer peak hours.

Fan coils and split units allow optimal conditions in summer. More critical are radiant ceilings: humidity management can run out of control within limited periods in hot humid climates and buildings’ high efficiency standards. In case dehumidification is not foreseen (as is the case in most residential cases), radiant systems have to be oversized with respect to the space heating needs, in order to compensate the humidity discomfort occurrences with an optimal indoor radiant temperature control.

1.1.2 Energy use

The final energy needed to cover thermal loads strongly depends on the generation technologies selected. Interestingly, it depends only marginally on the distributions system employed, both in summer and in winter.

Especially in colder climates, there is an increase in cooling demand for the best insulated cases (EL15) compared to the worst (EL70) due to the higher insulation level. The increase of cooling demand is evident also passing from the reference to the renovated buildings. However, this effect is reduced thanks to the shading strategy that foresees a more aware behaviour from the users. As a result, the cooling demand in renovated buildings, increases in Oceanic and Northern Continental climates up to 10 times, while in the other climates the cooling demand is comparable to the non-renovated building. In those climates where the cooling demand is low enough (10-15 kWh/m^{2}y) it should be possible to meet comfort conditions with night ventilation.

Also in s-MFHs, It is difficult to reach the primary energy target of 50 kWh/m^{2}y without the use of solar technologies. It is easier to reach the target in the Oceanic and Northern Continental climate – low energy level buildings – thanks to the low cooling demands.

For heat pump systems it is possible to achieve the primary energy target of 50 kWh/m^{2}y in nearly all cases for the lowest energy levels, when solar thermal/PV or both solutions are installed. The area required depends on the climate and renovation level. For gas boilers it is not possible to achieve the primary energy target even with the largest solar areas. For pellet boiler it is easy to achieve the target even without solar devices (if only the non-renewable primary energy is used for evaluation).

For heat pump systems, the decrease in primary energy use is similar for solar thermal and PV systems for each installed m^2 of collector/PV panel, but the total primary energy savings are greater for PV than solar thermal in those cases where the cooling demand is relevant. For gas boilers solar thermal fields are more effective than PV, and larger primary energy savings are possible even with the smallest areas used in the simulations.

Solar thermal collectors are used both for space heating and for DHW preparation in the solutions we recommend. Due to the limited collectors areas possibly setup, the solar fraction relative to space heating is limited, varying from 5-10% in the Mediterranean countries (for heating demand standards from 70 to 15 kWh/m^{2}y respectively) to 2% in the Northern ones.

For large collectors' areas, the overall duration of the stagnation condition is strongly influenced by the inclination. While around 600 hours of stagnation are measured with regard to the 30° inclination, no such condition is revealed with the installation of the collectors onto the façade of the building.

Façades are the convenient surfaces from the technical point of view when large solar thermal collector fields are envisaged.

The study shows that the installation of 3 kWp to 4 kWp (24 and 31 m^2 PV field area) allows to self-consume all the PV electricity. When heat pump systems are exploited, around 45-60% of the renewable electricity is consumed by HVAC system and the rest by domestic appliances. In case boilers are exploited, only the 25-40% is consumed by the HVAC system. The small available surface of MFHs strongly limits the quantity of PV electricity fed into the grid. The inclination of the panels on the façade has a minor effect on the energy self-consumption for the HVAC system.

Clearly, solutions consuming large amounts of electricity benefit more from the integration of PV fields, the latter impacting more significantly on reducing cooling loads in summer.

On the opposite, solar thermal technologies are more effective with respect to boiler driven systems and impact more on reducing the energy needed to prepare DHW.

With respect to fan coils and radiators, the convective to radiative contribution is around 70% / 30%, allowing for a precise control of the indoor "convective" air temperature. On the contrary, the radiative contribution of the radiant ceilings (around 70%) impacts also on the external walls' temperature. Operative temperatures with radiant ceilings are closer to the convective, thus the perceived temperature is actually higher in winter and lower in summer compared to the fan coils and radiators cases, for a specific convective temperature set. With radiators and fan coils, the winter operative temperature is almost 1°C lower compared to convective set temperature.

Where renovations with limited amounts of insulation are performed in mild climates, the higher wall temperatures obtained with radiant ceilings results in increased transmission losses and final energy uses higher than expected. This result is consequent to the decision of using the indoor convective temperature to control the H&C system (as the majority of the thermostats do) as well as the same set point temperature for all distribution systems. In practice, users may well choose a lower set point for the convective temperature with radiant ceilings than with fan-coils. With a control on the operative temperature, slightly different results would be obtained.

If transmission losses are limited by means of effective envelope insulation and windows (standards 45 kWh/m²y and below), the quantity of energy needed to cover space heating loads is fairly independent of the way heat is delivered to the indoor.

During summer, fan coils and split units cover both sensible and latent loads (but not independent), while radiant ceilings only treat sensible loads. Split units and fan coils mainly remove energy from air, while radiant elements act both on air and walls to produce the same convective temperatures by means of lower operative temperatures. Despite this, Used Energy for cooling is in the same range for all systems.

1.1.1 Investment and running costs

With respect to the investment costs, gas boiler solutions are clearly cheaper than heat pump ones in case only space heating and domestic hot water loads are covered. When cooling is also accounted for, the air-to-water heat pump with radiant ceiling solution is pretty much equivalent to the gas boiler one.

From the energy bill point of view, with the energy tariffs taken as a reference, the gas boiler plant is always much more expensive, the yearly annualised energy costs varying in between 3500 and 8500€/y versus 2300 to 5200€/y in case an air-to-water heat pump with radiant ceiling plant is used (costs for the entire building – 10 dwellings x 50 m^2 living area).

Consequently, the overall annualised costs of the latter solution are significantly lower than gas boiler ones: 20-26 €/m2y versus 25-30 €/m^2y (over an investment horizon of 30 years).

The incidence of solar technologies results in less than 2 €/m^2y on top of the total annualised investment costs, and even combinations of the two add around 3 €/m^2y.

Comparing the total investment costs with the ones of SFHs, the reduction is significant. In fact, looking to the case of air-to-water heat pump, the total annualised costs are assessed below 20 €/m²y, while in the SFH this value vary between 33 and 43 €/m²y.

Looking to the case of gas boiler, this difference is even higher as in the SFHs the costs are around 49 €/m²y in the northern climates and 42-45 in the southern ones.

The investment costs of the solution air-to-water heat pump in the s-MFHs is around 40-50% lower than in the SFH, varying between 550 – 800 €/m² (envelope, windows, generation and distribution system included) in the latter case and 260 – 330 €/m² in the first.

The investment costs to setup a pellet boiler system are significantly higher than the other solutions; the costs associated to a larger space occupation necessary to store the biomass should be also considered (which is not in this study). As already mentioned, on the opposite, solar technologies are not necessary with this combination. Accordingly, the total annualised costs of the latter solutions are comparable with the other combinations taken into consideration ranging in between 23 and 30 €/m²y.

2 Small Multifamily Houses from 1945-1970

In this report, we comment on the results relative to the reference buildings built within the first age (1945-1970), and renovated with 4 generation systems (air to water heat pump, ground water heat pump, gas boiler and biomass boiler) and 3 distribution systems (radiant ceilings, radiators and fan coils).

According to the buildings classification (see D2.1a and D2.1c), two different Multi Family Houses typologies are identified, based on the surface over volume (S/V) ratio. In the published database, only Small Multi Family Houses (s-MFHs) are included, varying the number of floors and, consequently, the S/V ratio from a value of 0.48 up to 0.61 (see Table 1).

As well as for the SFHs, we adopted a reference S/V ratio as the basis to define insulation, windows and mechanical ventilation measures to match the sought heating demand targets (15, 25, 45, 70 kWh/m²y): that is 5 floors and 10 apartments.

Table 1 Surface over volume ratio for target Multi Family Houses

Typology	***# floors***	***S/V***
s-MFH	**3**	***0.61***
s-MFH	**5**	***0.52***
s-MFH	**7**	***0.48***

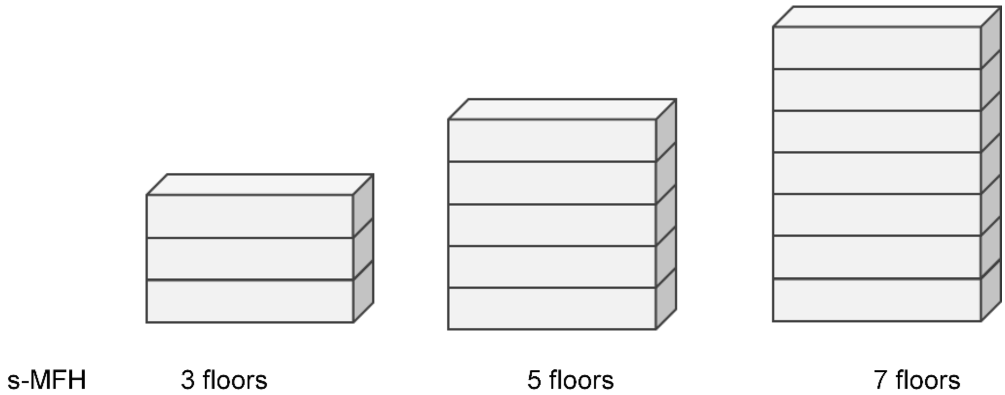

Figure 1 - Representation of the range of s-MFH types

The following is a list of the main assumptions and simplifications that were made in the simulation study, with a short description of the impact this has on the results. These should be kept in mind when analysing the results.

- The building is simulated as a detached construction without cellar, therefore without insulation below the ground floor. Simulations have been run for different number of floors (different S/V ratios), although in this report results refer to 5 floors only.
- The thickness of the roof insulation is the same as the one setup on the façades.
- The methodology was to adapt envelope renovation levels so that all climates have the

same heating demand for a given renovation energy level (EL15, EL25, EL45, EL70). The real demands vary, however, from these nominal demands, in some cases by quite a lot. In the warm climates the level of 70 kWh/(m²y) could not be reached even without any insulation. Despite having the same annual heating demand, the duration curve for heating load varies considerably between climates and this means that the design heating load, which is used for sizing purposes, also varies significantly between climates. This approach means that the energy use for heating is quite similar for all climates for a given energy renovation level, while the demand for cooling varies considerably.

- Indoor air control is with convective temperature. However, in real operation the user sets the temperature of the thermostat more based on operative temperature, resulting in lower convective set temperatures needed for radiant panels than fan-coils/radiators. In this study, this assumption leads to higher energy use for radiative ceiling compared to the other heat/cold distribution systems compared to if the systems provided the same level of comfort (based on operative temperature). The difference reduces with better envelope quality (as in low EL and in cold climates)
- Only PV electricity used to run HVAC systems is accounted for in the energy and economic analysis, as the contribution to the grid is not always paid off. This impacts on annualized costs (higher value), and primary energy analysis (lower value as we do not take the input to the grid into account).
- PV is calculated on an hourly basis, which overestimates self-consumption up to 5-10% compared to calculating on a minute basis, since hourly weather data are available.
- Good shading practices are assumed in all cases, but no other passive cooling measures (such as night ventilation) are used. Good shading leads to lower cooling demands while the heating demand is not significantly affected. For climates with low cooling demands it is questionable whether cooling would be used/designed for in practice. If no cooling system were installed, the total investment costs as well as running costs would be reduced significantly for the boiler systems as well as for the systems with heat pumps with radiators. In addition the self-consumption of PV would be lower, due to the lower summer load.
- The cost data have been derived for typical products on the market. The costs have not been adapted to the cost levels for the various climate zones/countries.

2.1 Air Source Heat Pump with Radiant Ceilings

As for the SFHs, the radiant ceilings have been 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 mode is set at 15°C.

2.1.1 Used Energy

The Envelope Renovation measures adopted produce an effect on the building heating demand as well as on the cooling demand.

Insulation thicknesses from one case to the other vary from a maximum of 14 cm for the Northern Climate energy level 45 kWh/m^{2}y, down to no insulation for the energy level 70 kWh/m^{2}y in many climates. The reduced need of insulation for MFHs, in comparison of detached SFHs, is the consequence of lower S/V ratios and higher specific internal gains. In Southern climates (i.e. Mediterranean), the only window replacement without any additional insulation, reduces the overall building heating demand below the 70 kWh/m²y.

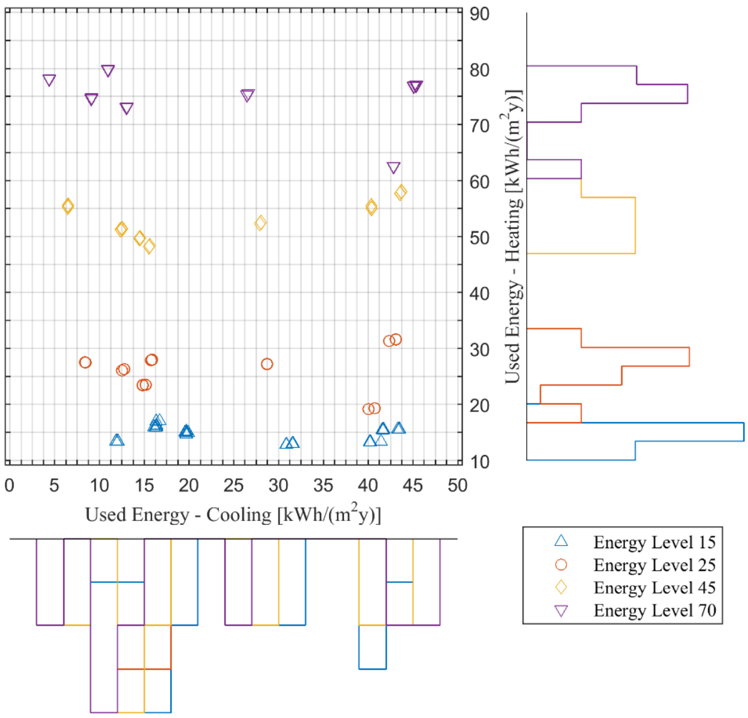

Figure 2 – Used Energy for heating and cooling of the different energy standards

The Used Energy shown in Figure 2 is the average of the whole building where the intermediate floors have reduced heating demands with respect to the highest and the lowest storeys. Moreover, as the ground floor is never insulated towards the ground, in some cases a big difference in terms of heating demand between the ground and the intermediate floor is verified. This difference amounts to 1.5 - 2 times for the Energy level 70 kWh/m²y (warmer and colder climates, respectively), up to more than 9 times for the 15 kWh/m²y coldest climates. This can cause some hours when discomfort is experienced in the edge apartments; they are anyhow maintained within the acceptable ranges (see database published on the iNSPiRe website).

As already noticed many times, the predominant radiative contribution of radiant ceilings impacts on the operative temperature that results as 1 ÷ 1.5°C as higher (in winter) than the convective temperature. This has the consequence of a better comfort but also a higher Used Energy for both heating and cooling with respect to systems with predominant convective distribution (fan coils and radiators).

As a consequence of the reduced building thermal losses through a renovated envelope their lower S/V ratio, cooling loads and demands are higher in MFHs than in SFHs due to and internal gains: 15-20% in Southern climates and 30-50% in Northern climates.

In absolute terms, the increase is around 2.5 – 9 kWh/m²y for the northern climates up to almost 20 kWh/m²y for the southern ones. For the former ones, it is possible to reduce this demand including free cooling (not implemented in the simulations), while for the warmest climates, particular attention should be paid on the use of effective cooling systems (as effective shading strategies are already implemented in this analysis).

2.1.2 Thermal comfort

Radiant panels cover both heating and cooling demands, in the latter case acting only for the sensible contribution. As for the SFHs, the radiant panels are sized for the heating load.

The penalties are slightly higher than in the SFHs for what concerns cooling loads and high standard energy level buildings. A higher cooling penalty for 35°C temperature supply is due to the smaller radiant panels area and, consequently, smaller available radiative area for the summertime operation.

Figure 4 shows the psychometric charts of two cases: Southern Dry for a warm-dry climate and Southern Continental for a more humid climate. The red dot lines delimit a recommended thermal comfort zone. Each point represents an average value over a 1 hour period.

In both cases, temperatures generally remain within the comfort zone or, in the worst climate conditions, in the close vicinity. In the most unfavourable apartments, the room air temperature may decrease down to 19°C for few hours in winter, providing however an acceptable comfort. In summer, a significant amount of time is spent at both high temperature (above 26°C) and humidity. In Southern Continental, several hours of high humidity in the dwellings is verified due to S/V ratio and the high flat occupancy. The average room temperatures in summer are always around 25 °C in any case. Either dehumidification or oversized radiant panels are needed in case optimal humidity control is needed.

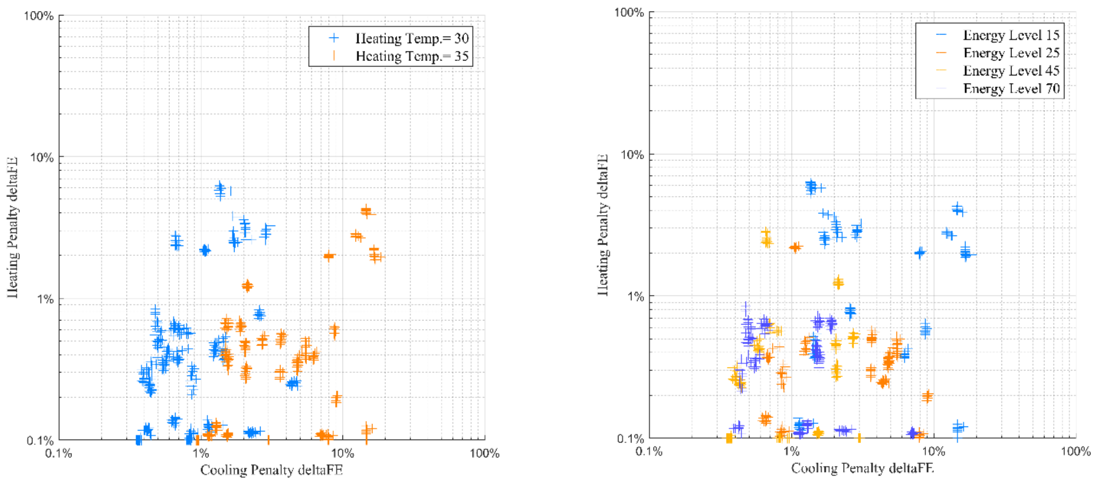

Figure 3 – Cooling and Heating penalty functions for different distribution water supply temperatures (a, left) and energy levels (b, right)

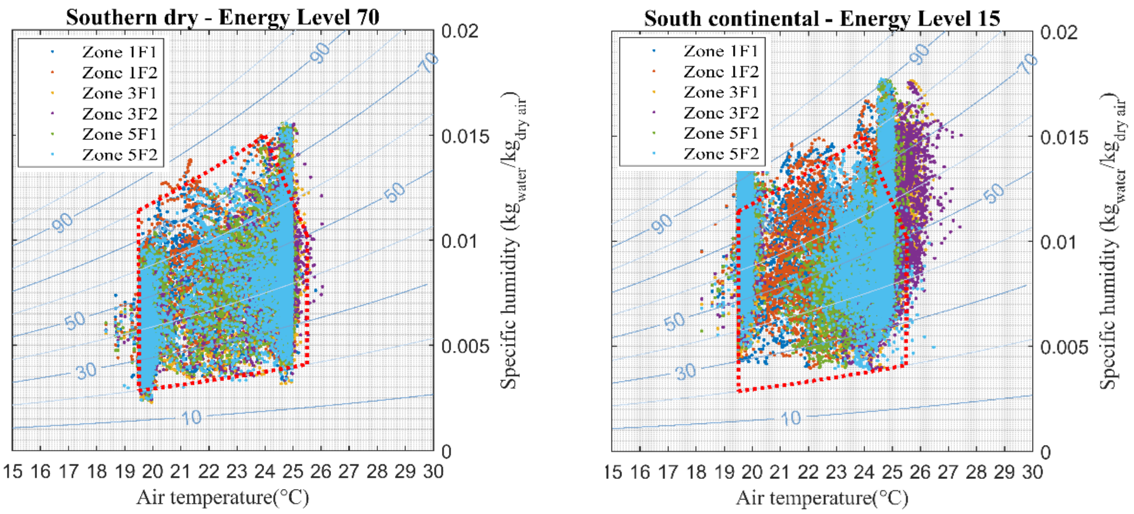

Figure 4 – Psychometric charts of {Southern dry, Energy Level 70, heating water temperature 35°C} and {Southern continental, Energy Level 15, heating water temperature 35°C}

2.1.3 Final Energy and SPF

Figure 5 shows the Final Energy consumption for the reported energy uses of the H&C system simulated for MFHs (distribution water temperature 35°C). The cases here reported refer to the base case without solar energy utilisation.

As well as for SFHs, in all cases apart for Southern Dry climate energy level 70 kWh/m^{2}y, the final energy consumption is lower than 40 kWh/m^{2}y. As a consequence, the consumption related to the DHW becomes significant in relative terms (in the order of 10 kWh/m^{2}y).

For the most energy efficient Envelope Renovation solutions (energy levels 15 - 25 kWh/m^{2}y) in the coldest climates and for the less efficient (45-70 kWh/m^{2}y) in the warmest, the final energy consumption for heating and for cooling has the same order of magnitude.

The final energy consumption for heating, when distribution water temperature decreases to 30°C, drops by around 5-7%.

Mechanical ventilation has same impact as space heating and cooling in the northern climates in high envelope efficiency buildings, while lower impact on the total energy consumption of buildings in the southern climates.

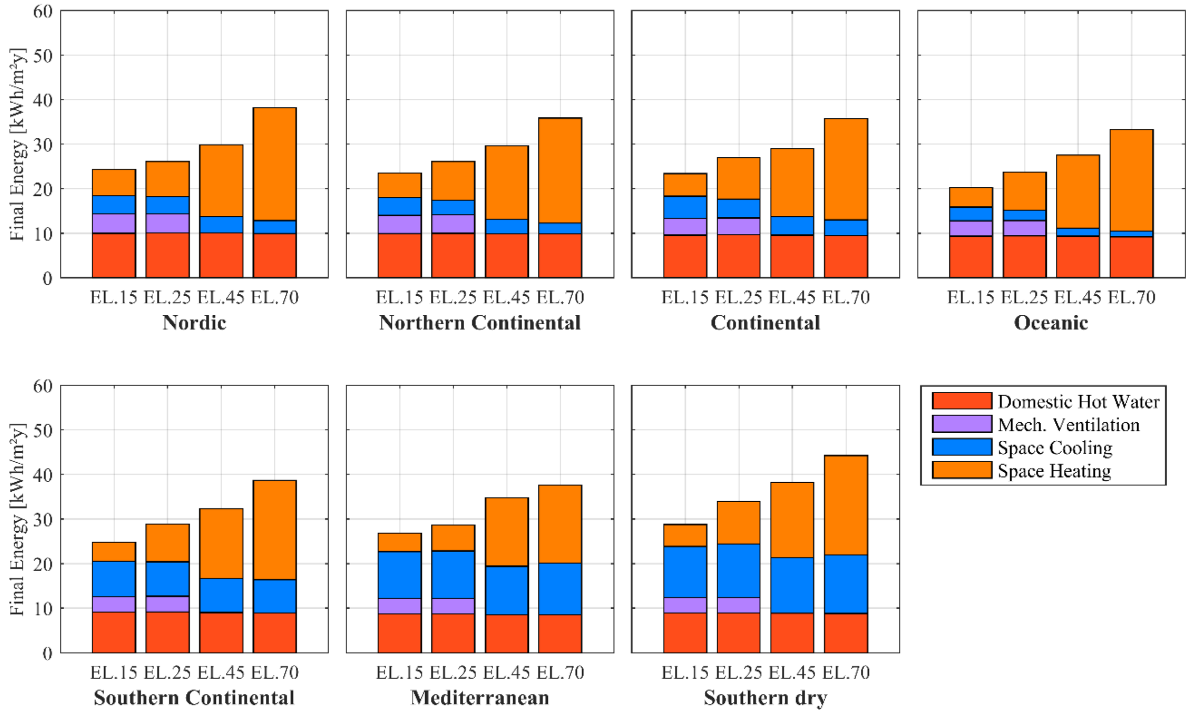

Figure 5 – Final energy distribution without solar systems and a heating water temperature level of 35°C.

The SPF figures (see Figure 52 to Figure 54) for heating loads vary between 3.6 and 4.2 (the highest in the Mediterranean climate) and between 4 and 5 for cooling loads (the highest in the Nordic and Northern Continental climate).

The SPFs related to the DHW preparation range between 2.8 and 3.6. As already observed in the SFHs, this is due to the comparable demands as for heating and DHW and higher generation temperatures.

According to this, the overall SPF for heating, cooling, DHW loads and ventilation vary in a range of 2.3 to 3.4 with lower values in the Northern climates and buildings with the highest envelope efficiency standards.

Using a CED_{NRE} of around 2.9 (see Deliverable 6.3a, electricity), only the solution for Oceanic 15 kWh/m²y is close to the target of 50 kWh/m²y of Primary Energy consumption with a value of 58 kWh/m2y.

2.1.4 Solar thermal energy utilisation

The use of solar thermal collectors is for both space heating and for DHW preparation. Due to the small size of the storage tank however, the basic solar system (8 solar collectors, 50 l/m^2) is only used for DHW preparation.

Figure 49 in Annex I shows as lower SF are obtained in the MFHs because of the ratio between solar field and total heated areas. While for the SFH this ratio ranges from 5% to 14%, in the MFHs, it reaches 7% with the largest solar field.

The minimum SF (8 collectors, 100 l/m², 30° of slope) for DHW in the northern climates is 45-50%, achieving almost 80% in the southern climates with the lowest heating demand (see Figure 49). Changing the collectors slope from 30° to 90°, the SF related to DHW preparation decreases of 10% in the coldest climates, while the reduction is up to 16% in the warmest ones. A reduction of the tank volume causes a small reduction of the SF for DHW (around 5%).

The increase of solar thermal collector area from 18.4 m² to 36.8 m² influences on the DHW preparation SF reaching 90% in the Mediterranean climate and 60% in the Nordic. The change of volume from 100 l/m² to 50 l/m² as well as a different collectors' inclination (from 30° to 90°) have a small effect in this case.

The stagnation hours are strongly reduced in the MFHs due to the smaller ratio of solar collectors over heated area. Despite that, the largest solar field size (37 m²) in the warmest climates with an inclination of 30° causes around 500-600 hours of stagnation. This effect is slightly reduced for the large tank volume, while completely eliminated with a collectors installed onto the main façade.

The total final energy consumed with respect to different variants is shown in Figure 50. Again, the amplitude of variation is mainly due to the solar collector field and building typology.

In northern climates, the biggest solar field allows a reduction of final energy consumption of 5 kWh/m²y while in the southern the energy savings amount to 8 kWh/m²y.

Using solar a solar thermal system, the total primary energy consumption of the buildings with the highest envelope efficiency and the largest collector fields lie around or lower than the target of 50 kWh/m²y.

2.1.5 Solar PV energy utilisation

Figure 51 shows the utilisation of the PV electricity to drive the HVAC system and appliances, and the surplus production fed to the grid. Calculations are made considering the hourly production/consumption without any battery.

Installing 3 kWp (24 m² PV field area both 30° and 90° slope) almost the entire energy produced is self-consumed.

The utilisation of PV electricity with 3 kWp installed by the HVAC system varies from 2000 - 3400 kWh/y in the southern countries to 1300 - 2200 kWh/y in the northern climates (at 90° and 30° panels slope respectively). In case of a 5 kWp installation, the figures increase by 20-30% (depending on climate and heating standard), that means in absolute terms around 600-1600 kWh/y. As already seen, the inclination of the panels has a non-negligible impact on the total self-consumed energy.

The effect of PV field utilisation on the buildings' specific final energy is reported in Figure 6 that accounts only for the electricity self-consumed to drive the HVAC system (in order to allow a comparison with the solar thermal cases).

Similarly to solar thermal plants, in northern climates, the final energy reduction is in the extent of 6 kWh/m²y, whereas in southern climates, the electricity savings rise up to 10 kWh/m²y (34 m² - 5 kWp cases).

2.1.6 Final Energy and Primary Energy considerations

The energy harvested is sufficient to reach the target of 50 kWh/m²y of Primary Energy consumption in almost all the most efficient buildings (15 kWh/m²y energy level). For the other cases, a combination of PV and solar thermal systems is needed.

Figure 52 to Figure 54 report on the HVAC system SPF for DHW, space heating and space cooling for all combinations of solar thermal and PV fields analysed. The red marker represents the average value of all considered cases, the blue box contains 66% of all cases, while the black markers show the maximum and minimum values assessed.

Both solar thermal and PV energy utilization have a small impact on the DHW production in the northern climates, the solar thermal system contributing to a larger extent. This effect is clearly observed, instead, in the southern climates where the thermal system strongly contributes on the DHW production, with a higher impact on the more efficient buildings.

With regard the space heating, the behaviour is similar although the PV and solar thermal system contributes equally. Again, this effect is more evident in the building with lower heating demand.

The SPF for space cooling is influenced by the PV system only; no relevant improvements are shown moving from 3 to 5 kWp installed, whereas an increase of SPF from 5 to 10 is verified from the south to the north.

Figure 6 shows as the total final energy for the northern climates ranges around 15 kWh/m²y for the lower building energy level and 30 kWh/m²y for the higher ones. The larger values of final energy with respect to SFHs are due to the higher cooling demands.

Figure 7 reports on the total Primary Energy for all the cases, with PV or STC only and with the combination of the two. The maximum primary energy consumption in all the cases with at least one solar technology is in the range of 80 - 90 kWh/m²y.

If we consider the existing buildings before renovation that mostly use a gas boiler for the heating and DHW production with an annual primary energy consumption around 320 kWh/m²y (Southern Dry climate), the primary energy savings amount to 130 kWh/m²y in the worst case.

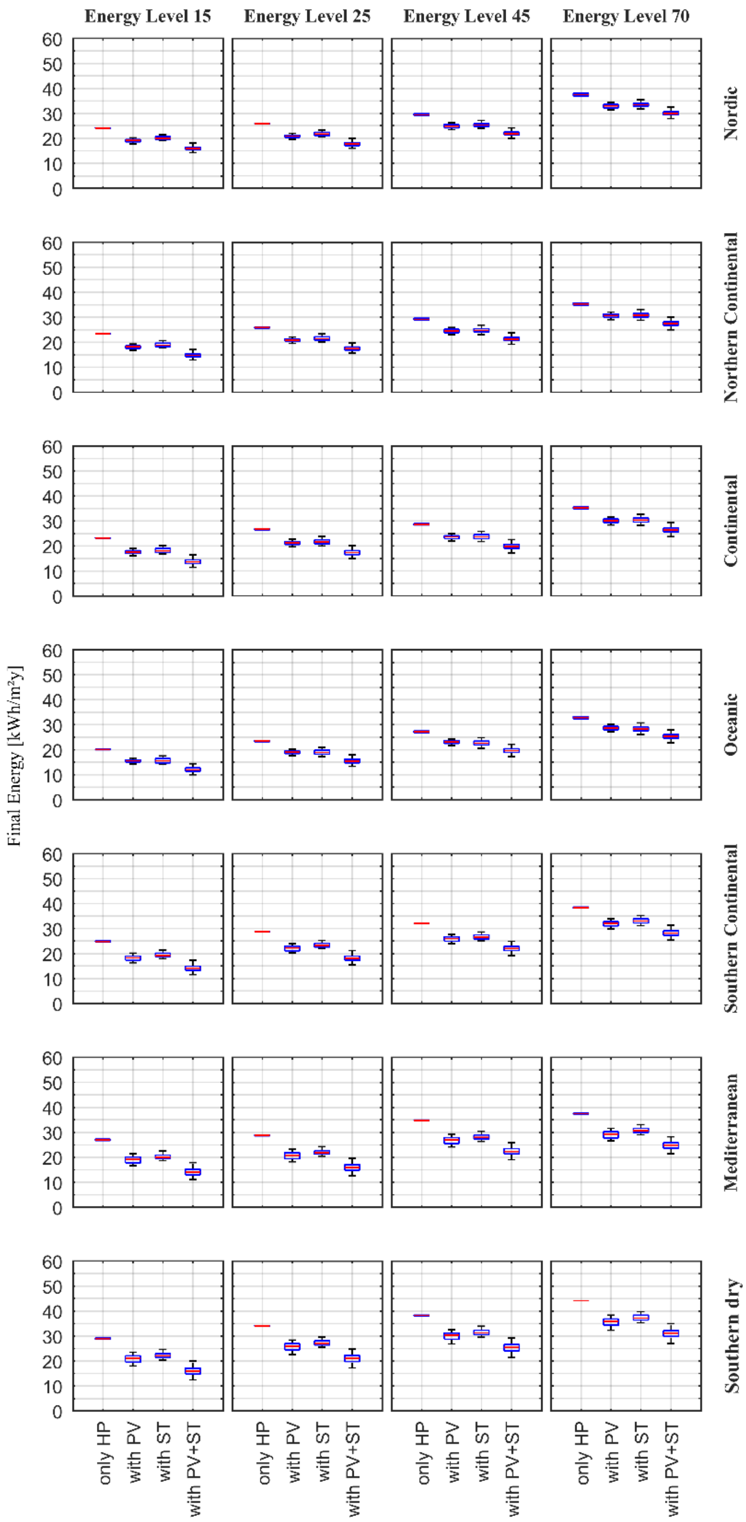

Figure 6 – Total final energy range for different HVAC installation types

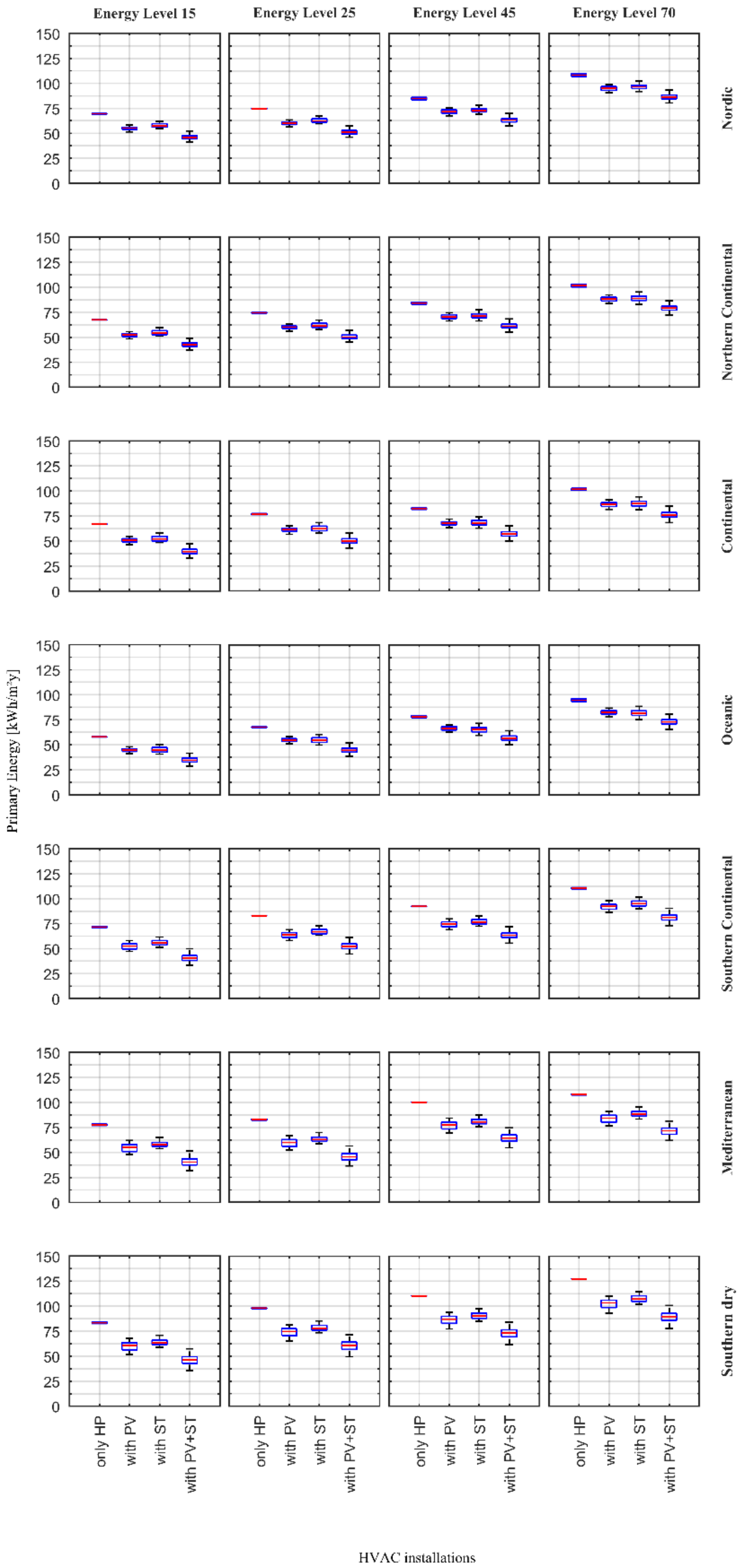

Figure 7 – Total primary energy range for different HVAC installation types

2.1.7 Economic evaluations

Figure 8 shows investment costs per unit living area both initial and annualised. Also in the MFHs, the envelope initial expenditures (insulation and windows) are larger than for generation and distribution systems. However, the proportion is reduced due to the smaller S/V ratio and glazed surface to volume ratio: 1:3 instead of 1:5.

Initial investment costs of the simulated cases for generation and distribution systems range between 75 and 110 €/m² (of living area).

Looking at the annualized costs, the investment for the envelope and windows remains almost the same as life duration of insulation is considered to be 30 years and for windows 25 years.

The costs for generation system, instead, increase since the lifespan of most of the components is considered to be 15 years.

Annualised costs in the range of 130-250 €/m² (strongly reduced with respect to SFHs) and 100-200 €/m² are assessed for insulation + windows, and generation + distribution systems respectively.

The incidence of ST system and PV system on the overall generation system annualized costs is between 10-20% with a slightly higher contribution of the ST plants. In absolute terms, the incidence of annualized costs for the solar systems (considering the biggest solar fields analysed here) amount to 58 €/m² for the ST system and 38 €/m² for the PV system.

The incidence of the utilisation of solar technologies on the investment costs (annualised costs considered) results in less than 100 €/m² even with combinations of the two (necessary to cut primary energy consumption to lower than 50 kWh/m²y).

For the comparison between investments, maintenance and energy costs, the first have been divided by the duration of the investment itself (30 years). Figure 9 reports on the yearly annualized costs for generation and distribution system, envelope and windows, plus the costs of final energy and maintenance.

With respect to the SFHs, in the MFHs the investment costs have still a large influence on the total yearly costs, but with a lower impact: the final energy impact ranges between 25% and 35%.

In any case considered and excluding solar technologies, the range of variability of total yearly annualised costs is between 20 €/m²y and 26 €/m²y.

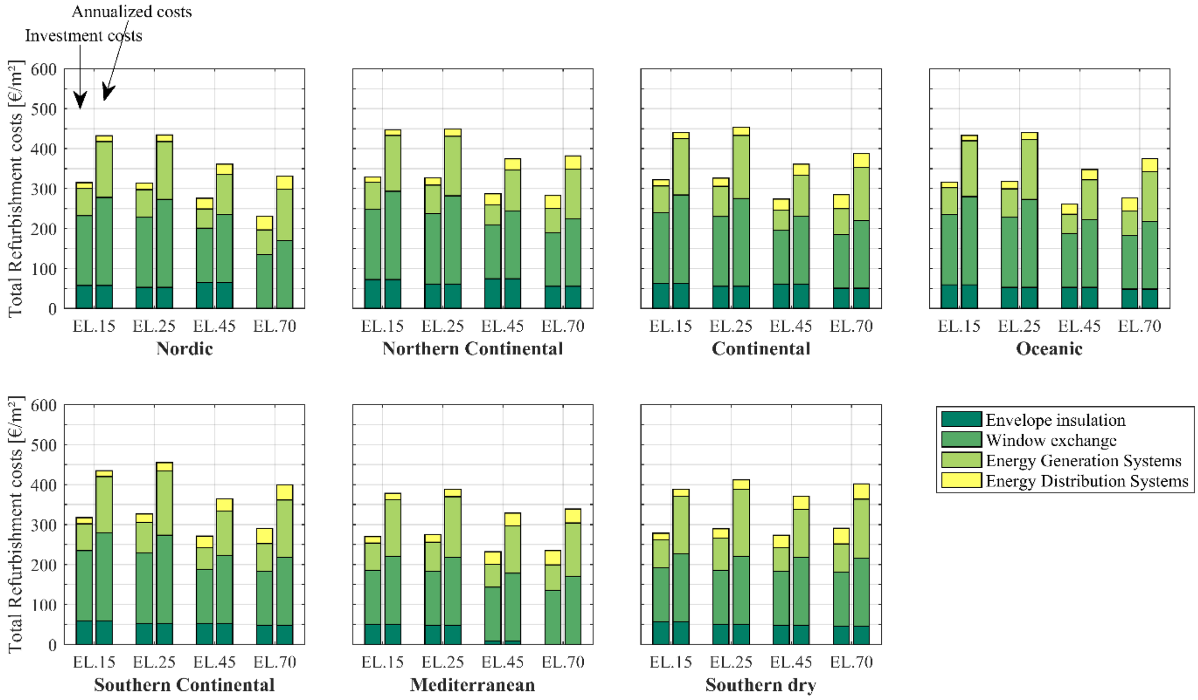

Figure 8 – Investment costs distribution (first year investment and annualized costs over 30 years) without solar systems (35 °C water distribution temperature)

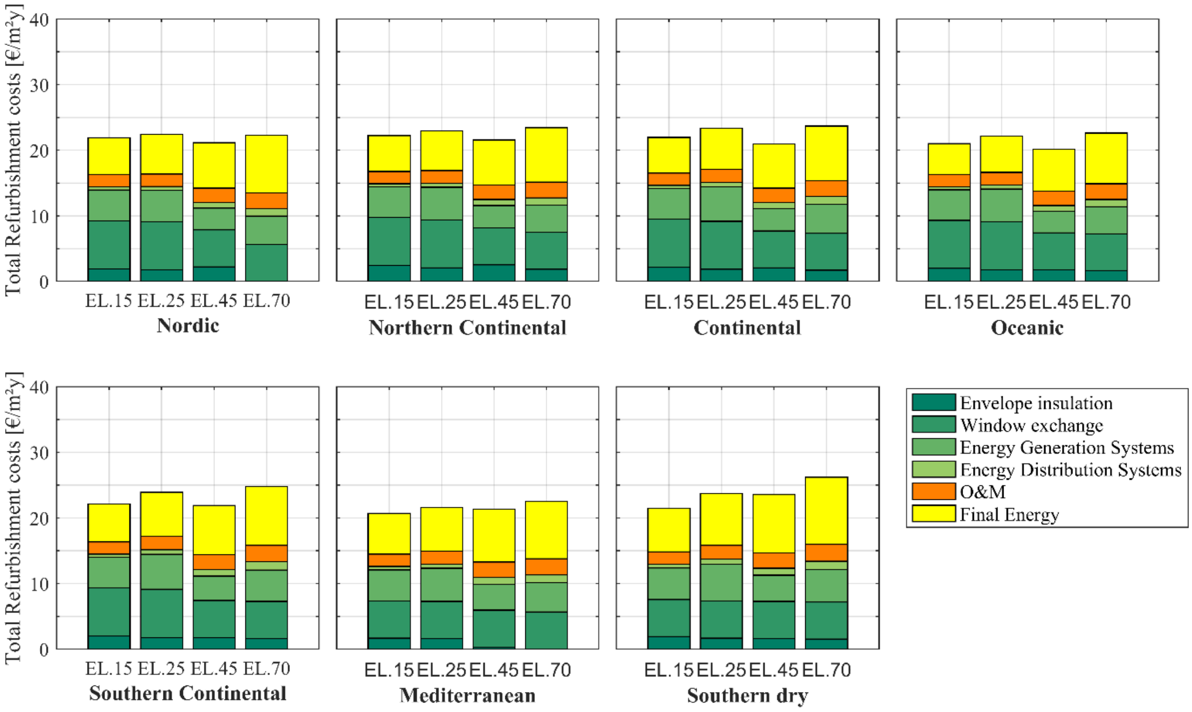

Figure 9 – Yearly annualised costs distribution for variants without solar systems

2.2 Ground Source Heat Pump with Radiant Ceilings

Having the same distribution system as in the previous case, Used Energy and comfort conditions are affected in the same way. The same holds for solar thermal energy and PV electricity contributions. Therefore, they are not discussed any further in this chapter.

2.2.1 Final Energy, SPF and Primary Energy

Figure 10 shows the final energy consumption of the H&C system simulated, following the energy uses reported (distribution water temperature 35°C). The base cases without solar energy utilisation are reported.

As already observed for the SFHs, the absolute values are slightly lower compared to AWHP systems due to the improved effectiveness of the heat pump when working in a more profitable range of working conditions at the evaporator. The effect of using the ground source instead of the air results in around 2 kWh/m^{2}y.

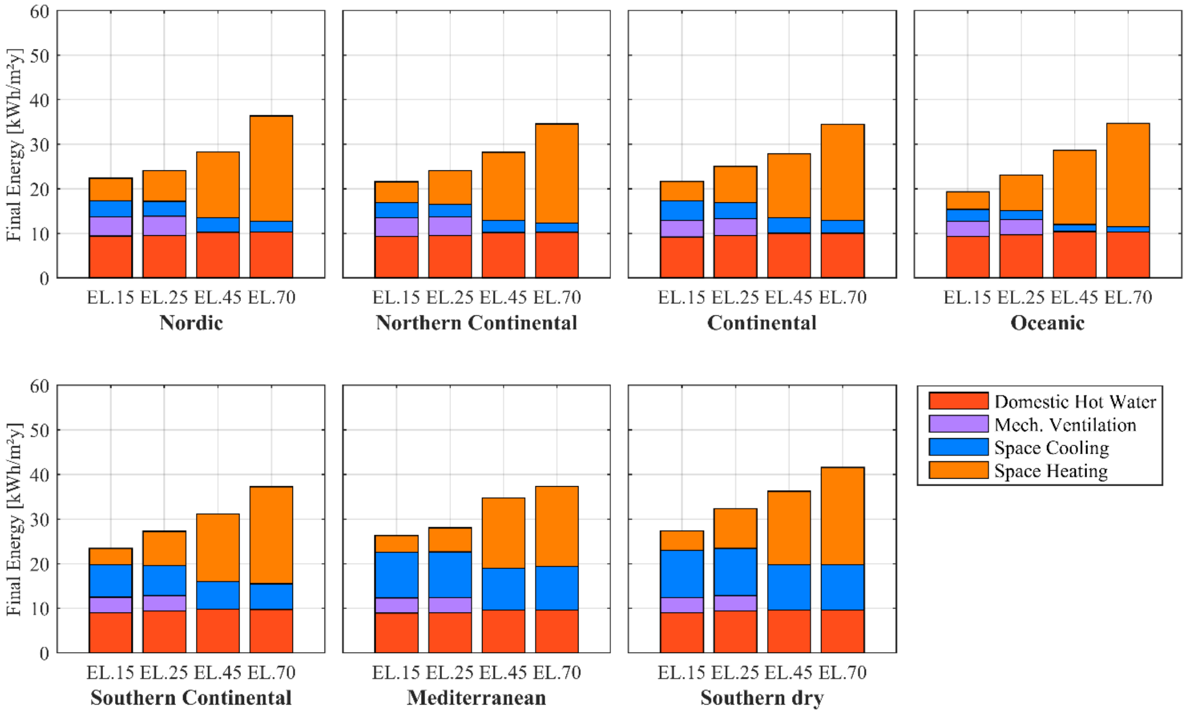

Figure 10 - Final energy distribution without solar systems and a heating water temperature level of 35°C.

The SPF figures for the space heating are slightly higher than the ones for the SFHs and are assessed around 3.5 for all the cases, while the ones for the cooling are in the same range, between 3.9 and 4.6, with an increase in the coldest climates. For the DHW production, the SPF is higher in this case and vary for all the cases between 2.1 and 2.5.

The overall SPF for heating, cooling, DHW and ventilation vary between 2.0 and 3.0. The lowest values are referred to the highest envelope efficiency standards.

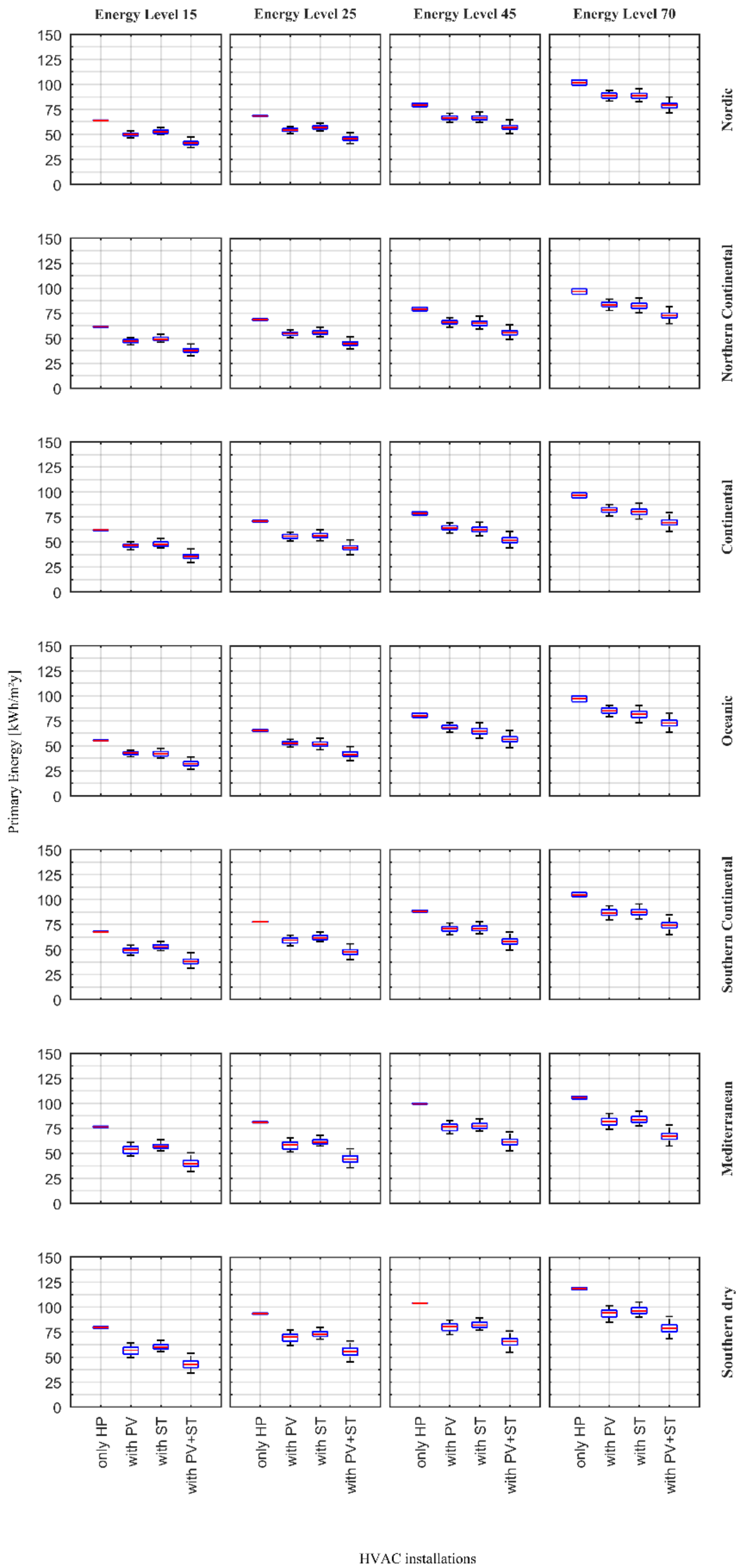

Figure 11 – Total primary energy range for different HVAC installation types

The reduction of primary energy consumption with respect to the air to water heat pump is in the range of 1 to 7 kWh/m^{2}y (see Figure 11). In particular, in the majority of the climates, the primary energy savings amount to 4-5 kWh/m^{2}y, in the Mediterranean climate the minor value is verified while for the 70 kWh/m^{2}y building in the Southern Dry the primary energy savings are the highest.

2.2.2 Economic evaluations

Figure 12 shows investment costs per unit living surface area. Envelope initial expenditures (insulation and windows) in this case are similar to the generation and distribution system costs due the additional costs for the bore holes installation.

Assuming that the life span of the latter is 30 years and only the heat pump is substituted after 15 years, the investment costs for generation and distribution systems range in the simulated cases between 160 and 300 €/m^2, while the annualised costs vary between 230 and 380 €/m^2. These values correspond to around 3 times the ones of an air-to-water heat pump system.

Figure 13 shows that in this case the entry costs impact for around 60 - 70% on the yearly costs (15 - 20 €/m^{2}y). Total annualised costs vary in a range of 23 - 32 €/m^{2}y.

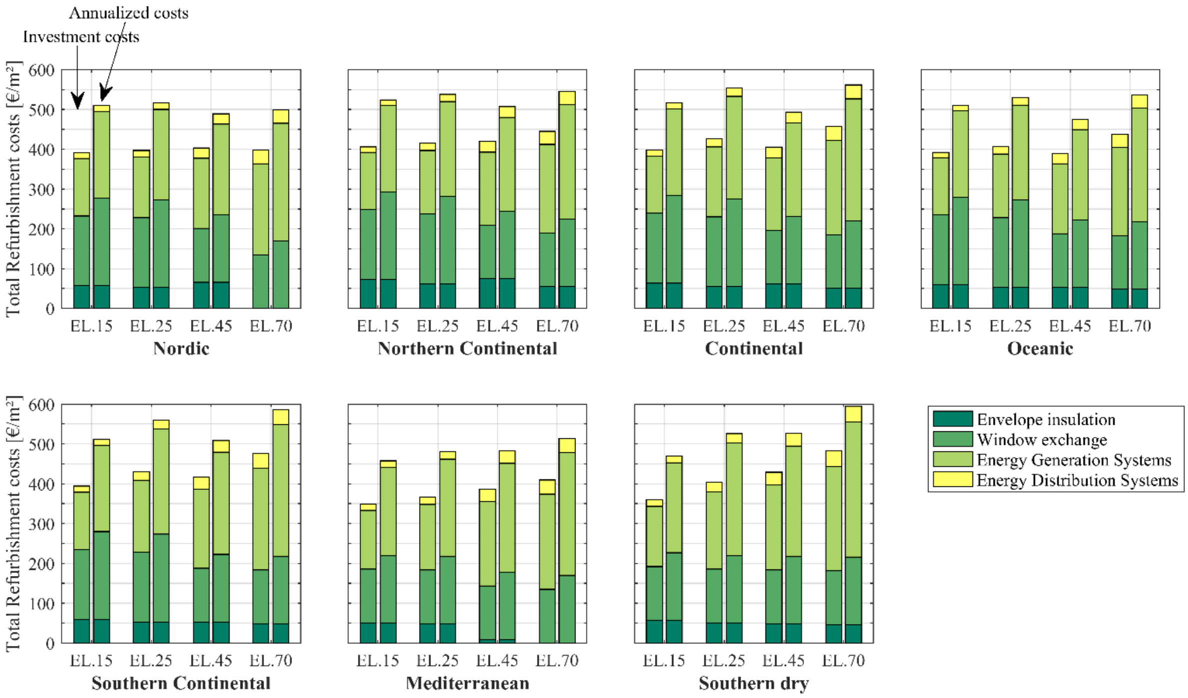

Figure 12 – Investment costs distribution without solar systems (35 °C water distribution temperature)

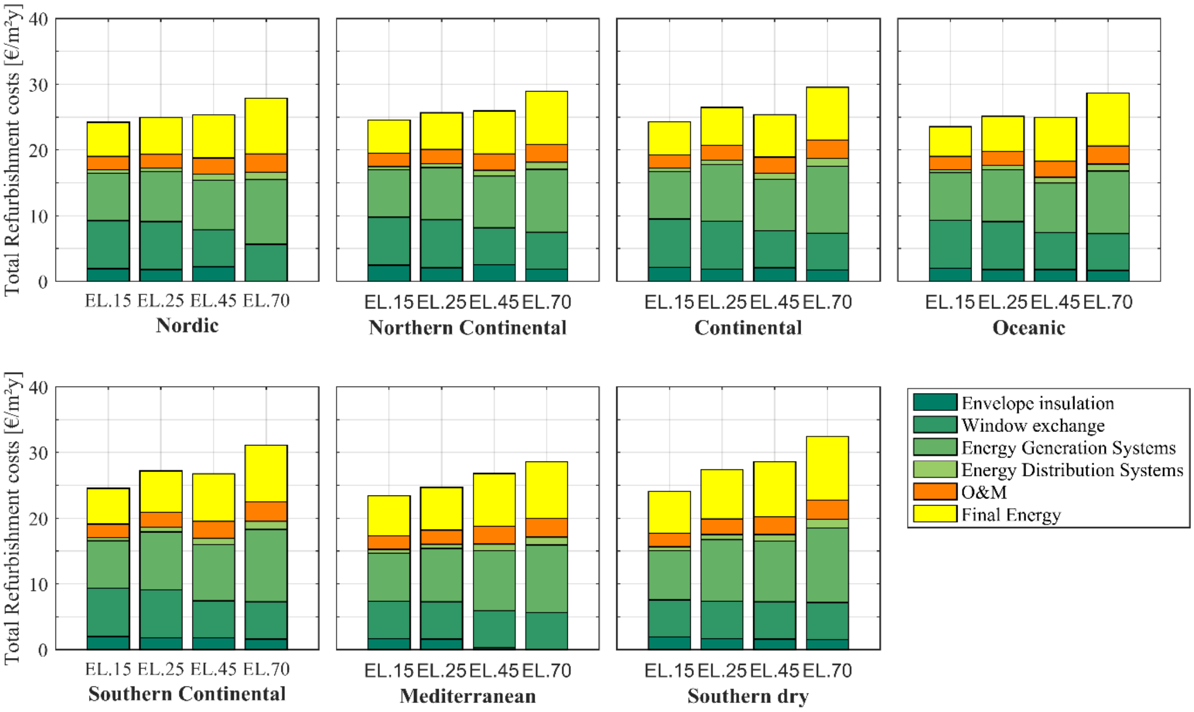

Figure 13 – Yearly annualised costs distribution for variants without solar systems

2.3 Gas and Pellet Boilers with Radiant Ceilings

For the boiler case, we have considered two typologies, gas and pellet driven. The difference between the two lies in the thermal efficiency, consequently, distinct considerations are reported for those performance figures that are related to the final energy. The seasonal efficiency of the condensing boiler varies between 0.92-0.94 in the different climates and buildings, while the one for the pellet boiler ranges around 0.85. The minimum boiler size used is 25 kW, despite the lower loads encountered.

Used energy and comfort conditions are the same as for the previous sections, therefore considerations on this are not here reported.

Where the behaviour is comparable to other previous cases, graphs only are reported in Annex I – Simulation results, section 3.3.

2.3.1 Final Energy, Primary Energy and SPF

In the northern climates the use of a pellet boiler brings an additional final energy use for space heating of around 7-8% with respect to using a condensing boiler system, achieving a maximum of 10% in the Continental climate 70 kWh/m²y buildings. For the DHW preparation, instead, the difference is assessed around 6-8% for all climates.

Looking at the primary energy consumption, the results are completely different due to the conversion factor from final to primary energy of gas and pellet. Figure 14 and Figure 15, in fact, show that almost any case (with exception of the buildings with 15 kWh/m²y energy levels in the southern climates, and the combination of the two solar technologies) cannot achieve the target of 50 kWh/m²y of primary energy consumption with the condensing boiler.

The use of a pellet boiler, instead, allows to achieve the target primary energy consumption in almost all cases without the combination of any solar technology; exceptions are the southern climates where the cooling demand is dominant.

The reduction of total Primary Energy consumption with the use of solar technologies varies from 15% in the northern climates up to 25% in the southern ones thanks to the use of solar thermal collectors and PV panels.

With respect to the latter, renewable electricity here is considered as acting on the HVAC system consumption only: since this is relatively low, the savings in absolute terms are negligible and most of the PV production is used to drive appliances and is fed into the grid.

Finally, a consideration on the SPF for the space cooling is needed. As already explained, the combinations with boilers accounts for split unit covering space cooling demand. Looking at the models currently present in the market, the nominal EER of the split unit is higher than the one for the heat pump in cooling mode, due to missing water distribution energy use. For this reason, the average SPF for the cooling in this case is around 5.2 against the 3.7 with an air to water heat pump and 4.1 with a ground water heat pump.

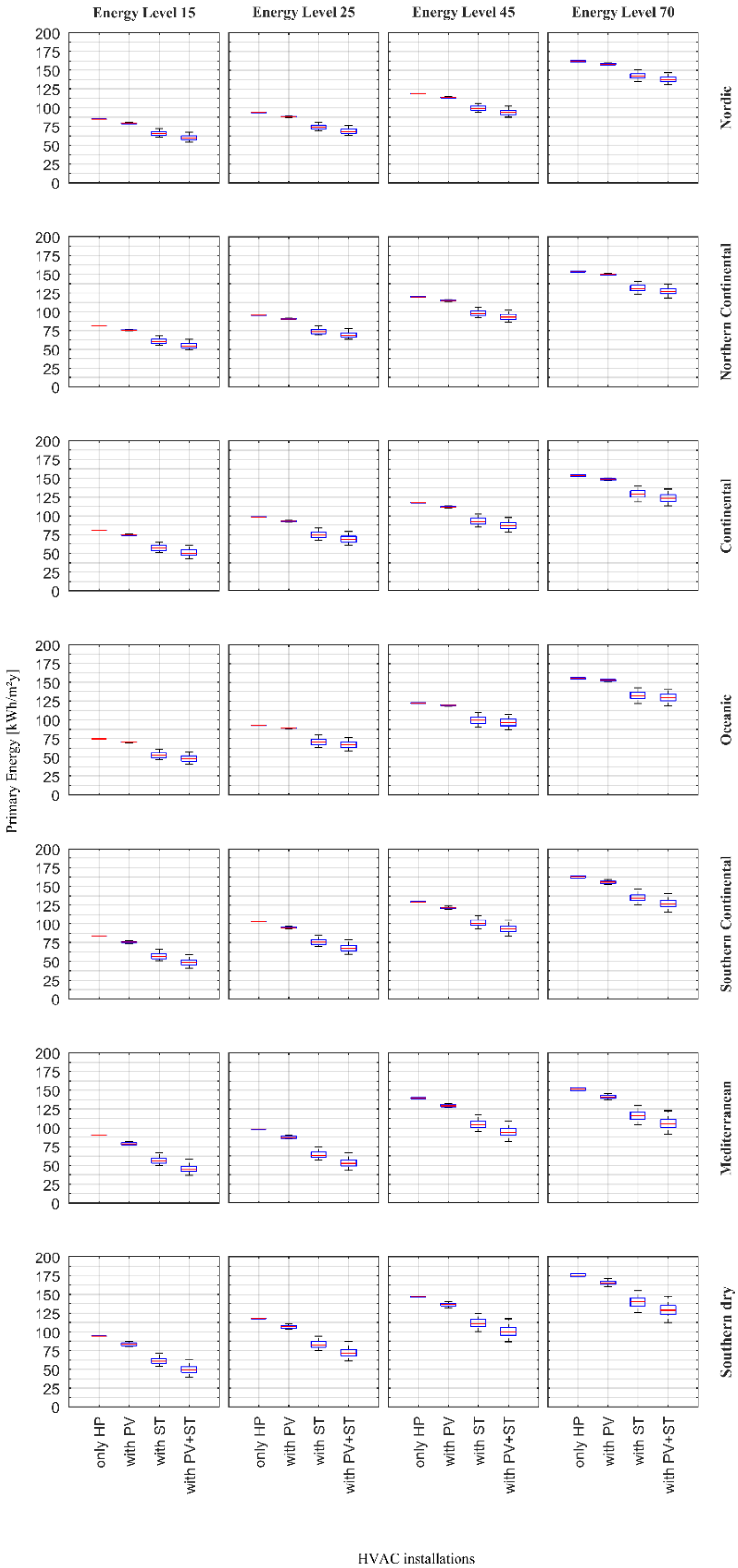

Figure 14 – Total primary energy range for different HVAC installation types – Gas boiler.

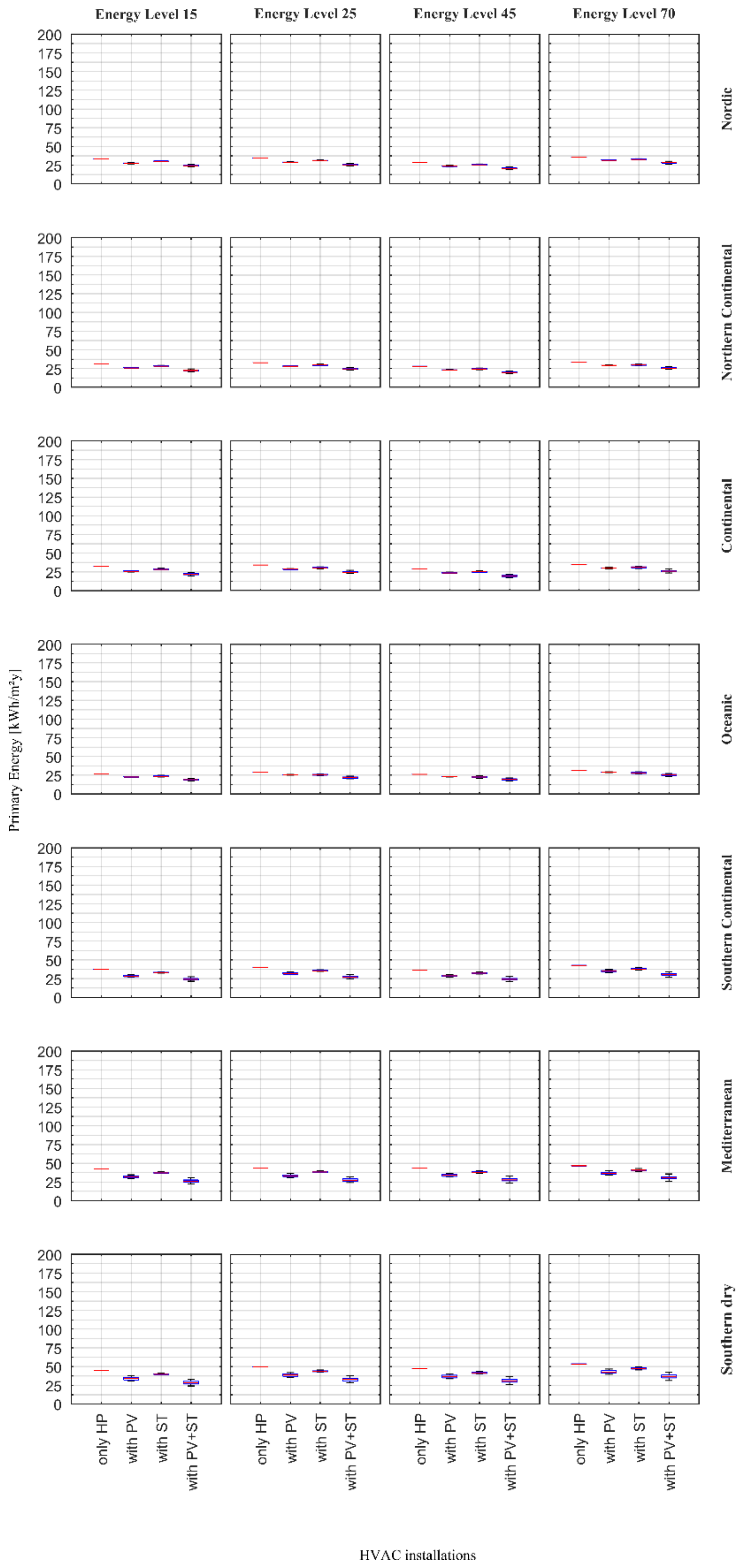

Figure 15 - Total primary energy range for different HVAC installation types – Pellet boiler.

2.3.2 Economic evaluations

Same considerations as for the previous cases (section 2.1.7 and 2.2.2) are valid here for what concerns envelope and distribution system.

2.3.3 Gas boiler systems

In the northern climates and in the buildings with higher efficiency, the generation costs are slightly higher than in the air to water heat pump case. Although the cost of a boiler is lower than a heat pump, the installation of one split unit in each dwelling causes a higher cost for the whole generation system. This might not be needed, therefore considerations could change accordingly.

In the warmer climates and especially in buildings with low building standards (energy level 45 and energy level 70 kWh/m^{2}y) instead, the generation costs are lower than for air to water heat pump driven plants.

Gas boilers have an investment cost of around 4500 €, since in all cases the thermal capacity installed is 25 kW (minimum considered). The annualised investment costs of the entire HVAC system vary between 110 and 225 €/m^2, in cases without and with eventual air handling unit respectively.

Once again, the incidence of the utilisation of solar technologies on the annualised investment costs ranges between 55 and 100 €/m^2 in all cases studied.

Maintenance costs are comparable when comparing gas boilers with air to water heat pump systems, while the overall annual costs are higher in the boiler combinations since the fuel costs are significantly higher (see Figure 17).

As a result, despite the obvious reduced initial costs related to using a traditional technology such as the gas boiler one, the total costs over 30 years are slightly higher than for air to water heat pump systems: 25 – 30 €/m^{2}y.

2.3.4 Pellet boiler systems

25 kW thermal capacity units have been considered also for pellet boilers combinations with an initial cost of around 15000 €.

Pellet boilers systems initial investment cost (installation included) varies between 40000 and 60000 € in the cases simulated, corresponding to roughly 160 – 230 €/m^2 of living area for the annualized costs.

Since fuel costs are significantly lower in our calculations (40% less) compared to gas, overall annualised costs of around 24 – 28 €/m2y.

Moreover, as already discussed, pellet boiler driven plants do not need solar technologies to reach the primary energy target. Therefore, these solutions are cheaper compared to gas boiler ones, if an investment horizon of 30 years is considered.

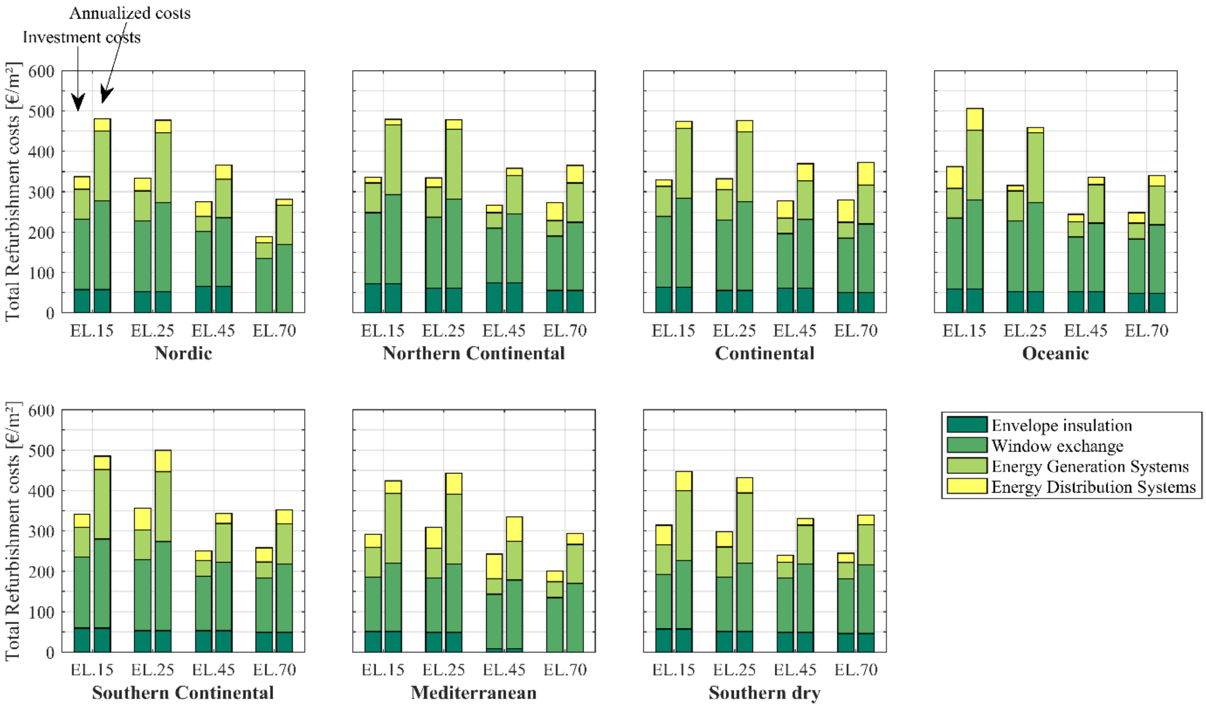

Figure 16 - Investment costs distribution (first year investment and annualized costs over 30 years) without solar systems (35 °C water distribution temperature) – Gas boiler

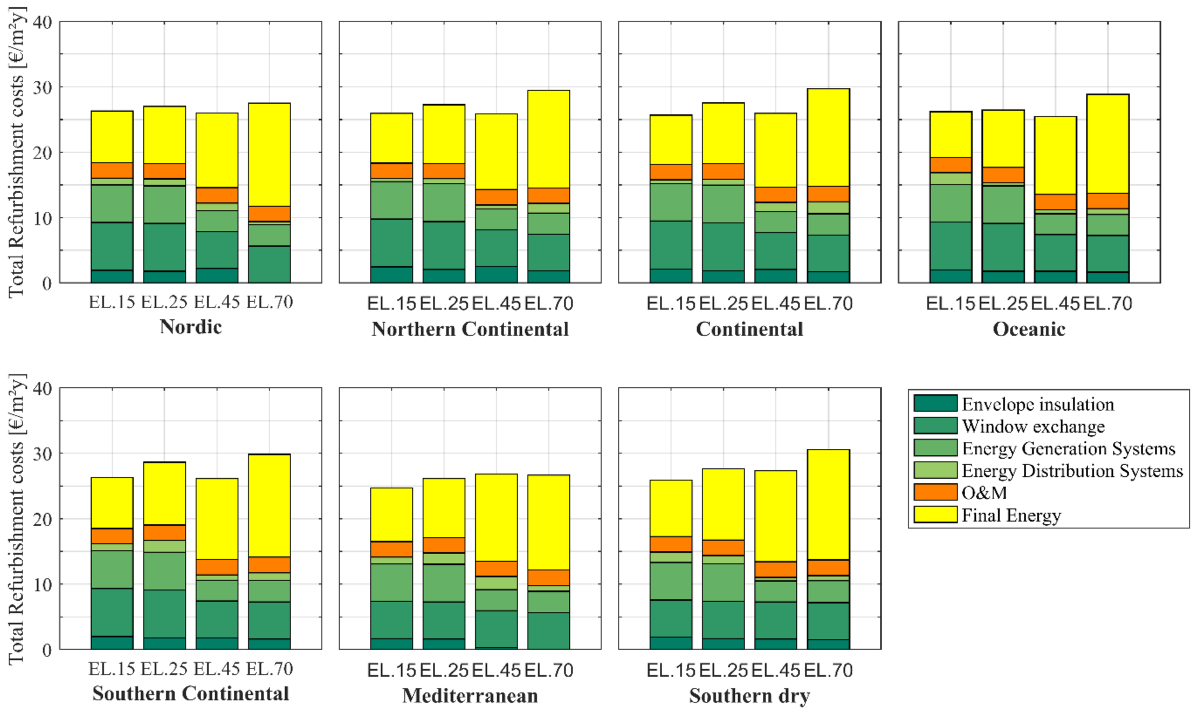

Figure 17 - Annualised costs distribution for variants without solar systems – Gas boiler

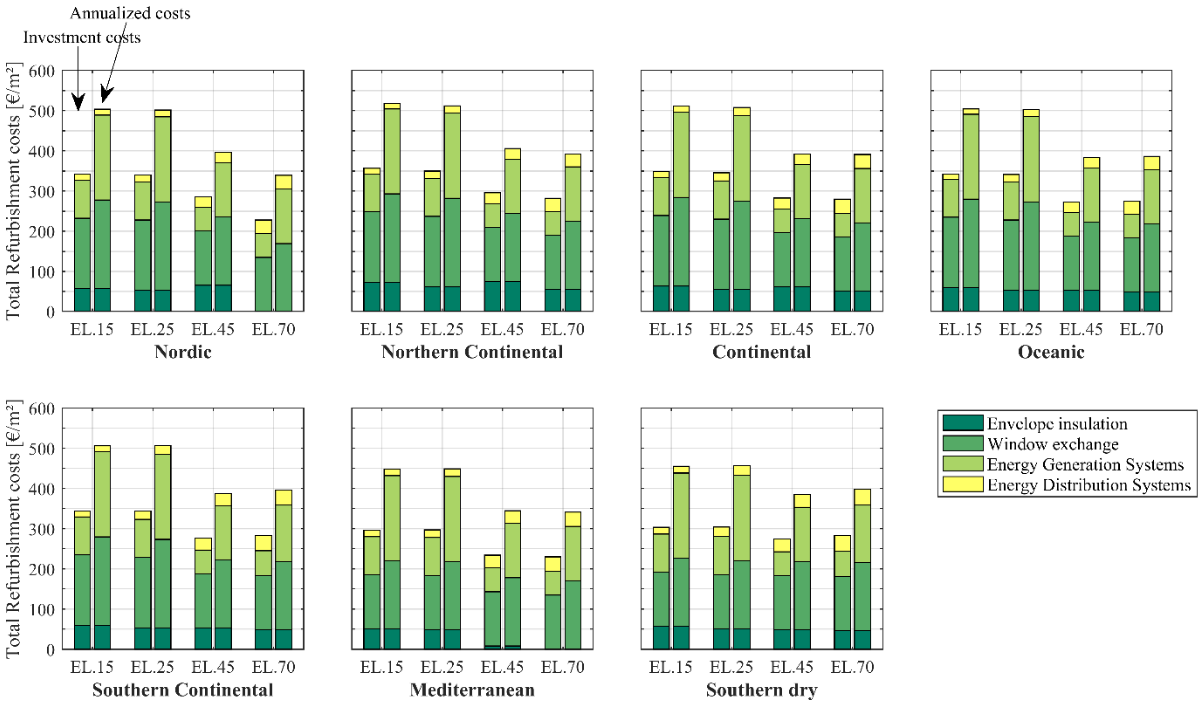

Figure 18 - Investment costs distribution (first year investment and annualized costs over 30 years) without solar systems (35 °C water distribution temperature) – Pellet boiler

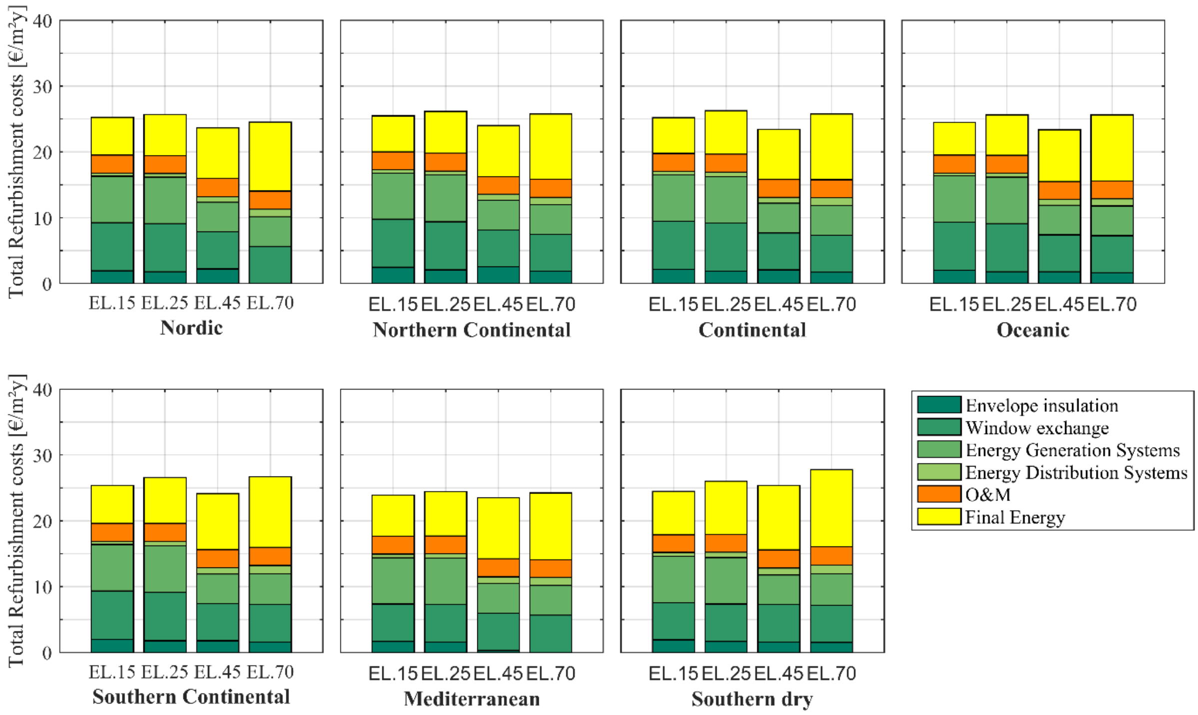

Figure 19 - Annualised costs distribution for variants without solar systems – Pellet boiler

2.4 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.

2.4.1 Used Energy

Figure 20 shows Used Energy for both heating and cooling for the range of climates. Used Energy in the case with fan coils is closer to the energy level target than in the radiant ceilings solutions due to the prevailing convective contribution to heating provided by fan coils. 5 to 10 kWh/m^2y lower thermal energy needs are encountered if fan coils are used as distribution units.

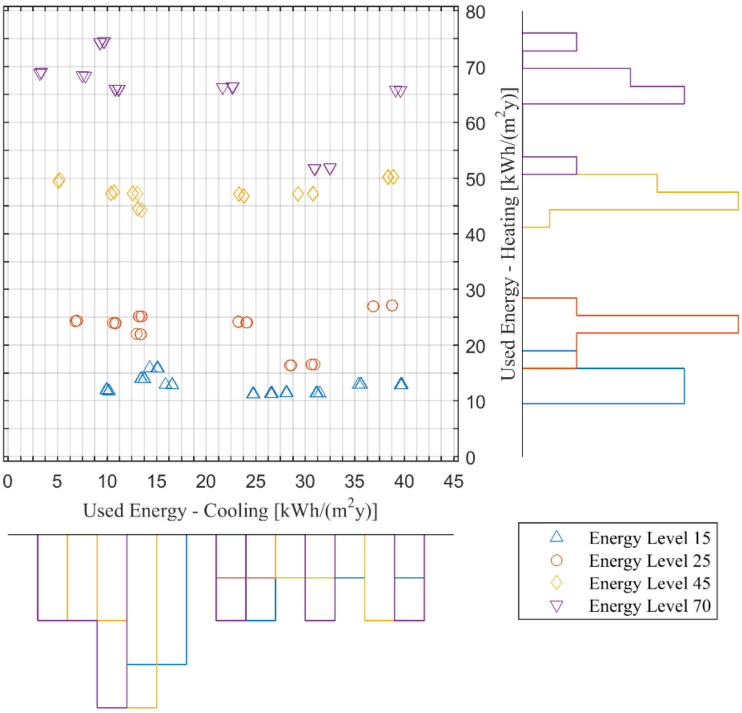

Figure 20 – Energy Used for heating and cooling of the different energy levels

2.4.2 Thermal comfort

As already stated in section 2.1.2, the small penalization in the MFHs for the heating is due to the big difference on the heating demands between ground and intermediate floors. The higher cooling penalty, instead, is related to the sizing based on the heating demand. Despite this, the average temperature in the dwellings is around 25°C once more with highest temperature in the intermediate floors. The highest penalty factors are verified in those cases with smaller fan coils sizes, that is, high efficiency buildings and 45 °C supply water temperature.

Same relative humidity behaviour in winter as for the radiant ceilings is here verified.

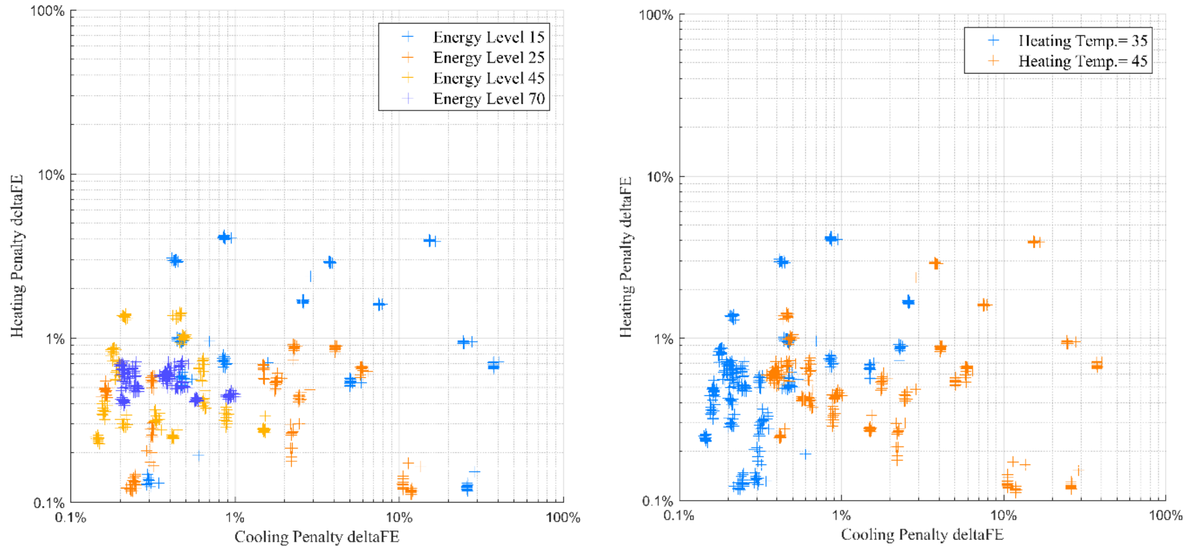

Figure 21 – Cooling and Heating penalty functions for different energy levels and heating water temperature

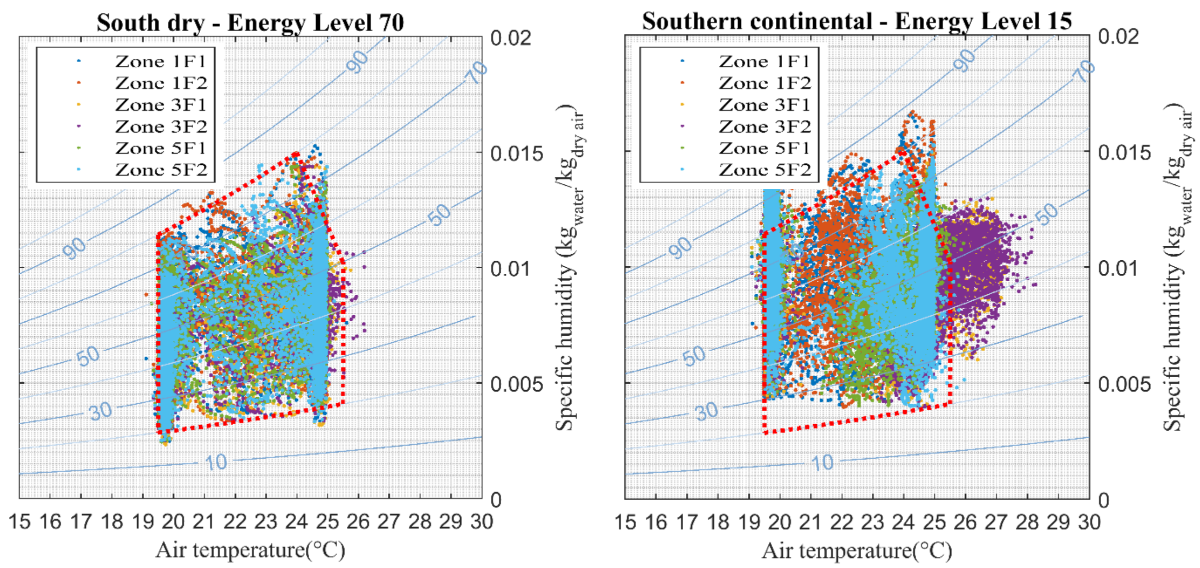

Figure 22 – Psychometric charts of {Southern dry, Energy Level 70} and {Southern continental, Energy Level 15}

2.4.3 Final Energy, SPF and Primary Energy

Despite the lower Used Energy in the fan coils than in the radiant ceilings cases, the Final energy is higher in the former due to the electricity needed to run the fans (45 W_{el}/kW_{th}). The difference is higher in the buildings with higher heating demand (up to 20% of the system with ceilings) with a difference, in absolute terms, between 1 and 9 kWh/m^{2}y.

Without considering the solar technologies, the SPF for space heating ranges between 1.6 in the coldest countries and 2.4 in the warmest ones. Same range is verified for the SPF of cooling with the highest value in the Southern Dry climate and the lowest in the Mediterranean. The different supply temperature in winter (35 versus 45 °C) plays only a minor role on the total SPF. Same SPF values as for SFHs are encountered here obviously: 1.6 to 2.4.

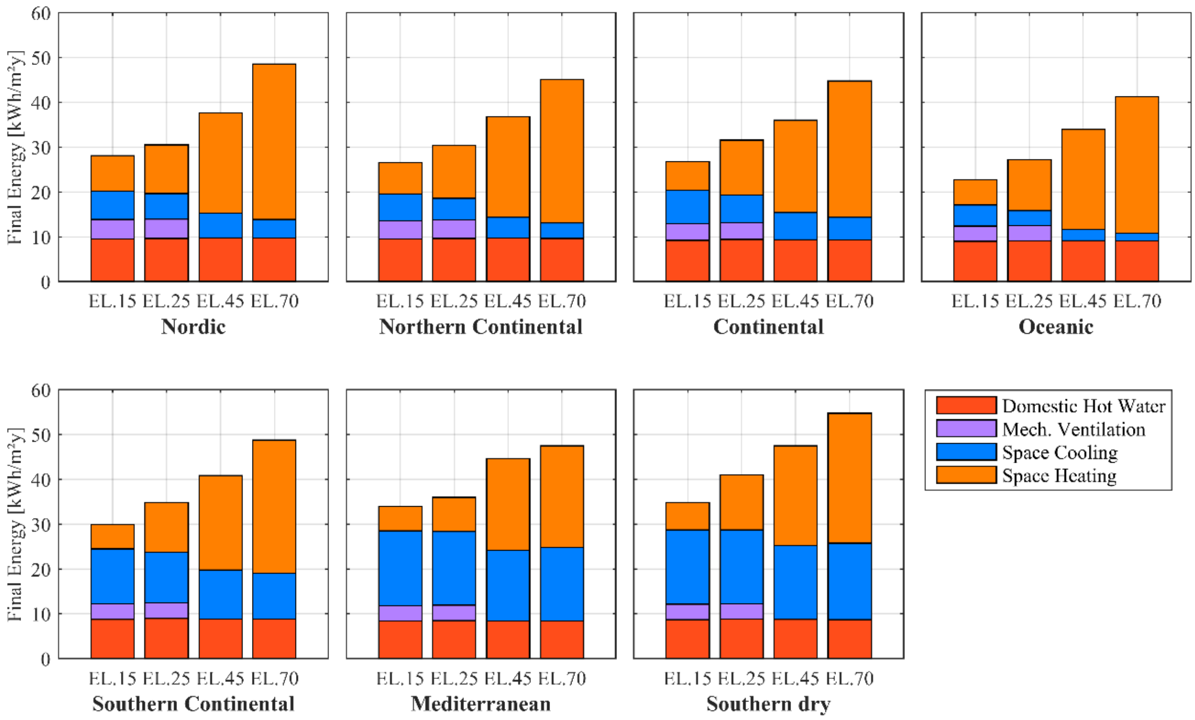

Figure 23 - Final energy distribution without solar systems, and a heating water temperature level of 35°C.

The utilisation of solar energy has comparable effect as for the cases with radiant ceilings, therefore it is not discussed further. However extensive charts are reported in Annex I (section 3.5) and Figure 24 - Figure 25 summarise such effects.

Similarly to air to water heat pumps with radiant ceilings, the target of 50 kWh/m²y of Primary Energy consumption is reached in few cases only. In case of fan coils, the additional electricity consumed for the fan even reduces the number of cases.

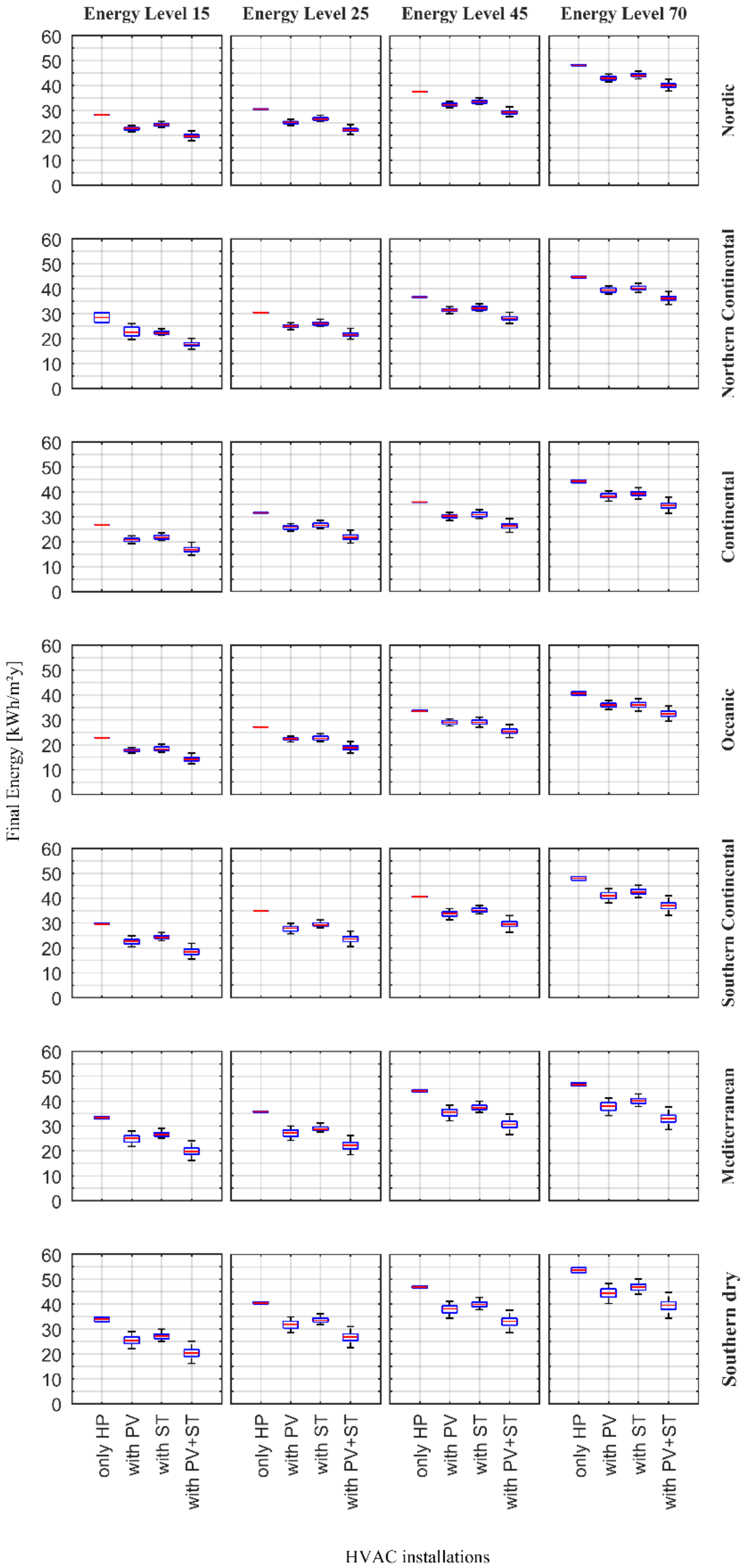

Figure 24 – Total final energy range for different HVAC installation types

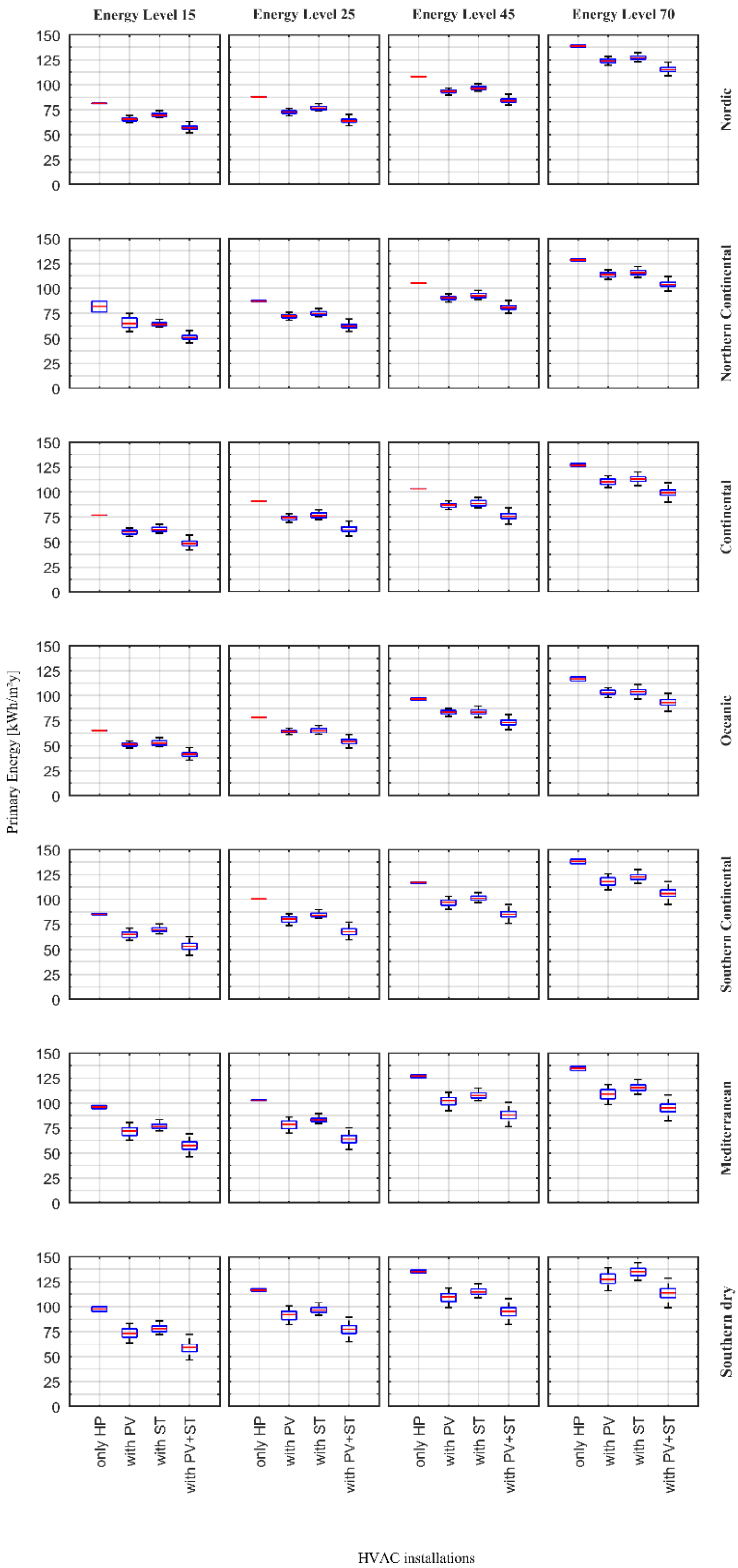

Figure 25 – Total primary energy range for different HVAC installation types

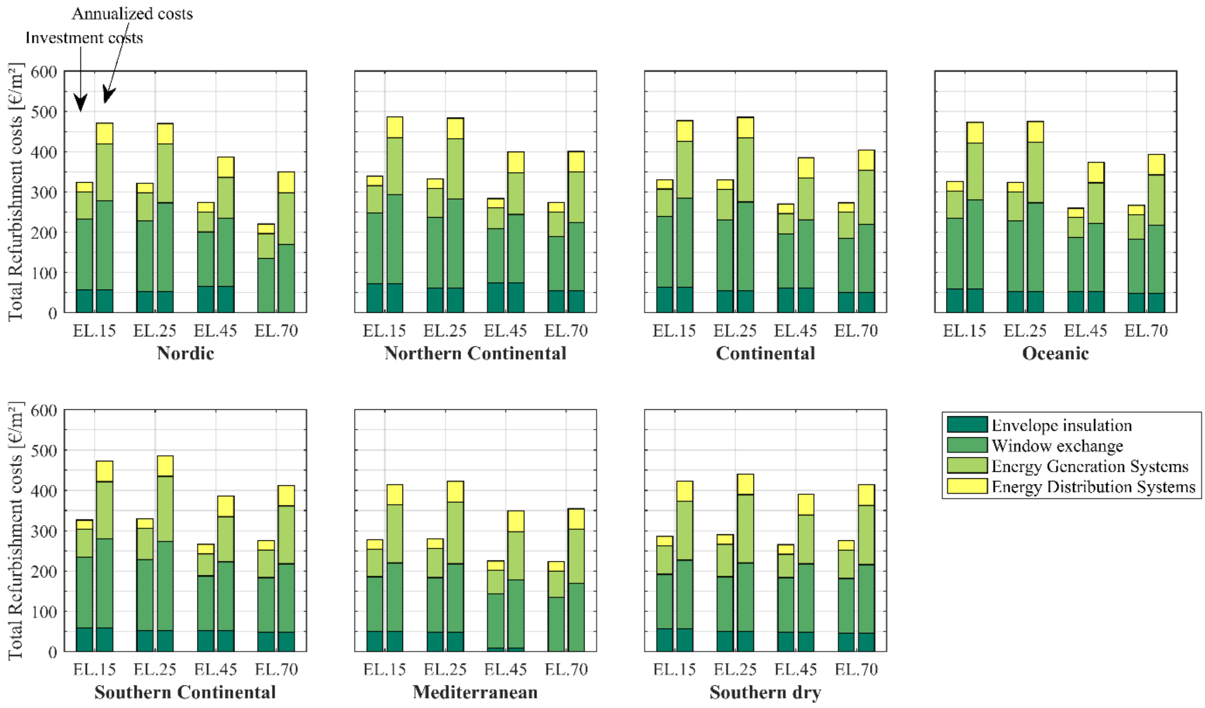

Figure 26 – Investment costs distribution (first year investment and annualized costs over 30 years) without solar systems (35 °C water distribution temperature)

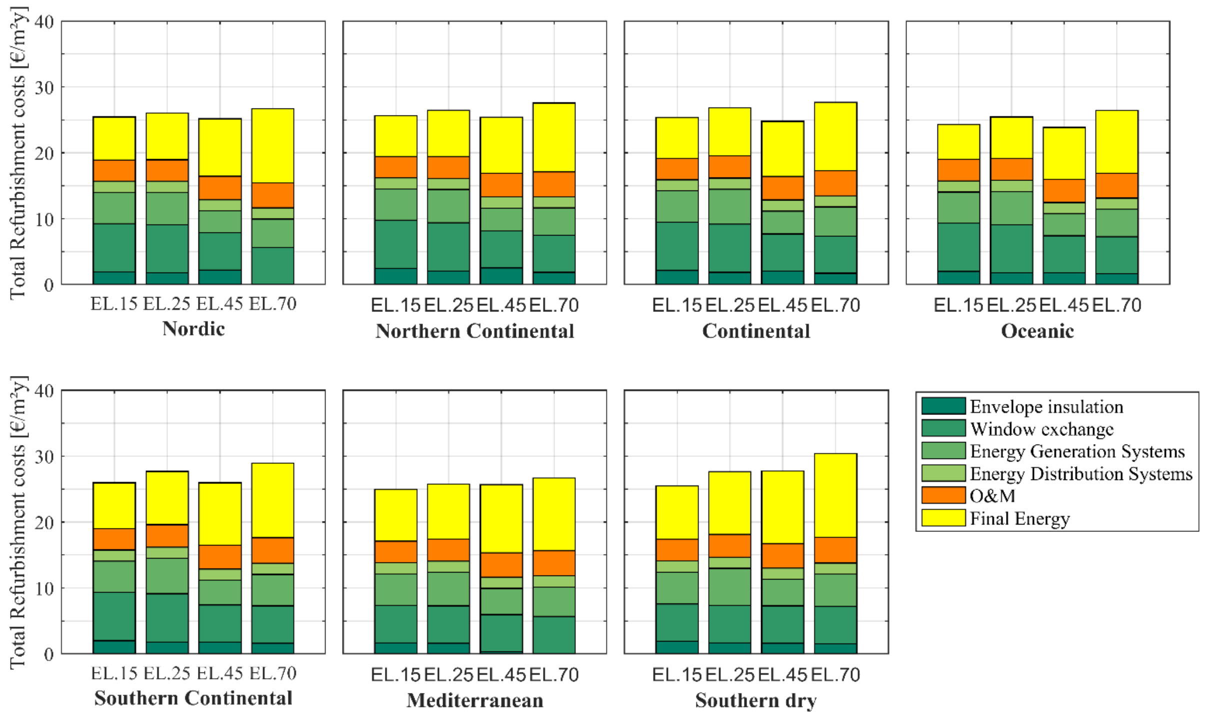

Figure 27 – Annualised costs distribution for variants without solar systems

2.4.4 Economic evaluations

In terms of investment costs, considerations on the case air to water heat pump + radiant ceilings are valid also here. A larger difference lies in the annualized costs as the lifespan of fan coils is supposed to be 15 years, thus the calculation includes a complete substitution of the units (Figure 26).

Figure 27 shows as annualized costs for investment, maintenance and final energy are higher than in Figure 9 due to the higher final energy consumption. The difference amounts to around 10% for all the climates.

Annualised costs in the range of 150-220 €/m² are assessed for generation + distribution system, resulting again in 24 – 30 €/m^{2}y overall annualised costs.

2.5 Ground Source Heat Pump with Fan Coils

As already stated in the previous cases, those behaviour similar to other cases are not here re-presented. More graphs that show in details the results are in section 3.6.

2.5.1 Final Energy, and Primary Energy

Comparing the cases with ground water heat pump and air to water heat pump both with fan coils, the former has lower final energy consumption due to heat pump performance when working in a more profitable range of working conditions at the evaporator. In absolute terms, the maximum difference is in the range of 2.5 kWh/m²y in the northern climates for the heating and 3.5 kWh/m²y in the warmer climates for the cooling.

Comparing this case to the one with ground source heat pump and radiant ceilings, higher electricity is consumed both for space heating and cooling (around 10% more) due mainly to fan coils, while the electricity used at the heat pump is almost unaffected, despite the different water temperatures at distribution.

Again, also in this case, only with few configurations, it is possible to achieve the target of 50 kWh/m²y of primary energy consumption.

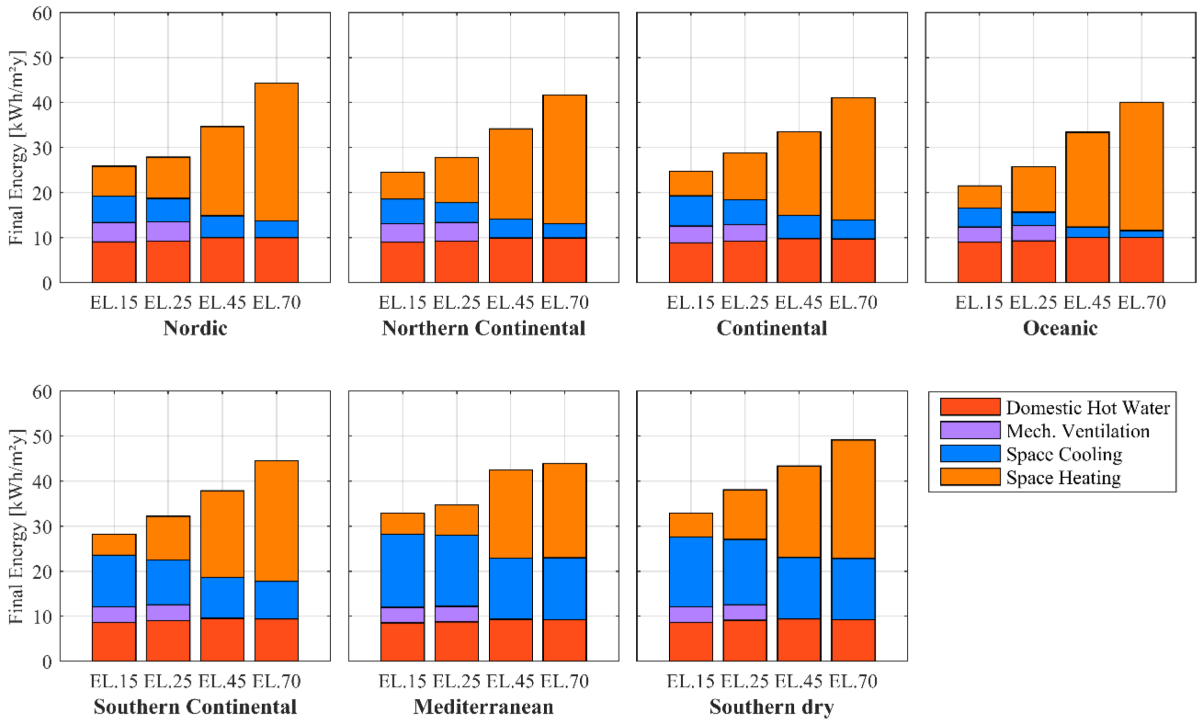

Figure 28 - Final energy distribution without solar systems, and a heating water temperature level of 35°C.

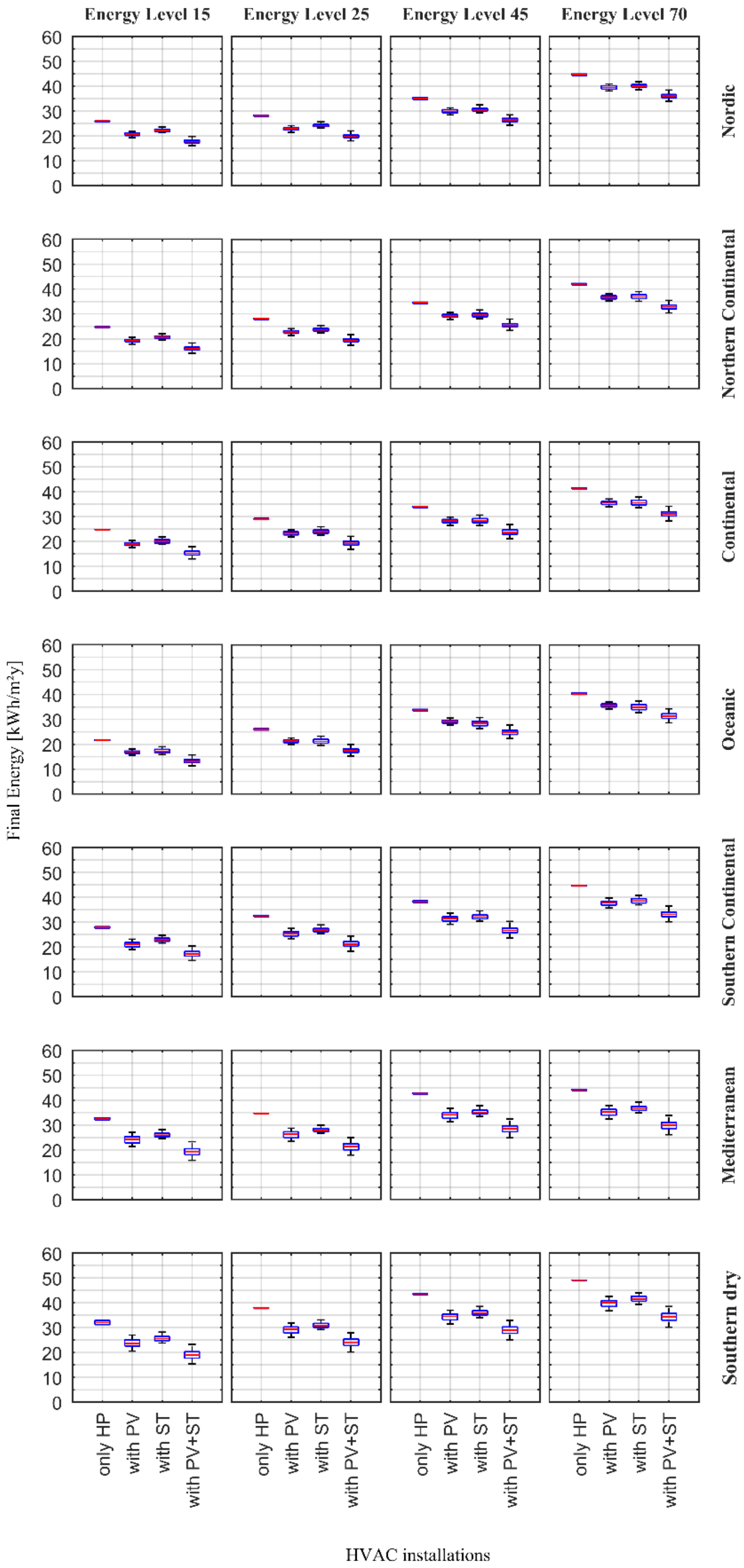

Figure 29 - Total final energy range for different HVAC installation types

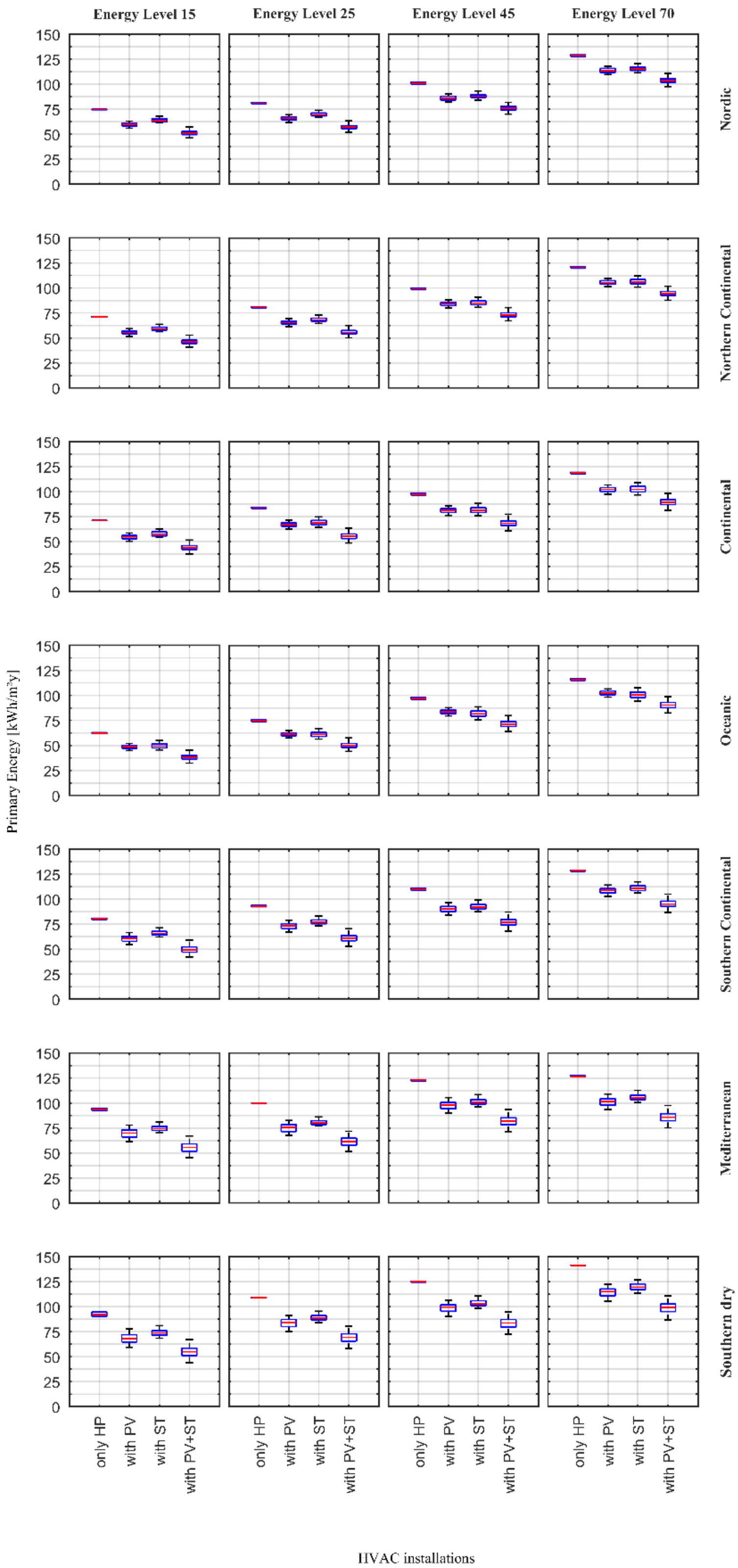

Figure 30 - Total primary energy range for different HVAC installation types

2.5.2 Economic evaluations

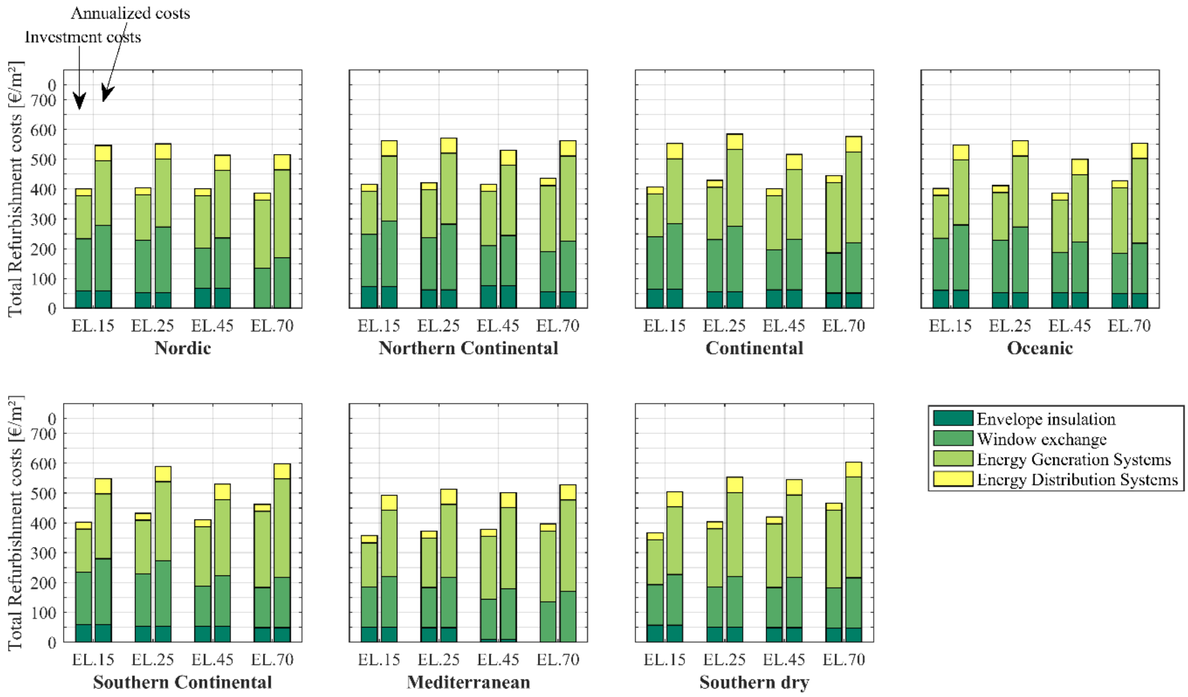

Figure 31 - Investment costs distribution (first year investment and annualized costs over 30 years) without solar systems (35 °C water distribution temperature)

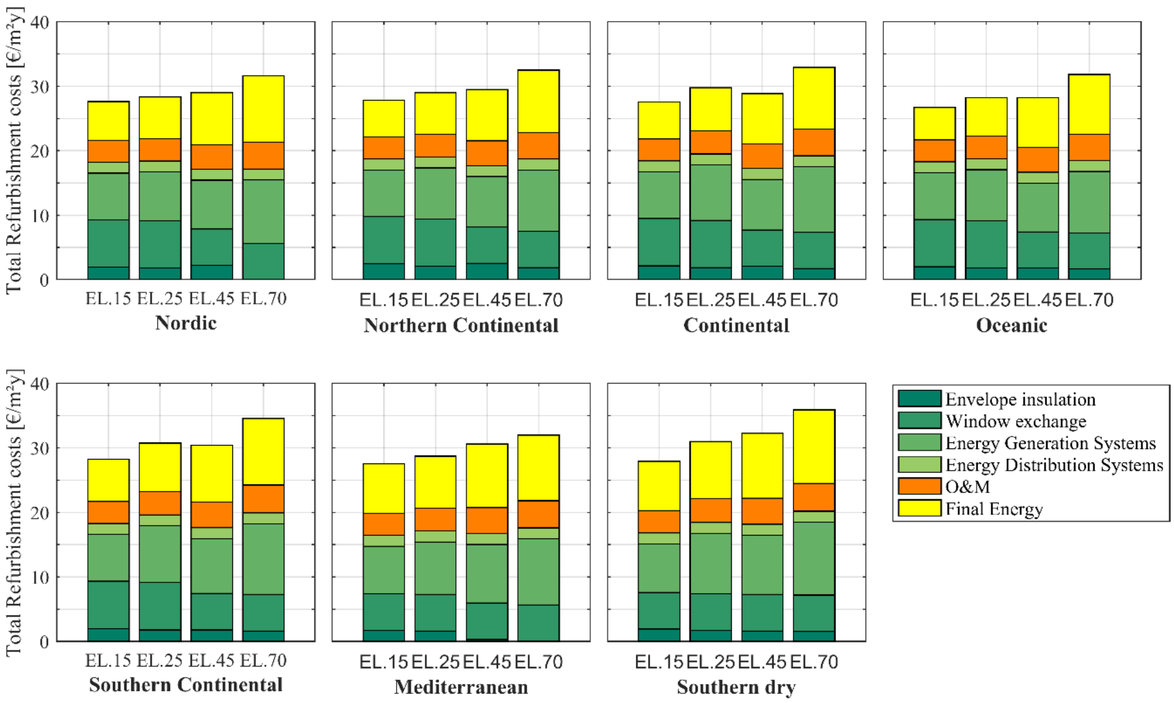

Figure 32 – Yearly annualised costs distribution for variants without solar systems

As already stated in par. 2.2.2, the additional investment costs shown in Figure 31 in comparison to Figure 26, are due to the extra cost of geothermal probes and fan coils as it is foreseen to install one fan coils per room (5 per dwelling).

The investment costs for distribution and generation system range between 170 €/m² (lower energy level buildings 15 kWh/m²y) and 285 €/m² (higher energy level buildings, 70 kWh/m²y). The annualised costs, consequently, vary between 500 and 600 €/m².

When considering the maintenance and final energy costs too, it results that the highest yearly annualized costs lies in the southern climates in buildings with low energy efficiency, with a total of 36 €/m²y, while the lowest costs are assessed in the northern ones and highly energy efficient buildings with around 27 €/m²y.

The investment costs for the renovation (envelope, windows, generation and distribution system) impact by about 50 - 70% on the total yearly annualised costs.

2.6 Gas and Pellet Boilers with Fan Coils

The same trends and considerations applies for boilers driven solutions as for heat pumps driven. Therefore, the results are not further discussed and main results are reported in Annex I, section 3.7 and 3.8 for the eventual comparison with other relevant cases.

2.7 Air Source Heat Pump with Radiators

The configuration with radiators has been simulated twice for the same case, once with a design supply temperature of 35 °C and once with 45 °C, with relative sizes.

2.7.1 Used Energy

Figure 33 shows Used Energy for both heating and cooling for the range of energy levels. The behaviour is similar to the one already presented in section 2.4.1.

Cooling demand is covered by split units that work as the fan coils in terms of latent and sensible heat treatment.

The ten dwellings have a cooling load between 2.2 and 2.8 kW. One split unit per apartment with a rated cooling capacity of 2.5 kW (around 8500 Btu/hr) has been selected for all simulations.

As for fan coils Used Energy is very near to target space heating demands (15, 25, 40, 70 kWh/m²y) due to the prevalent convective contribution provided by radiators used as distribution system.

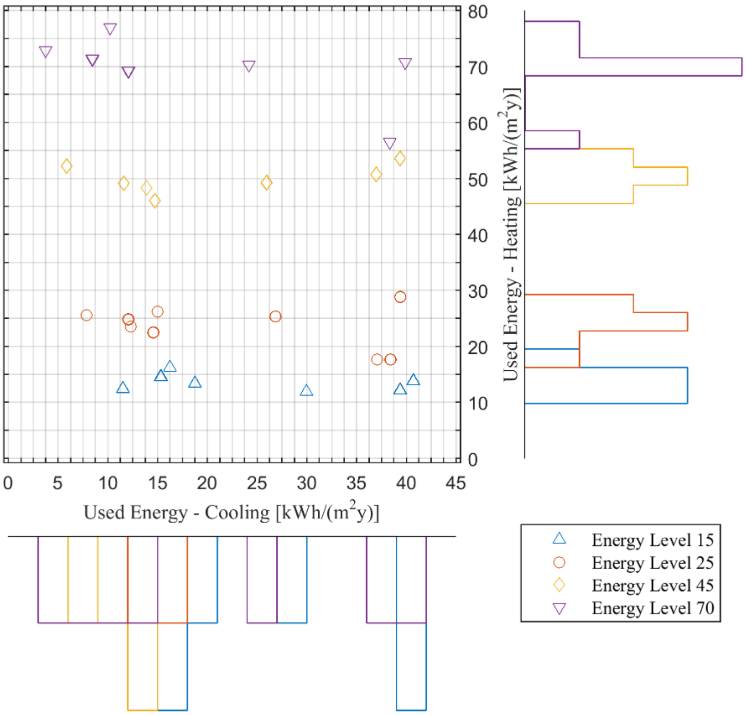

Figure 33 – Used Energy for heating and cooling of the different energy standard

2.7.2 Thermal Comfort

The heating comfort levels follow the same behaviour as in the previous cases (refer to section. 2.1.2).

Using split units leads to an excellent summer thermal comfort. The highest cooling penalty refers to the southern climates, intermediate floors where cooling loads are higher than the other flats (see Figure 34 and Figure 35).

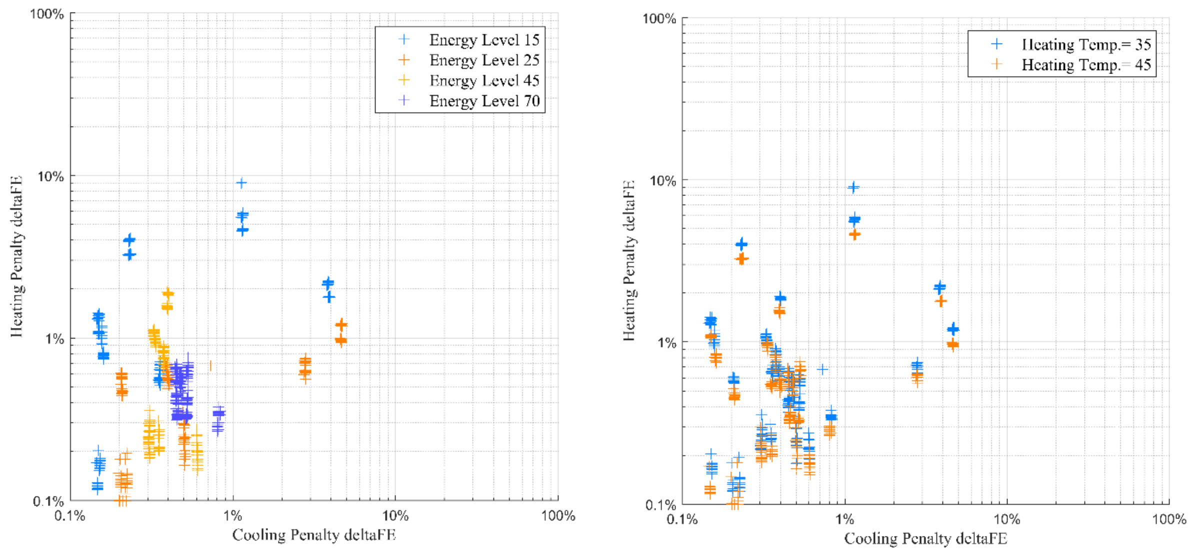

Figure 34 - Cooling and Heating penalty functions for different energy levels and heating water temperature

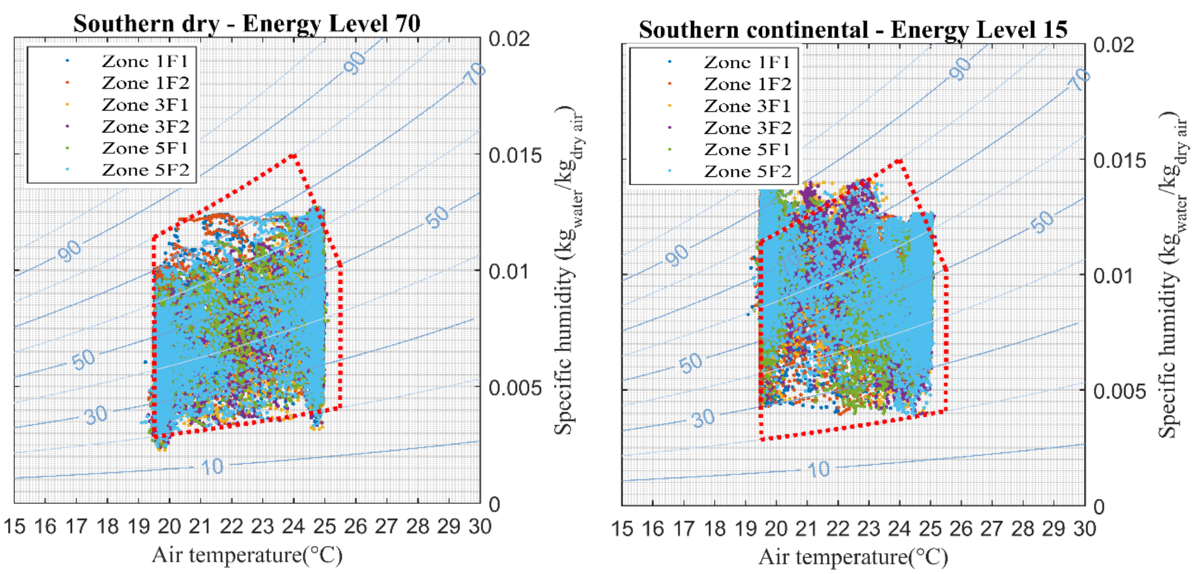

Figure 35 - Psychometric charts of {Southern dry, Energy Level 70, heating water temperature 35°C} and {Southern continental, Energy Level 15, heating water temperature 35°C}

2.7.3 Final Energy, SPF and Primary Energy

Figure 36 shows the final energy consumption of the HVAC system simulated (distribution water temperature 35°C). The base cases without solar energy utilisation are reported once more.

Lower final energy consumption compared to the previous case is encountered due to the missing fans' electricity consumption. Lower is also the final energy use compared to the case with radiant ceiling due to the lower used energy (see section 2.1.1)

For all the cases, the final energy ranges between 20 and 40 kWh/m²y for the highest heating demands buildings.

For the SPF of heating, same considerations already presented in section 2.1.3 are valid as same generation unit and supply temperatures are used. Regarding the SPF of cooling, instead, we have to refer to the values presented in section 2.3.1. In all the cases, the SPF is higher than 5.

The overall SPF varies from 2.4 in the northern climates in building with high efficiency buildings and 3.7 in the southern climates with low efficient buildings. This result is due to higher COP during the winter season in the warmer climates, despite the higher EER in the northern climates due to the more favorable external temperatures.

The water distribution temperature only plays a role on the final energy utilisation in the cases analysed (35 – 45°C), having an impact only on the winter operation. The SPF related to space heating increases significantly around 2.5 to 3.5, and final energy (as much as primary energy) reduces by around 20 %.

On the other hand, the lowest temperature leads to very large radiators for the high Energy Level cases (70 kWh/m^{2}y), with impractical frontal areas of more than 2 m^2 per room.

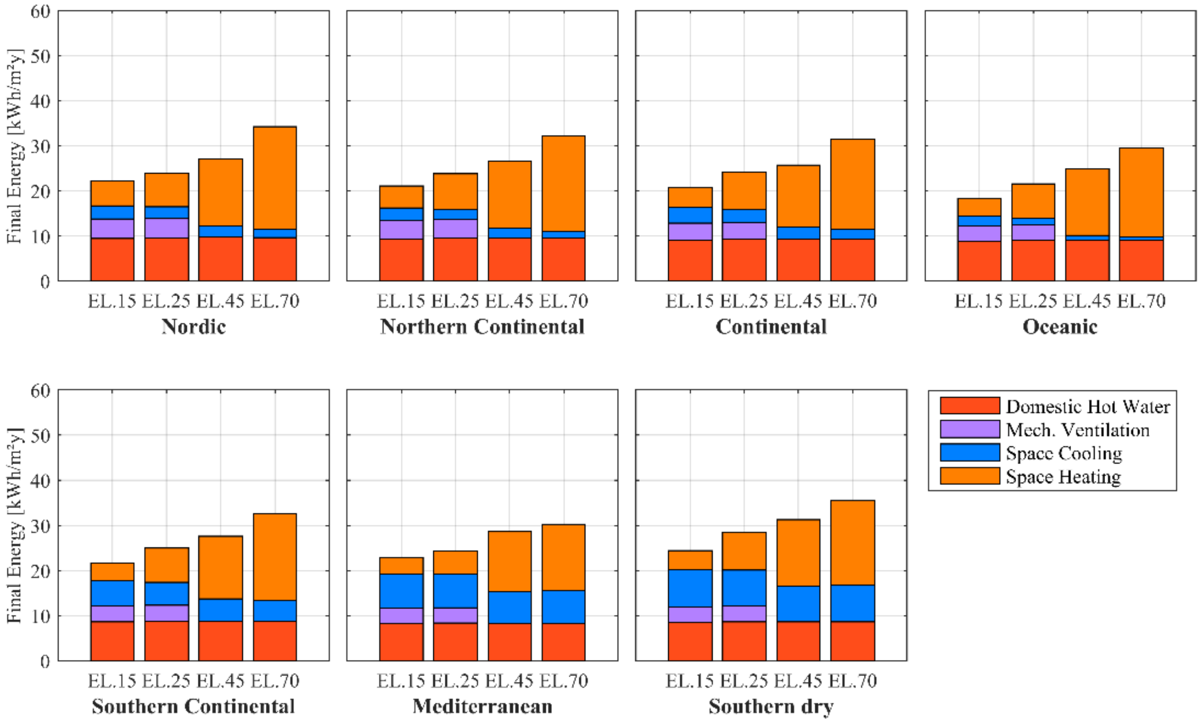

Figure 36 – Final energy distribution without solar systems and a heating water temperature level of 35°C.

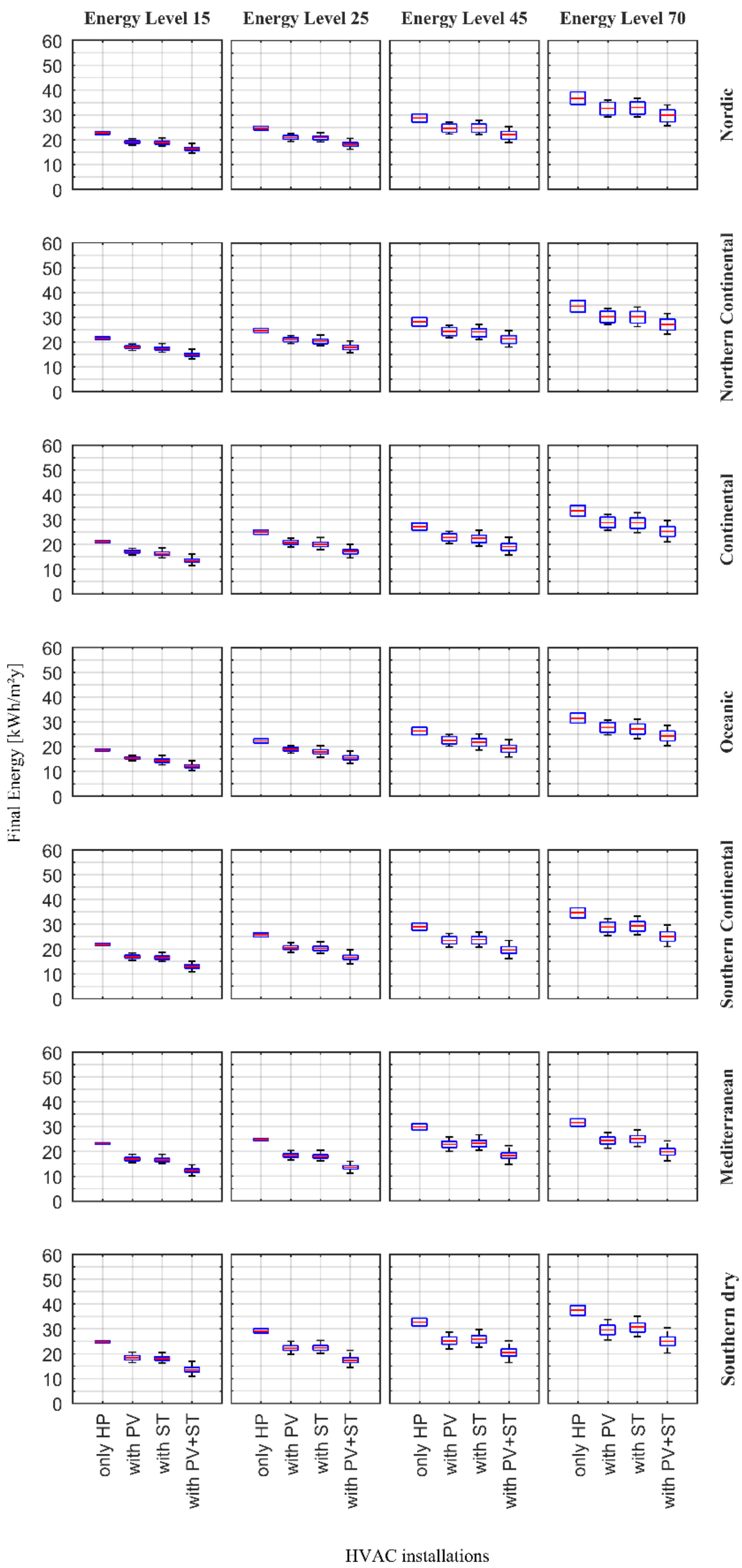

Figure 37 – Total final energy range for different HVAC installation types with solar variants

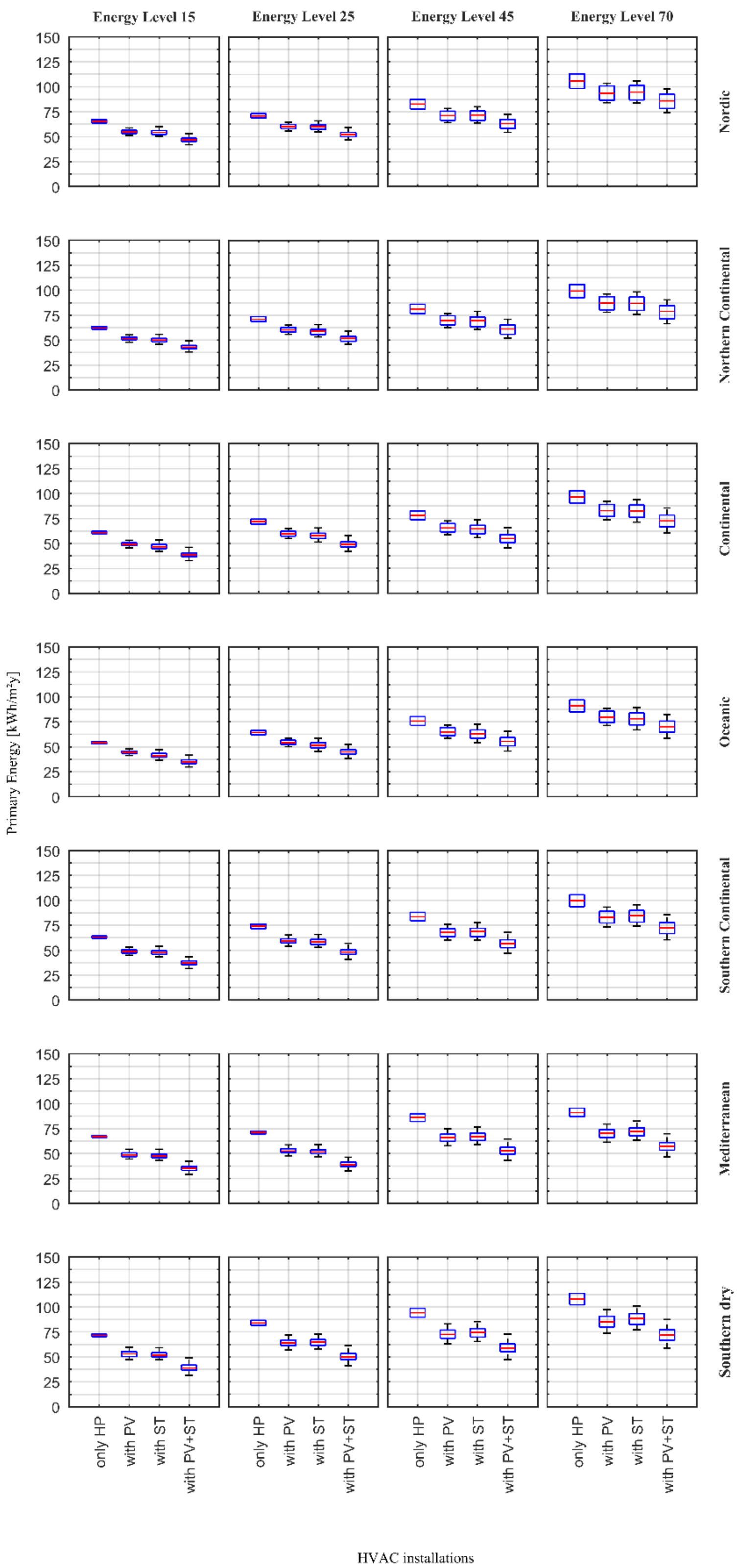

Figure 38 – Total primary energy range for different HVAC installation types with solar variants

Although the final energy consumption is slightly lower, none of these solutions is sufficient to reach the 50 kWh/m²y of Primary Energy consumption without the combination with solar technologies.

Considering a distribution temperature of 35°C, buildings with energy level 15 and 25 kWh/m²y and small solar ST or PV fields can achieve the target of the 50 kWh/m²y. The same is valid for the buildings with energy level 45 kWh/m²y, except for the Northern Continental and Nordic climates. If a supply temperature of 45°C is used, almost none of the buildings with energy level 45 kWh/m²y can achieve the target (see Figure 38). Buildings with energy level 70 kWh/m²y instead, cannot achieve the primary energy consumption level even with solar systems.

2.7.4 Economic evaluations

The same conclusions as for the other air-to-water cases can be drawn here. Annualised costs in the range of 210-290 €/m² are assessed for the generation and distribution system.

Yearly annualised costs including maintenance and energy used are again in the same range as the air-to-water cases, since the effect of using different distribution temperatures is limited.

Overall Yearly annualised costs between 22 and 27 €/m²y are calculated.

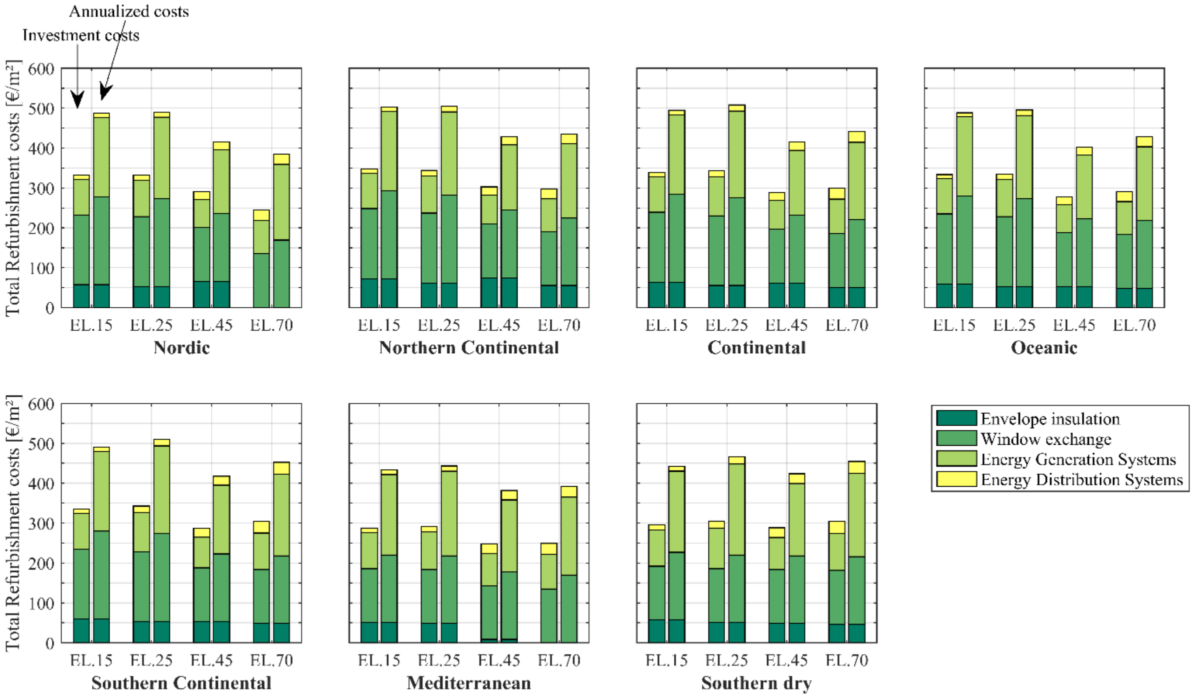

Figure 39 – Investment costs distribution (first year investment and annualized costs) without solar systems (35 °C water distribution temperature)

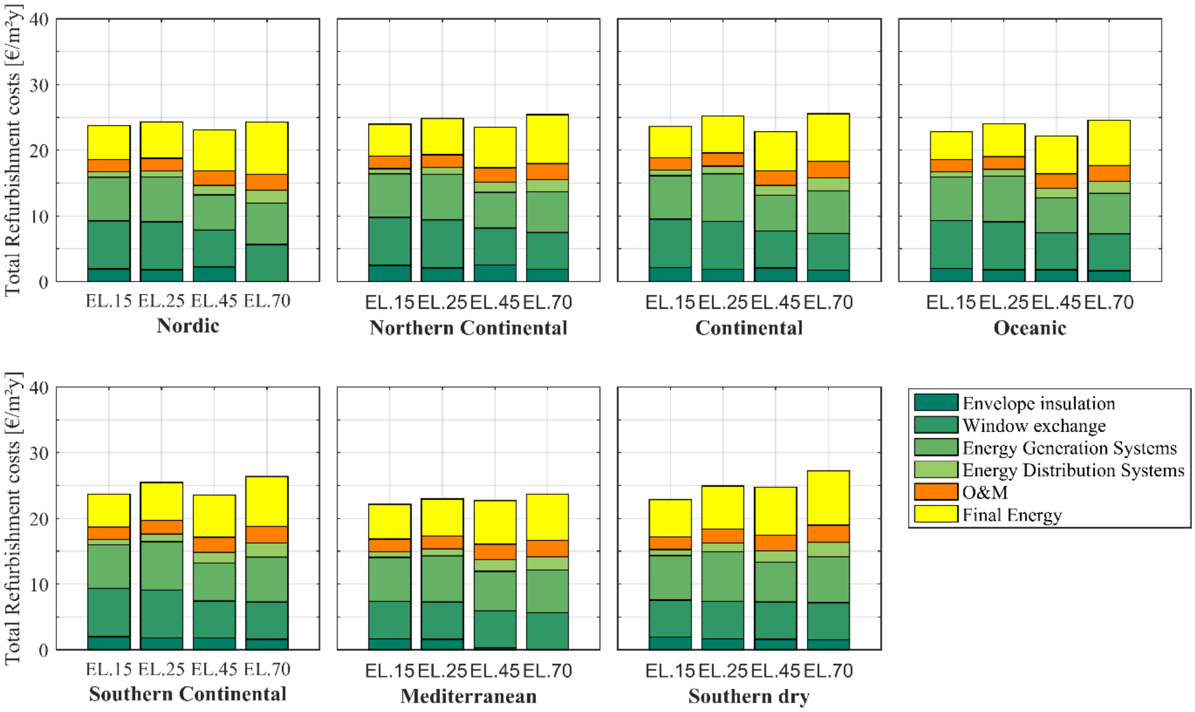

Figure 40 - Yearly annualised costs distribution for variants without solar systems

2.8 Ground Source Heat Pump with Radiators

Having the same distribution system as in the previous case, Used Energy and comfort conditions are affected in the same way. As such we limit the discussion here to the main differences noticed with air source heat pumps and report main results in Annex I for eventual further evaluations by the reader.

Figure 41 shows the Final Energy consumption of the H&C system simulated following the energy uses reported (distribution water temperature 35 °C). The base cases without solar energy utilisation are reported as in the previous sections.

The results are fully in line with the ground source heat pump and radiant ceilings systems since electricity is only used to drive heat pump, hot/cold water through the pipelines and for mechanical ventilation.

Again, SPF figures vary between 2.6 and 3.0 with respect to the heating loads and between 5.0 and 5.6 looking at the cooling loads. Similar to the space heating, the SPFs related to the DHW preparation ranges between 2.1 and 2.3. The overall SPF accounting for heating, cooling DHW loads and ventilation varies in a range of 2.3 and 3.1.

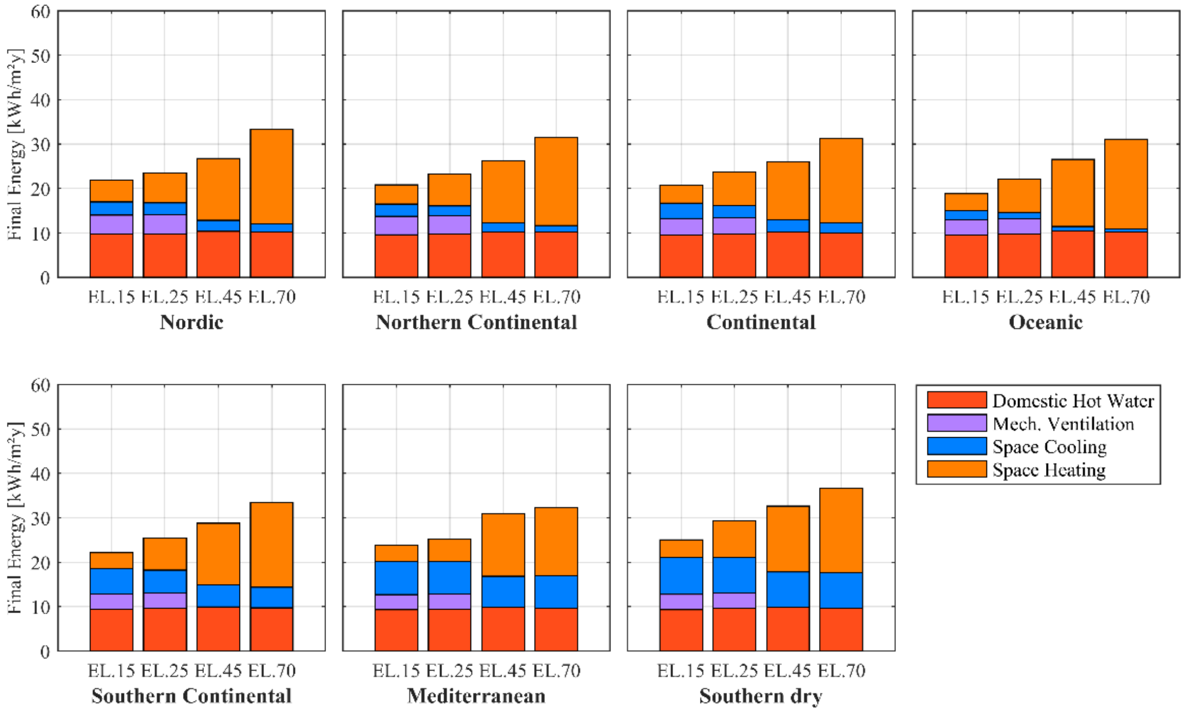

Figure 41 - Final energy distribution without solar systems and a heating water temperature level of 35°C.

The economics are well in line with the results reported in section 3.10, the distribution system costs contributing only marginally. The energy costs are only slightly higher – around 5 €/m²y, 10 % – due to the increased electricity used.

As stated in the previous cases, an additional investment cost is due to the geothermal probes for an amount around 100 €/m² with respect to the case with air to water heat pump. Consequently, yearly annualized costs for energy generation and distribution systems vary from 290 €/m to 430 €/m².

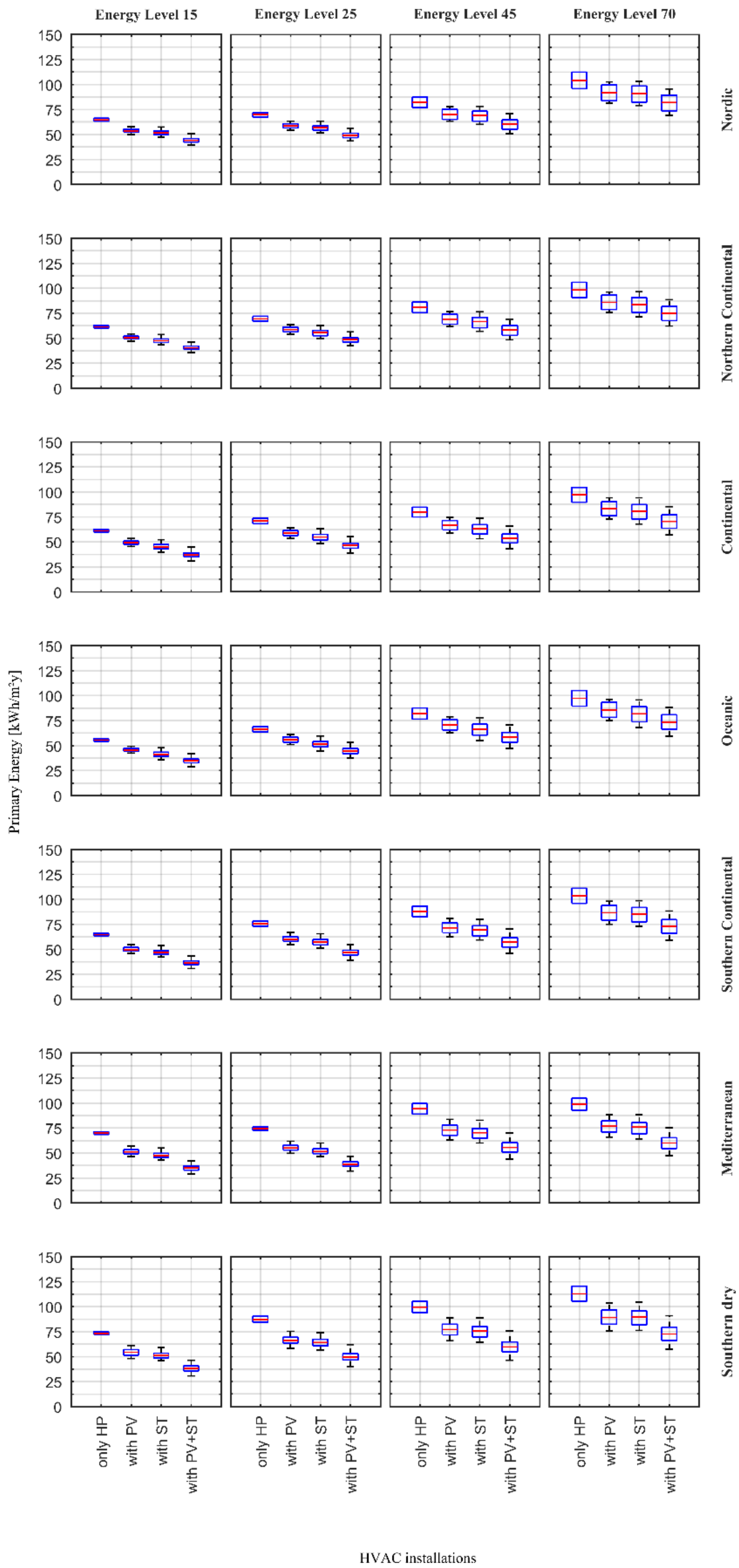

Figure 42 - Total primary energy range for different HVAC installation types.

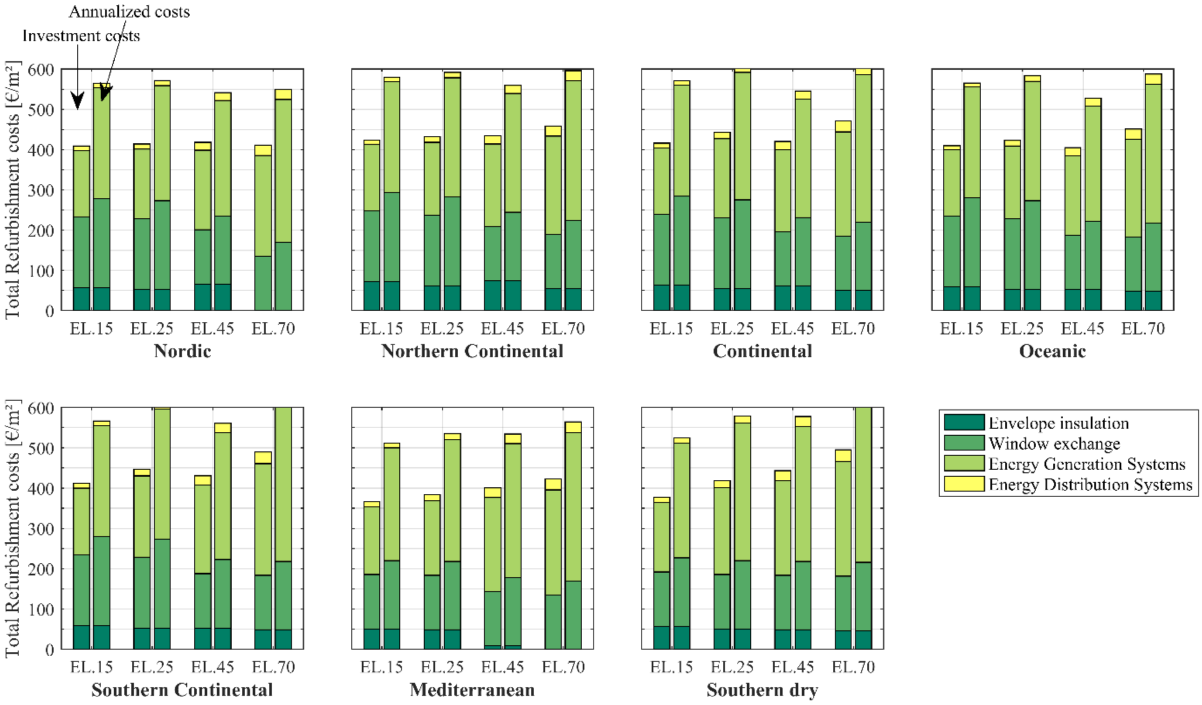

Figure 43 – Investment costs distribution (first year investment and annualized costs) without solar systems (45 °C water distribution temperature)

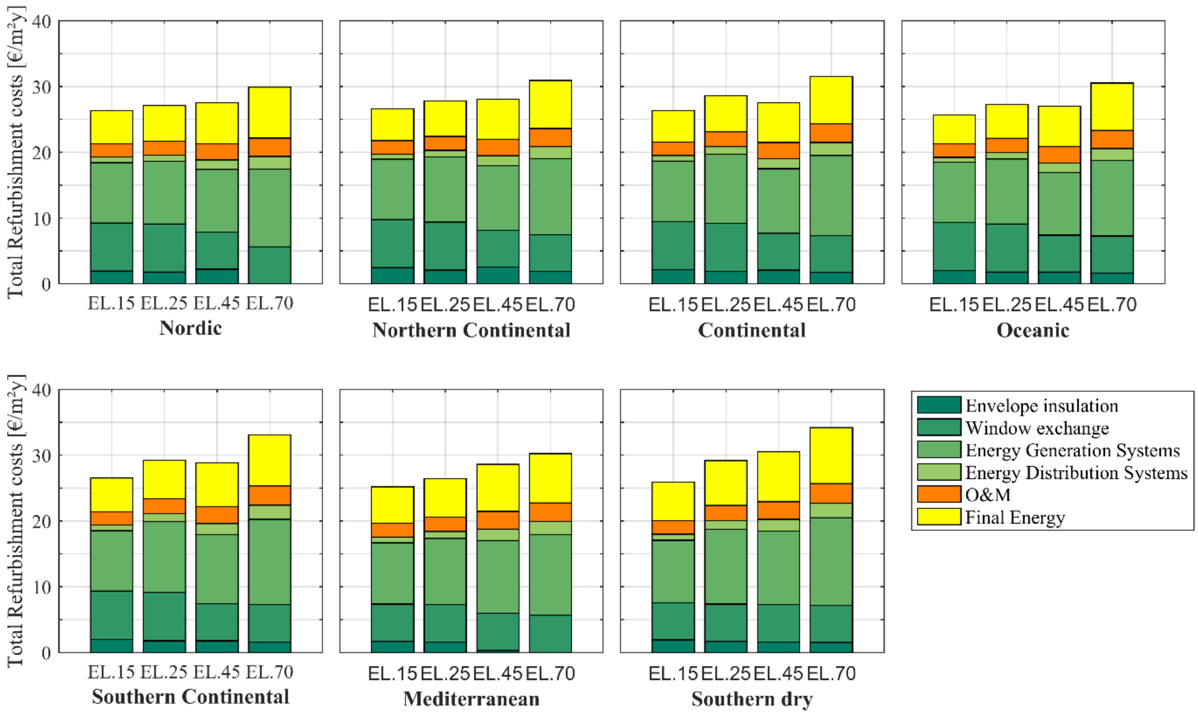

Figure 44 - Yearly annualised costs distribution for variants without solar systems

Over 30 years, it results that the higher final energy consumption of buildings with higher heating demand is compensated by the lower costs for the generation and distribution systems (mainly lower windows quality and no mechanical ventilation). In some cases, in fact, the lowest yearly annualized costs, where also maintenance is considered, is verified for those buildings with energy level 45 kWh/m²y.

In general, the overall annualized costs in all the countries is attested below 25 and 35 €/m²y (see Figure 44).

2.9 Gas and Pellet Boiler with Radiators

2.9.1 Gas boiler solutions

For what concerns the energy effectiveness, gas boilers hardly allow to reach the 50 kWh/m^{2}y primary energy consumption. Better results are obtained by using heat pumps: the primary energy reduction is relevant, if we take into consideration the best Energy Levels (15 kWh/m^{2}y space heating demand), in the range of 20 kWh/m^{2}y (around 20%).

When the 70 kWh/m^{2}y space heating demand cases are considered, the reduction is more than double 25 kWh/m^{2}y (around 30%)

With respect to the investment costs, gas boiler solutions are clearly cheaper than heat pump ones in case only space heating and domestic hot water loads are covered. When cooling is also accounted for, the air-to-water heat pump with radiant ceiling solutions is pretty much equivalent to the one considered in this section, since the additional cost of the heat pump is covered by the additional need of split units in this case.

From the energy bill point of view, with the energy tariffs taken as a reference, the gas boiler plant with radiators is always much more expensive, the yearly annualised energy costs varying in between 3000 and 10000 €/y versus 2500 to 5200 €/y in case an air-to-water heat pump with radiant ceiling plant is used.

Consequently, the overall annualised costs of the latter solution are significantly lower - and in general lower than all the other combinations taken into consideration – than gas boilers' ones: 20 – 25 €/m^{2}y versus 23 – 34 €/m^{2}y (solar technologies are not taken into account in this computation).

2.9.2 Pellet boiler solutions

Where the biomass availability is such that the pellet cost is affordable, the study shows that this is the solution allowing to reach the lowest levels of primary energy use. Primary energy values of about 30 - 50 kWh/m^{2}y can be obtained also without exploiting solar energy.

On the other hand, the investment costs to setup a pellet boiler system are significantly higher than the other solutions; the costs associated to a larger space occupation necessary to store the biomass should be also considered (which is not in this study). As already mentioned, on the opposite, solar technologies are not necessary with this combination.

Accordingly, the total overall annualised costs of the latter solutions are comparable with the other combinations taken into consideration ranging in between 23 and 30 €/m^{2}y.

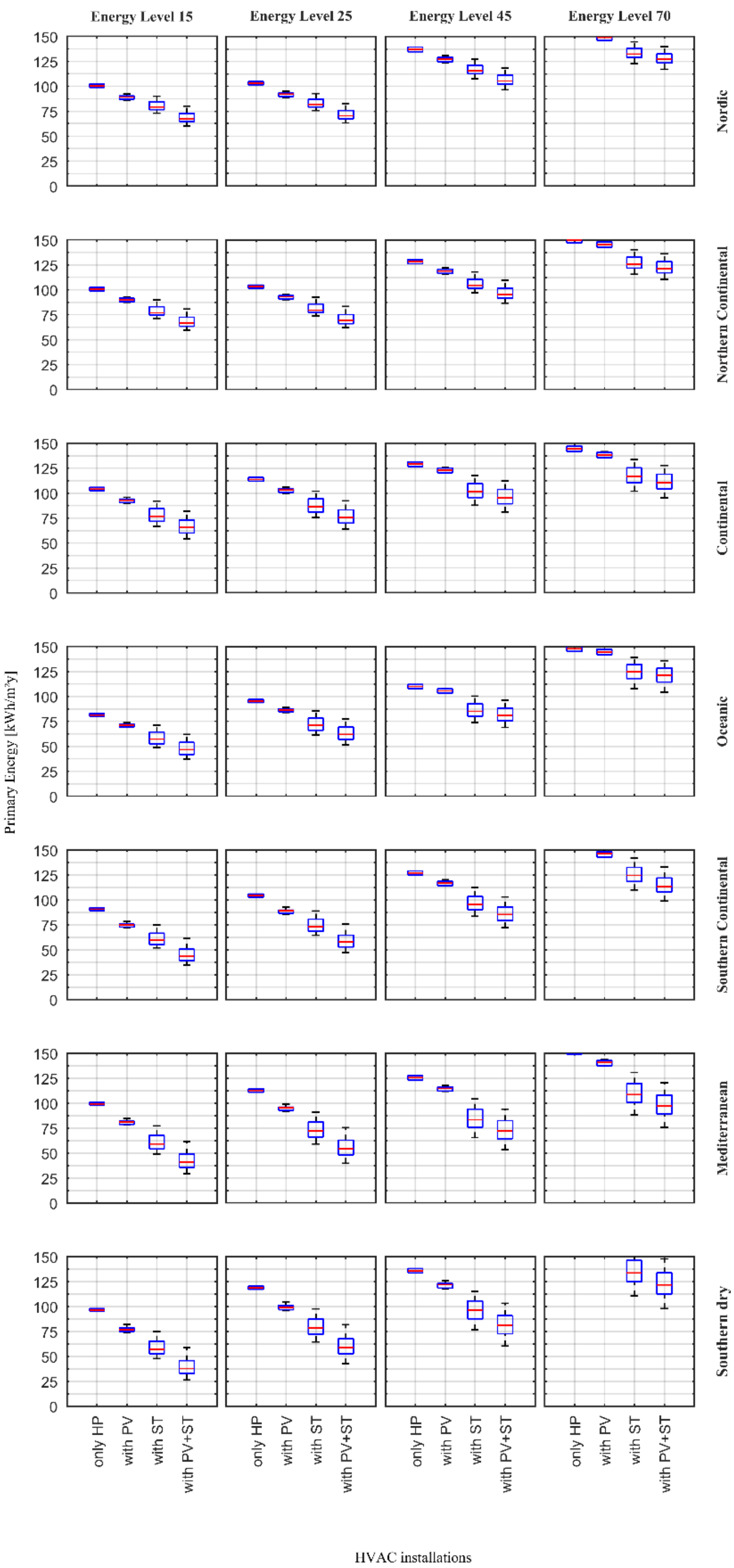

Figure 45 - Total primary energy range for different HVAC installation types with solar variants – Condensing boiler

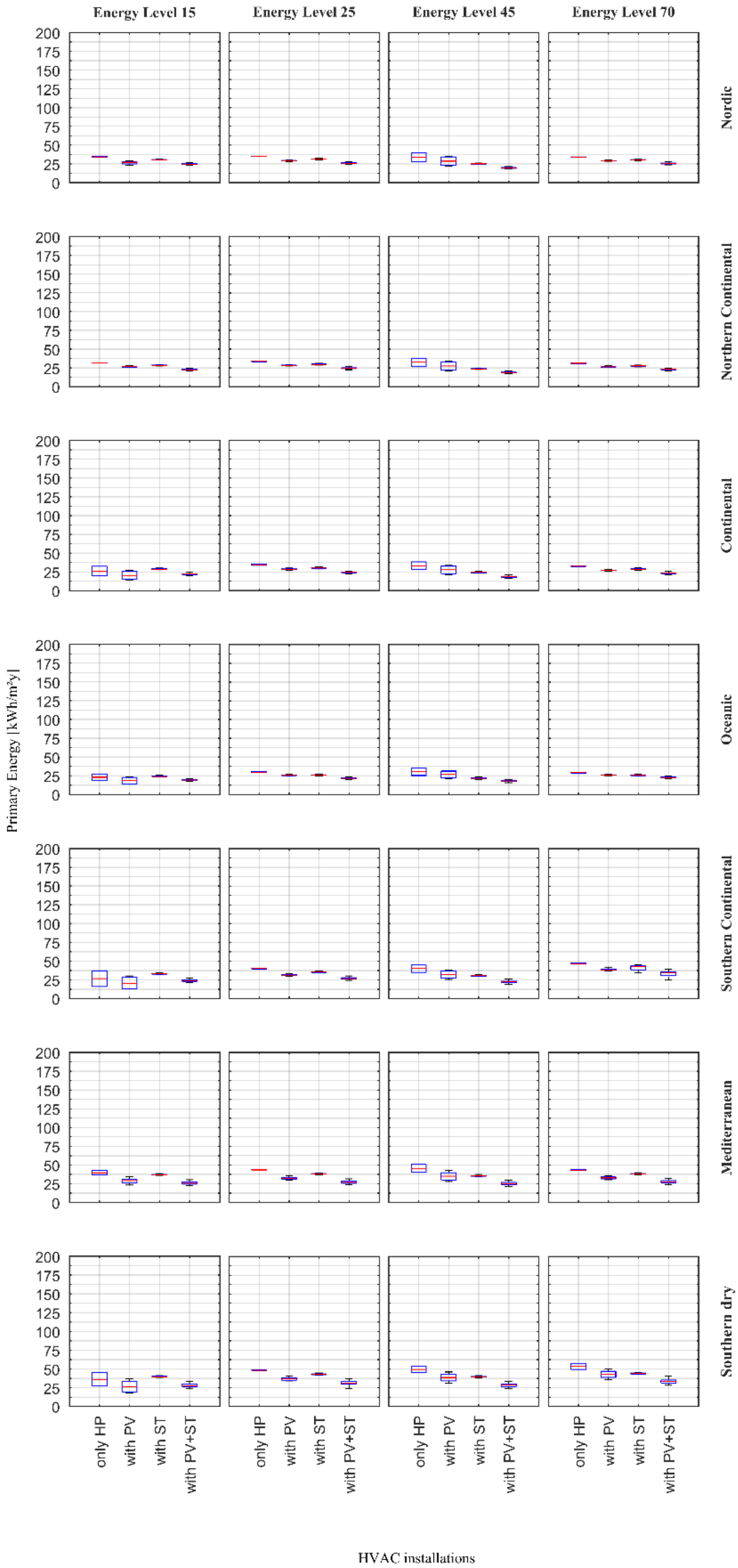

Figure 46 - Total primary energy range for different HVAC installation types with solar variants – Pellet boiler

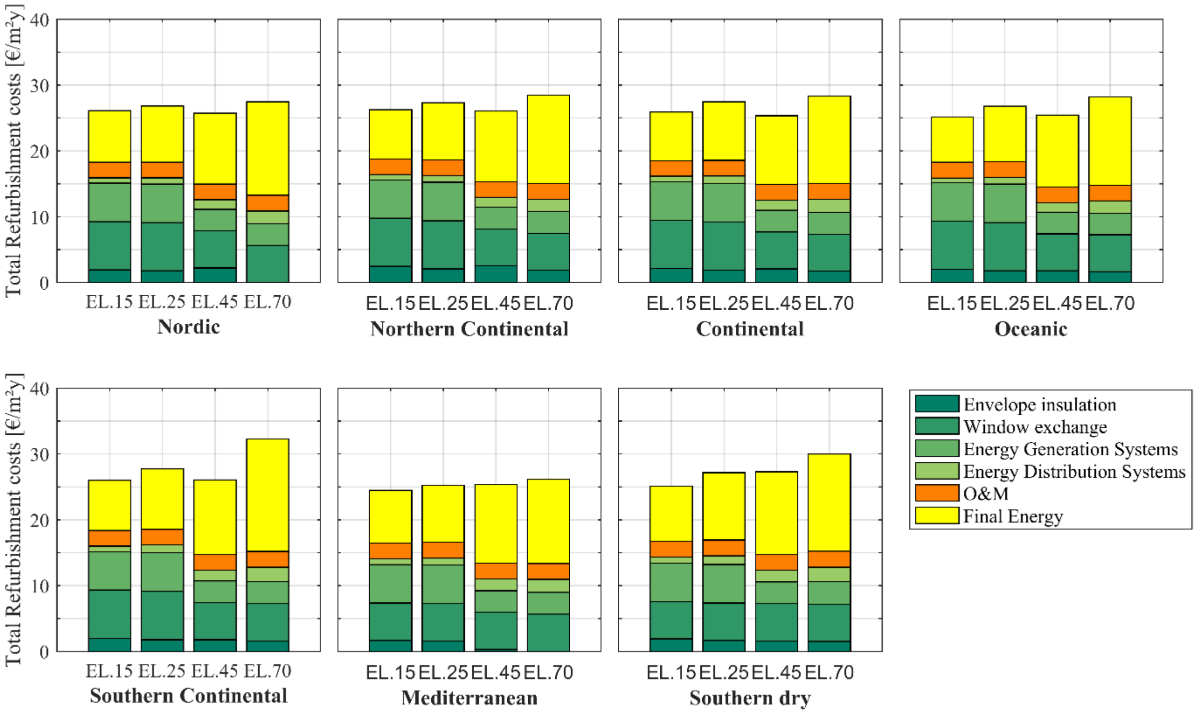

Figure 47 - Yearly annualised costs distribution for variants without solar systems – Gas boiler

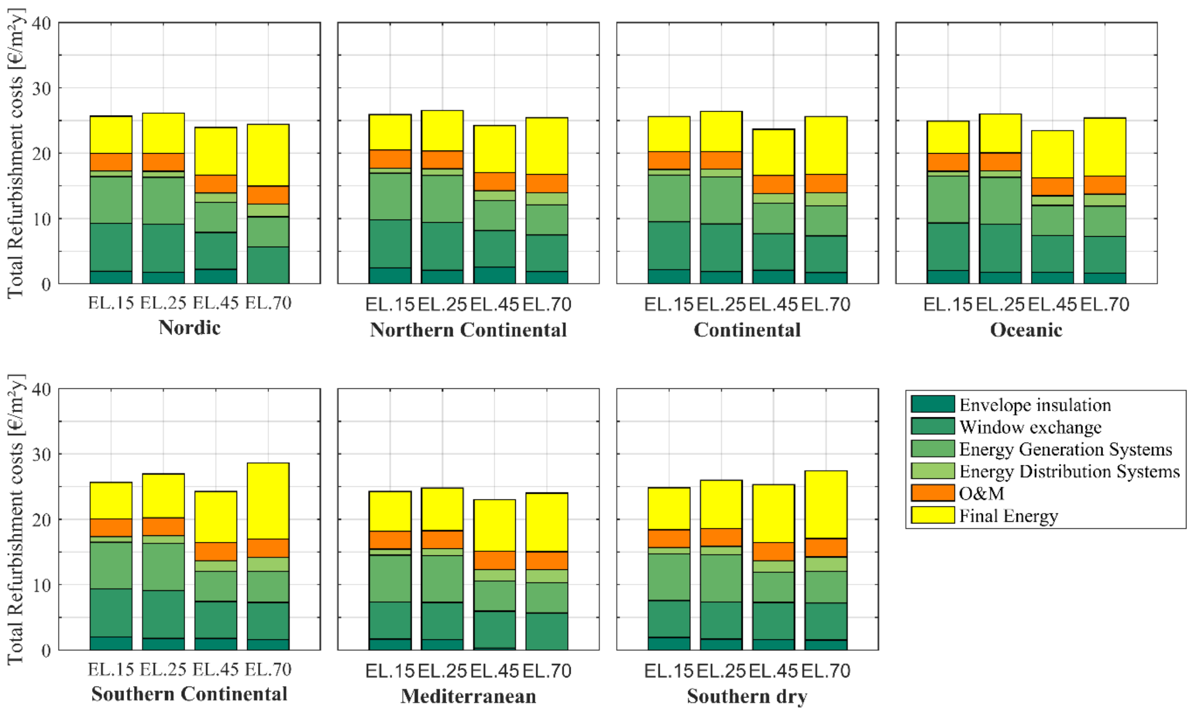

Figure 48 - Yearly annualised costs distribution for variants without solar systems – Pellet Boiler

3 Annex I - Simulation results

3.1 Small Multifamily Houses – Air to water heat pump + radiant ceilings

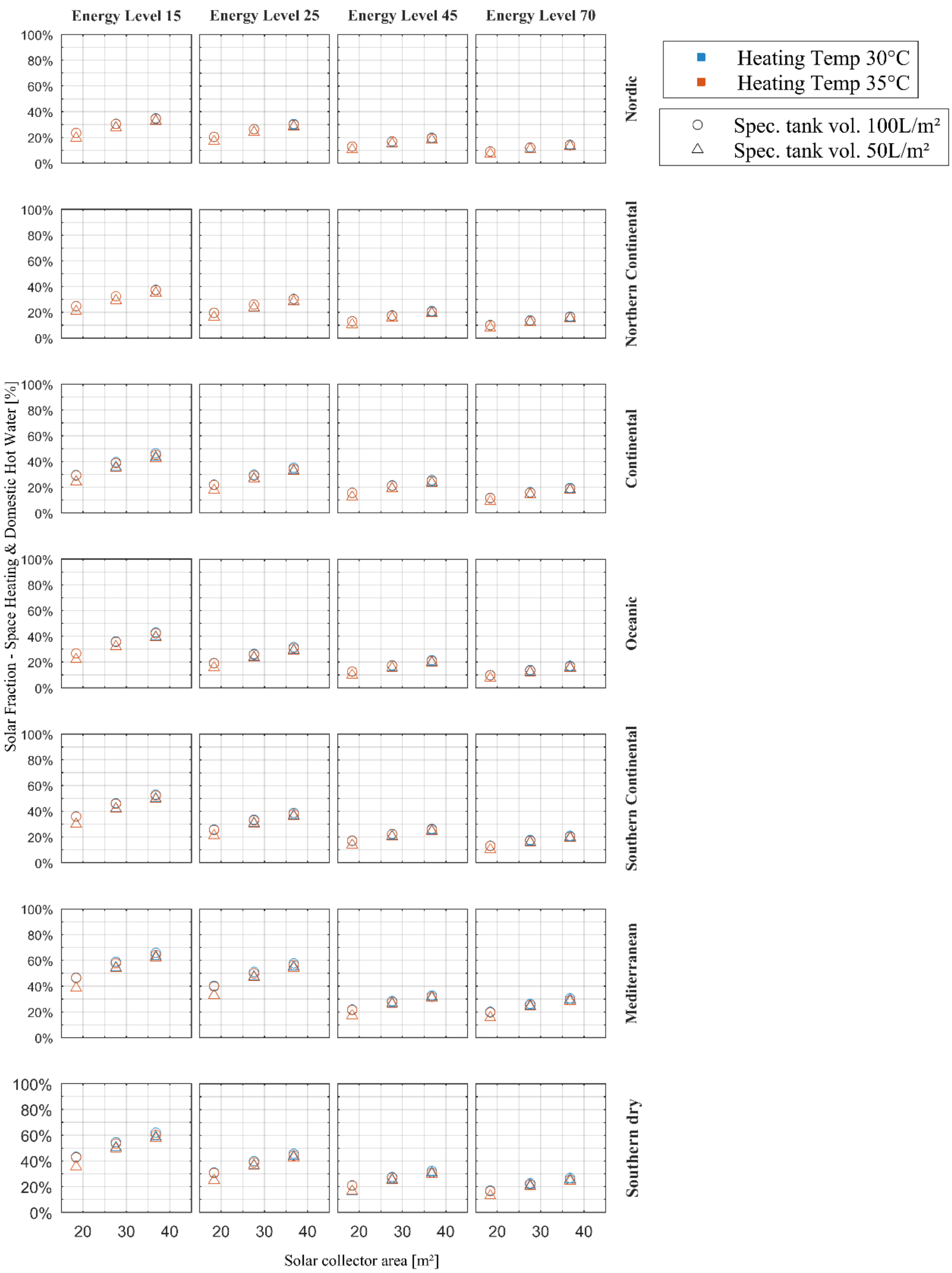

Figure 49 – Solar fraction for Domestic Hot Water and Space heating– 90° collectors' inclination

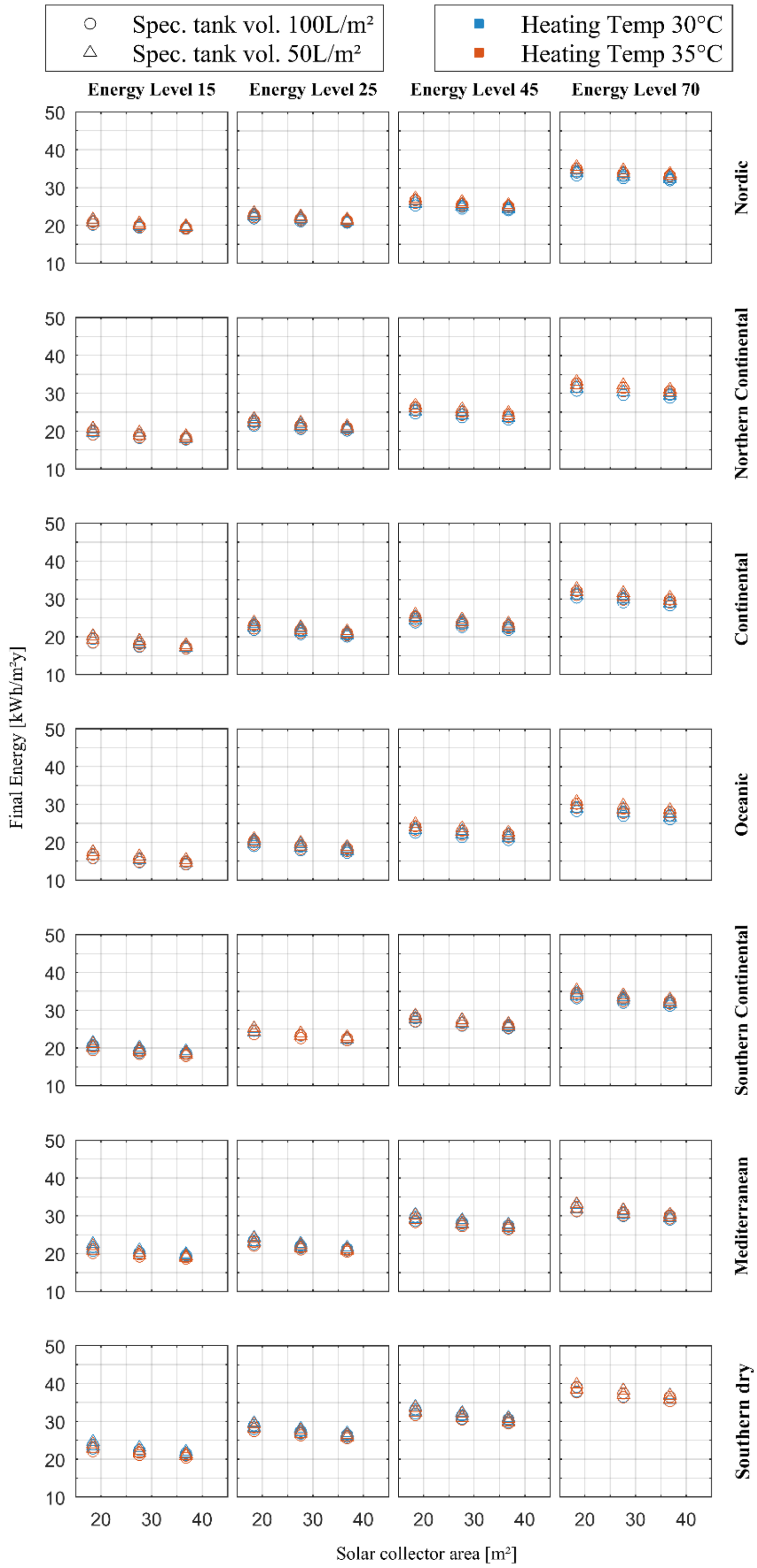

Figure 50 – Total final energy for several variants air-source heat pump and solar thermal system

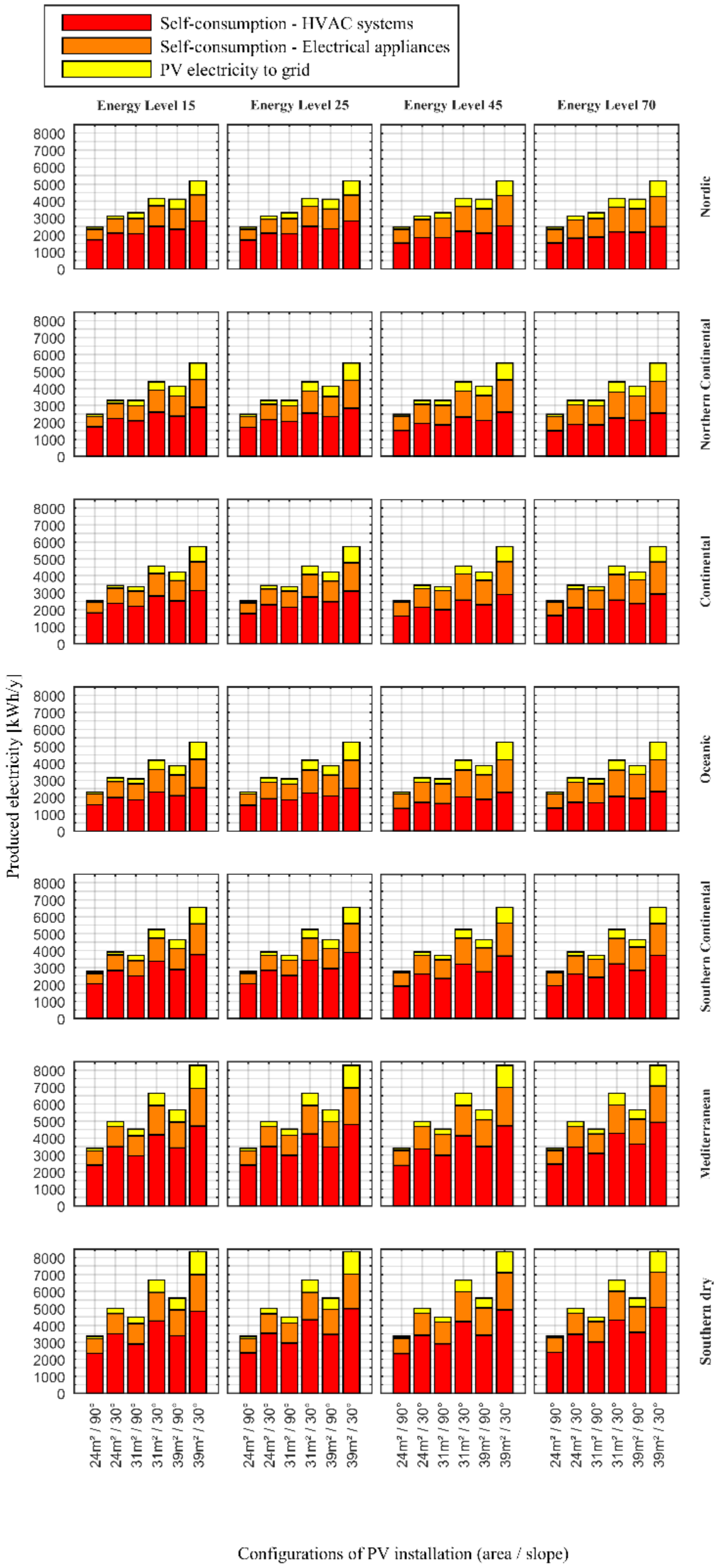

Figure 51 – Photovoltaic electricity

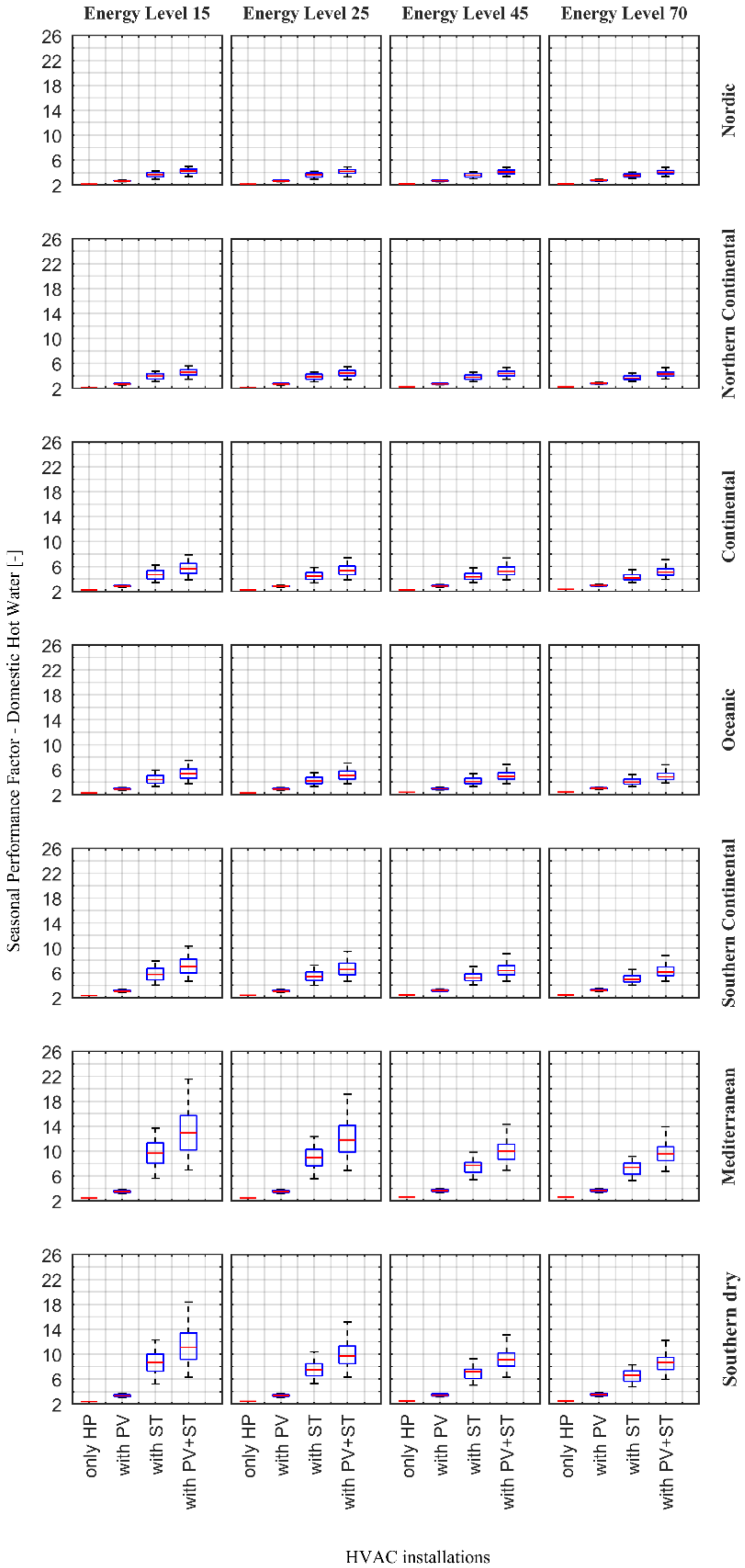

Figure 52 – Seasonal Performance Factor for Domestic Hot Water

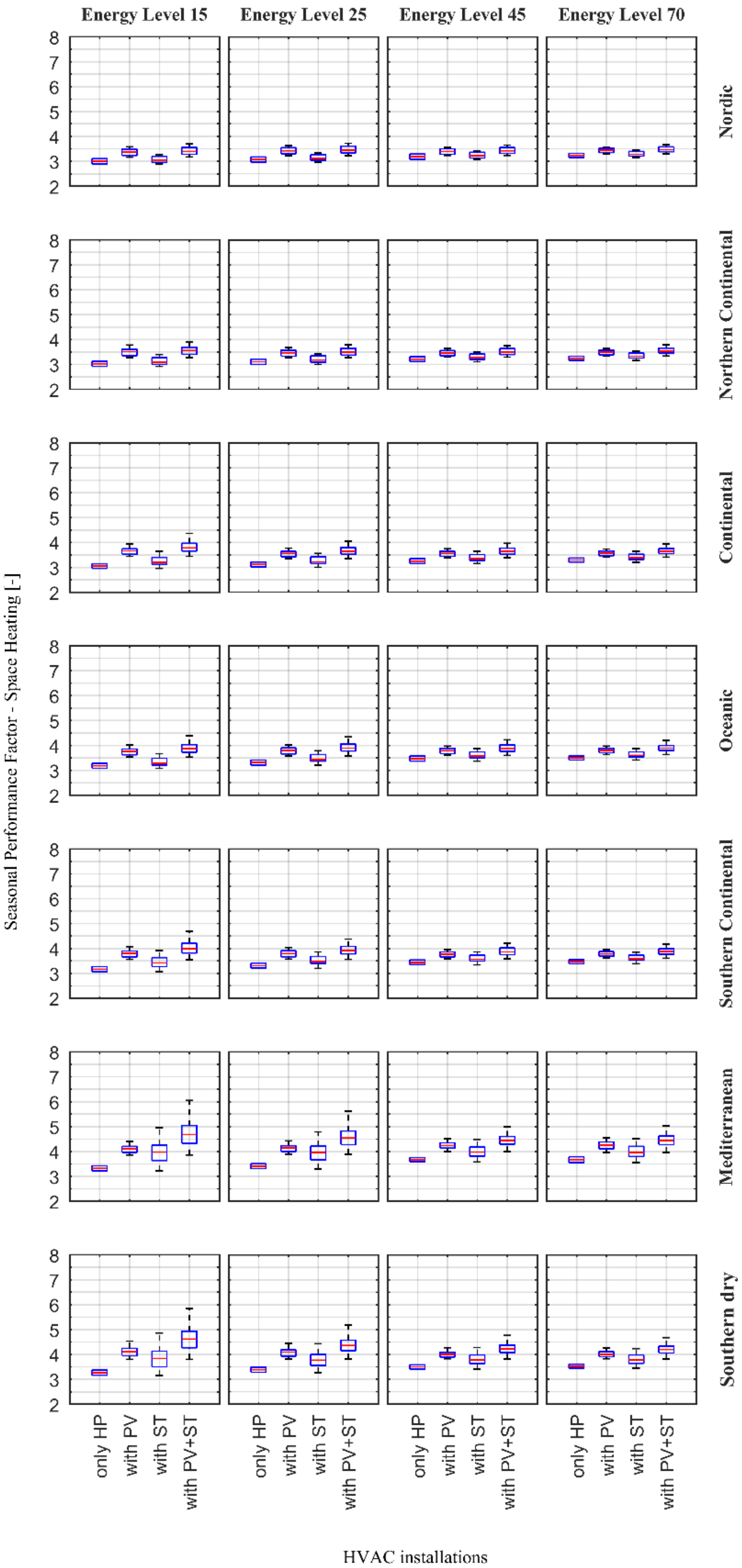

Figure 53 – Seasonal Performance Factor for Space Heating

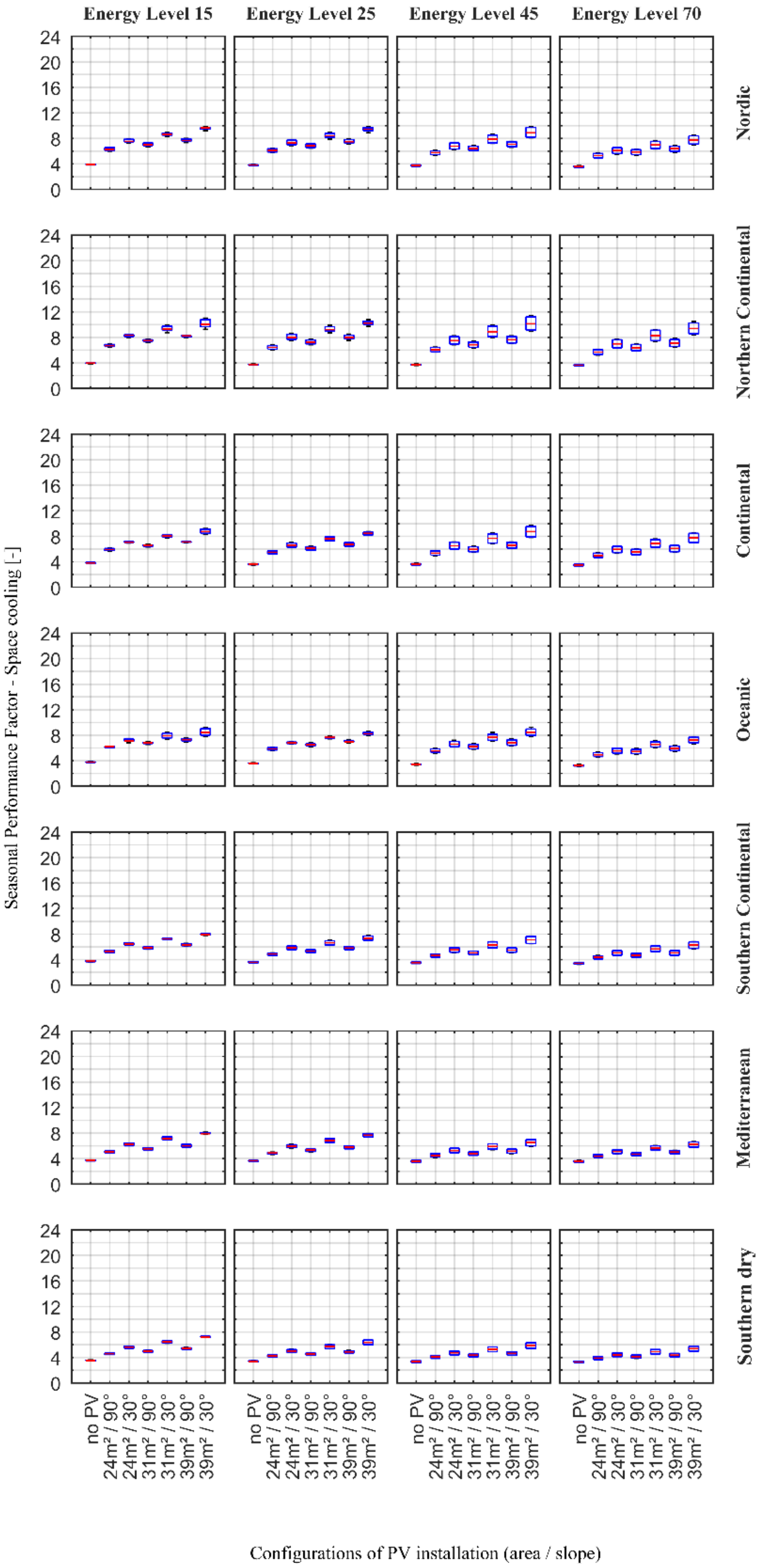

Figure 54 – Seasonal Performance Factor for Space Cooling

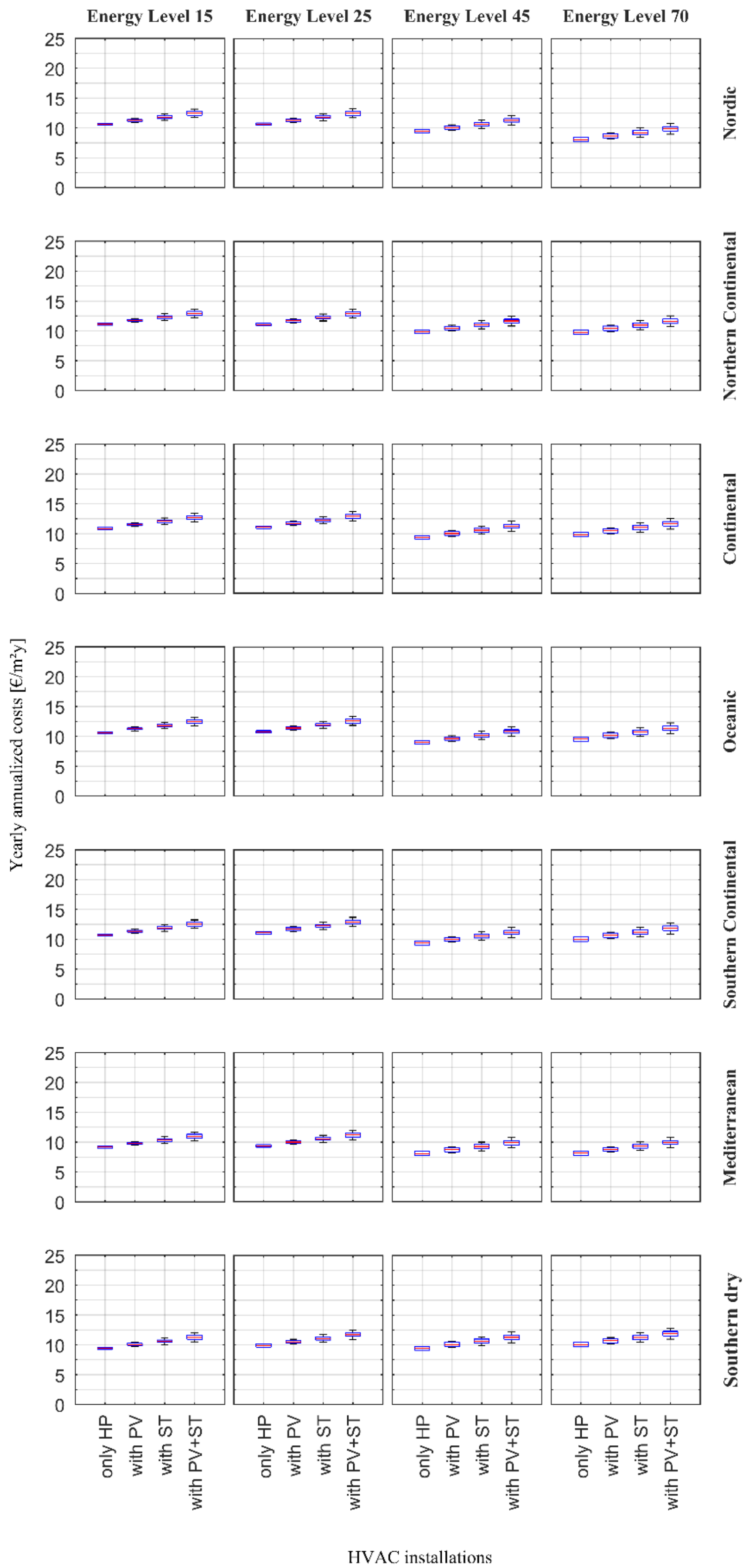

Figure 55 – Yearly annualised costs distribution for variants with solar systems

3.2 Small Multifamily Houses – Ground source heat pump + radiant ceilings

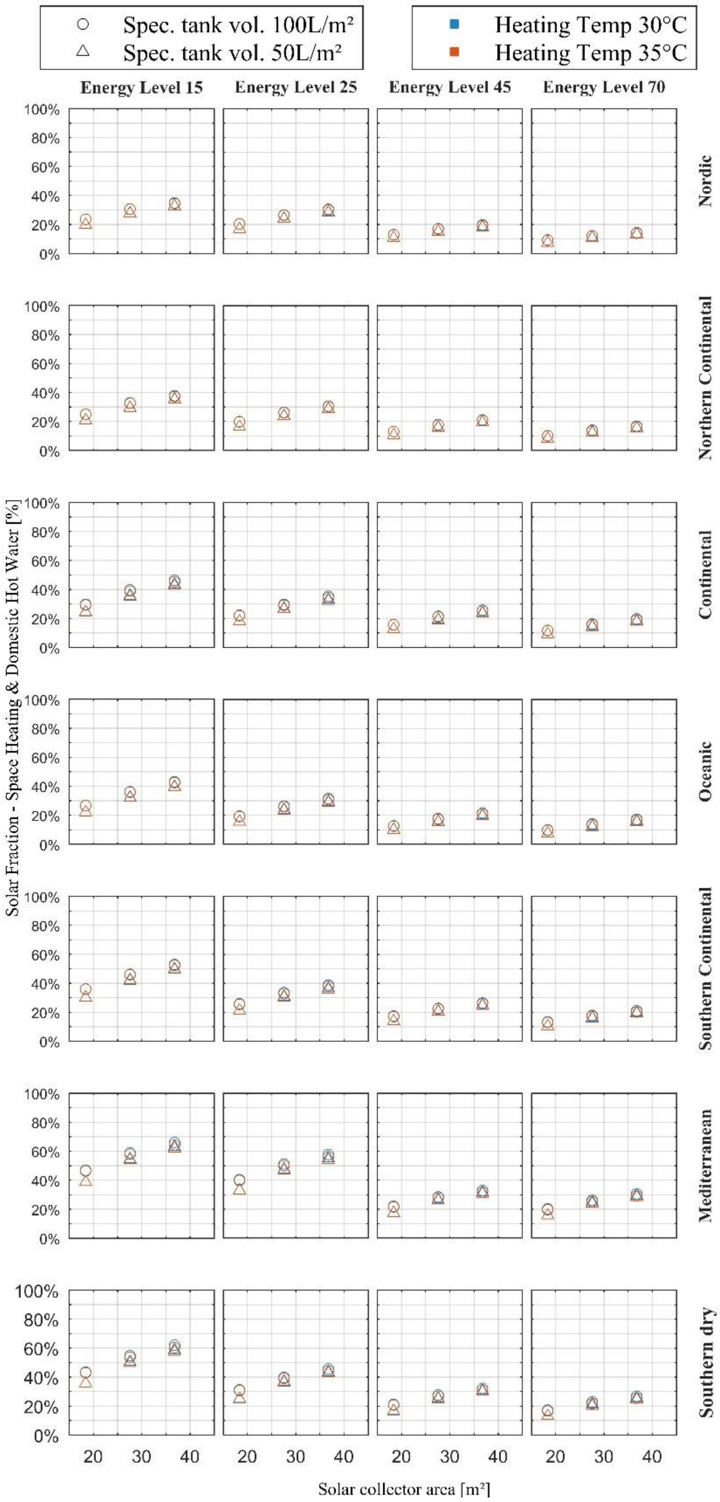

Figure 56 – Solar fraction for Domestic Hot Water and Space heating with solar collectors in the main façade.

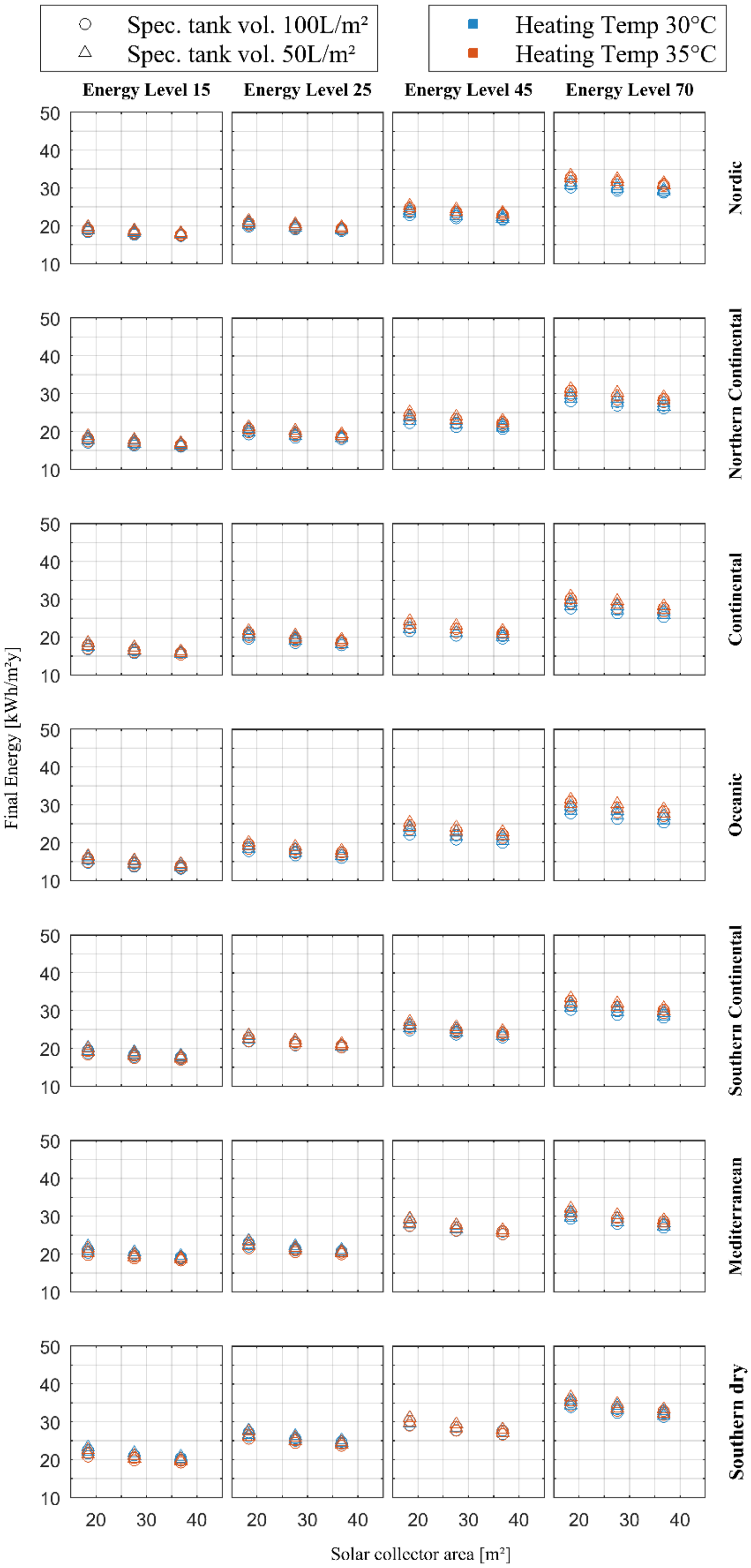

Figure 57 – Total final energy for several variants air-source heat pump and solar thermal system

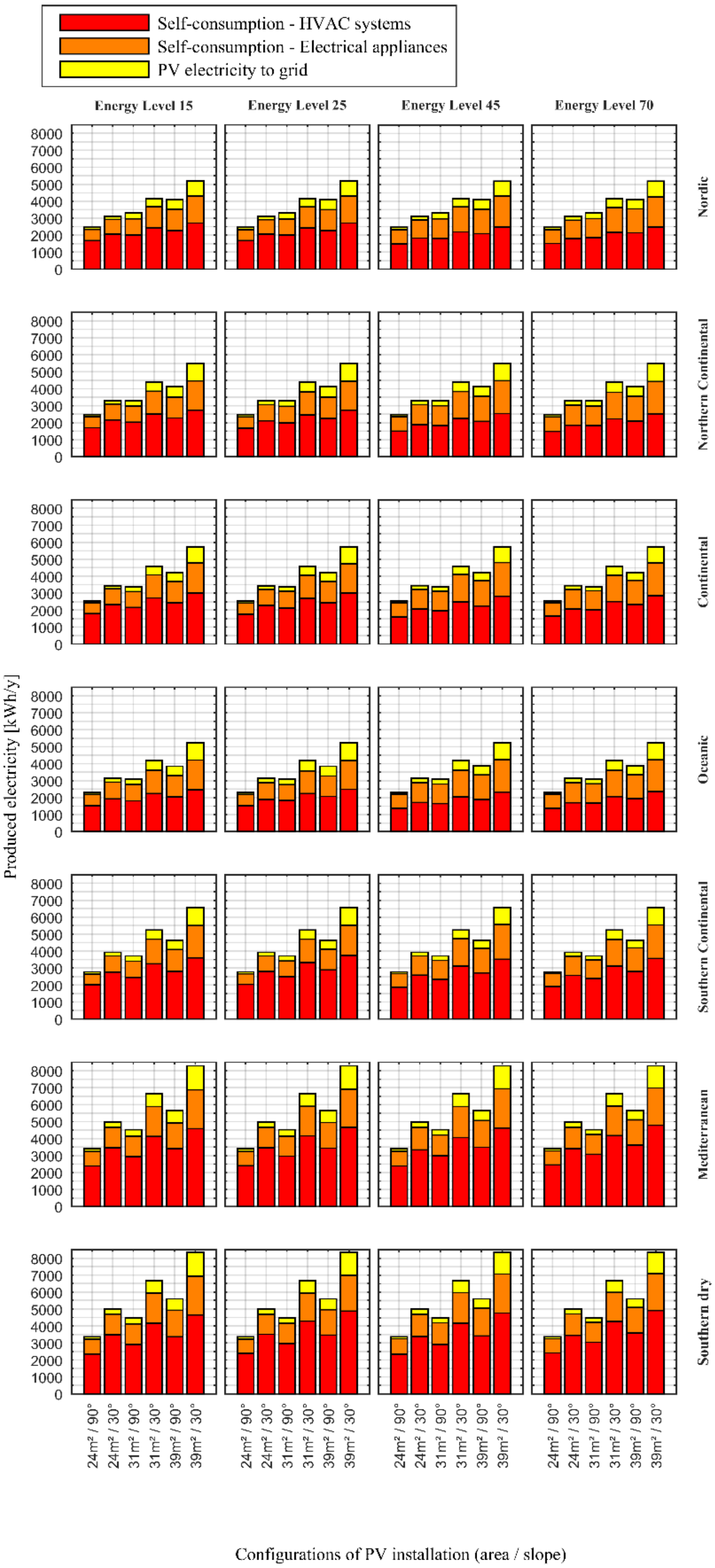

Figure 58 – Photovoltaic electricity production

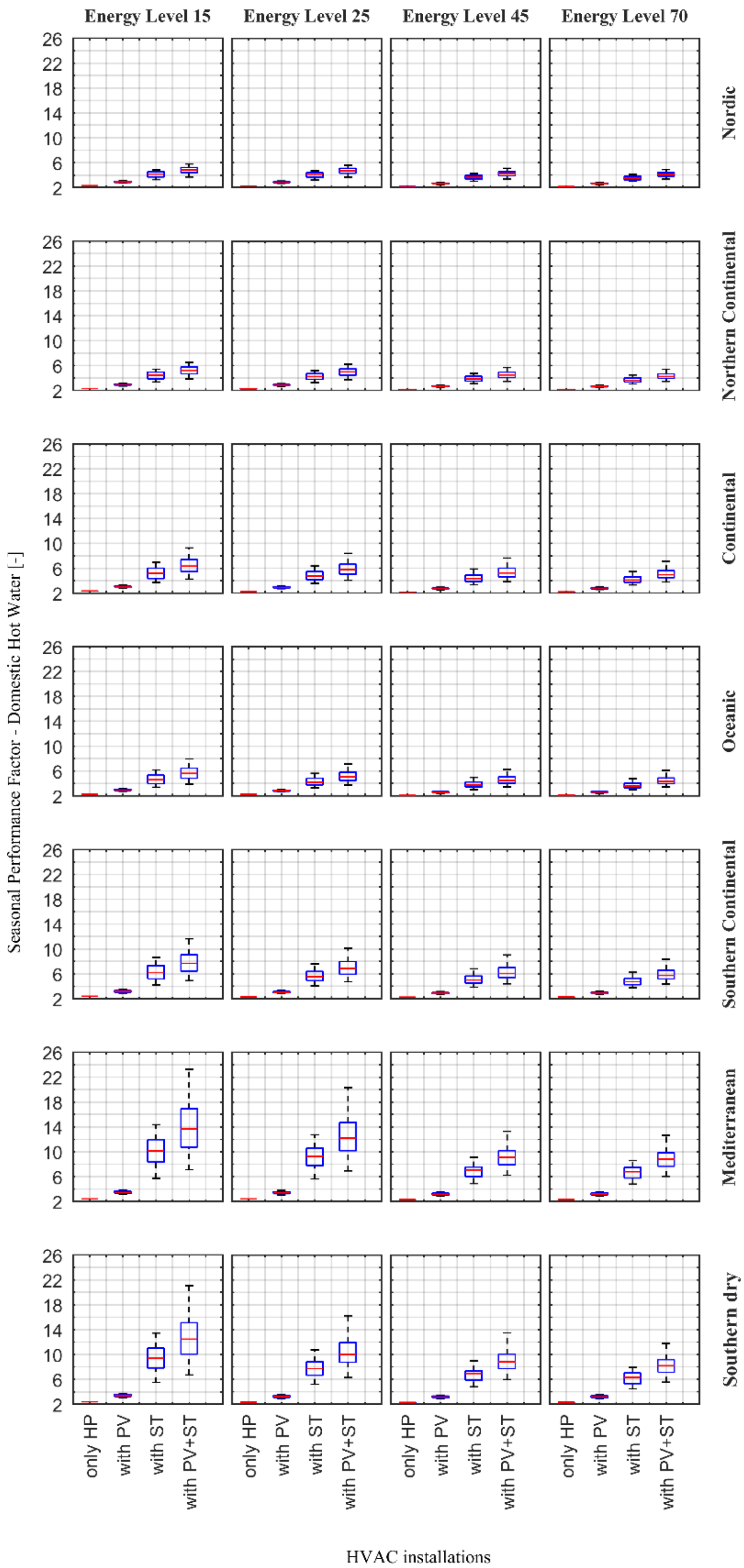

Figure 59 – Seasonal Performance Factor for Domestic Hot Water

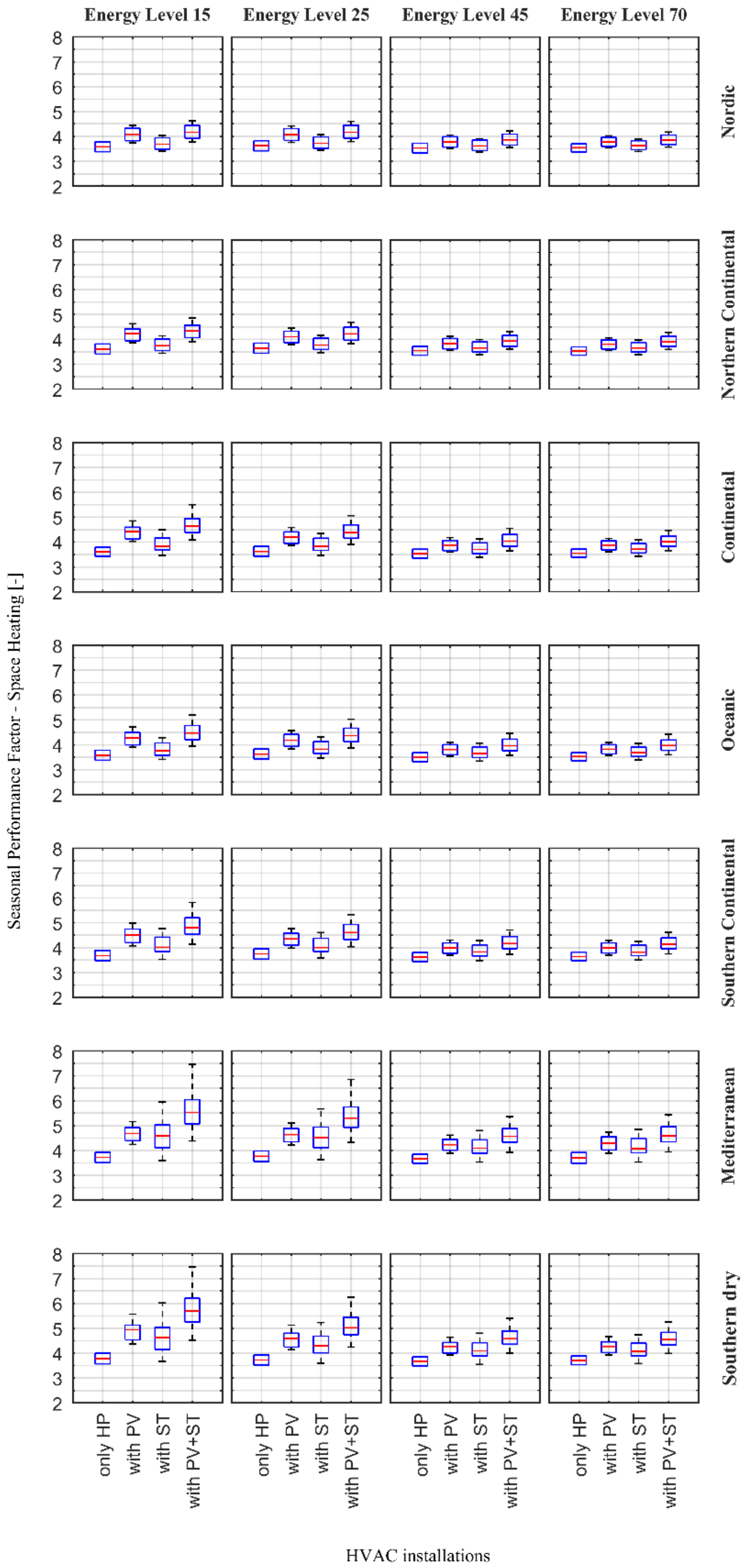

Figure 60 – Seasonal Performance Factor for Space Heating

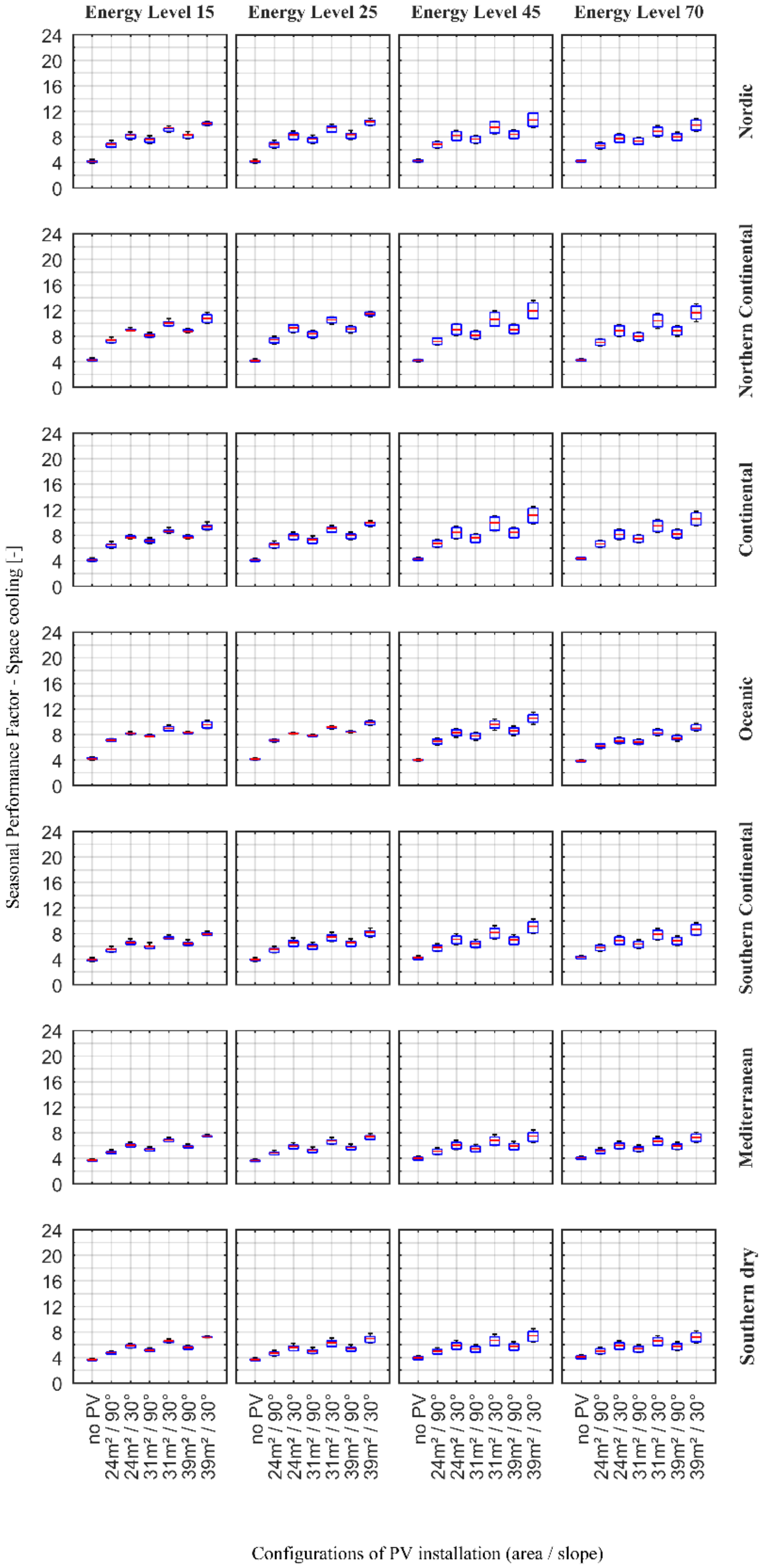

Figure 61 – Seasonal Performance Factor for Space Cooling

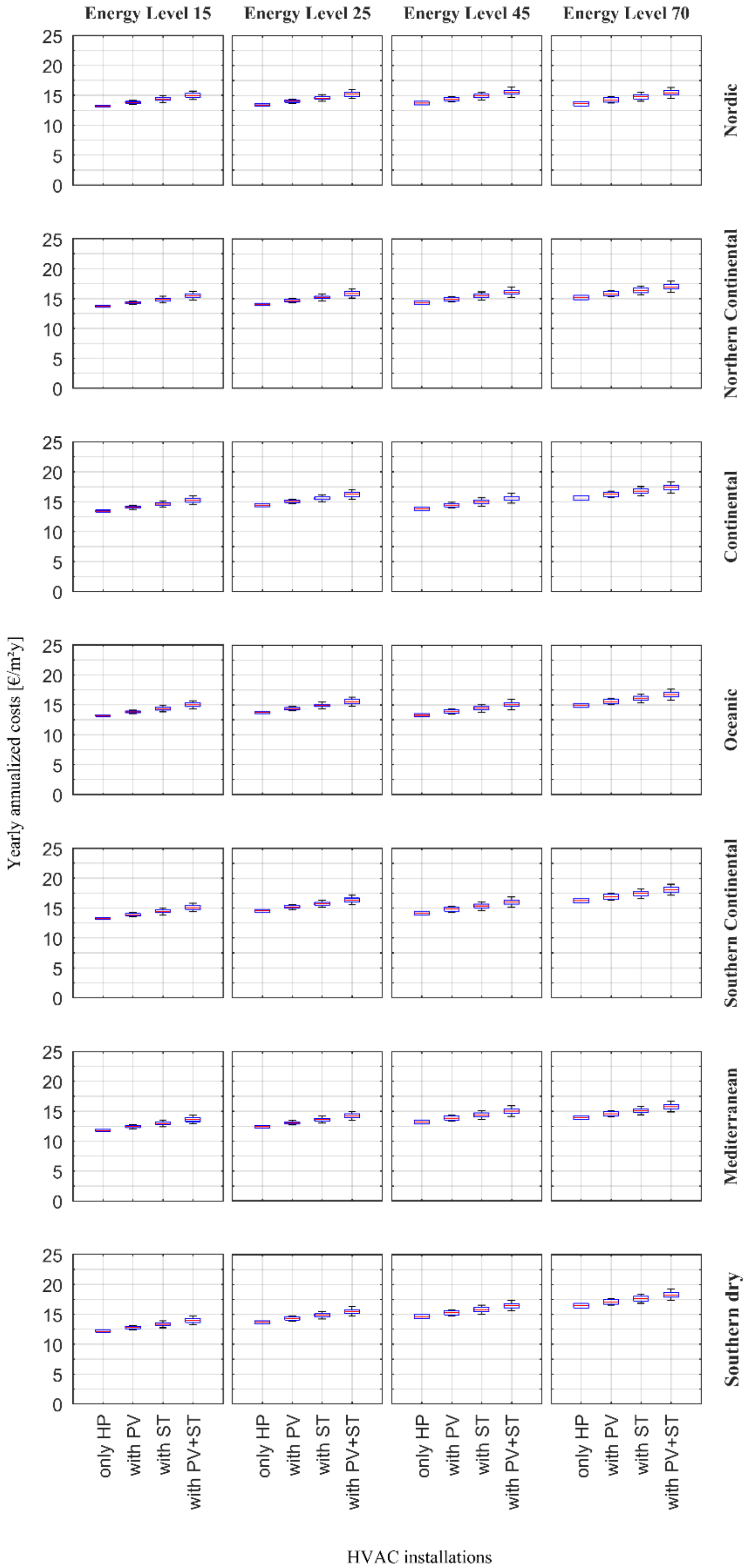

Figure 62 – Yearly annualised costs distribution for variants with solar systems

3.3 Small Multifamily Houses – Gas boiler + radiant ceilings

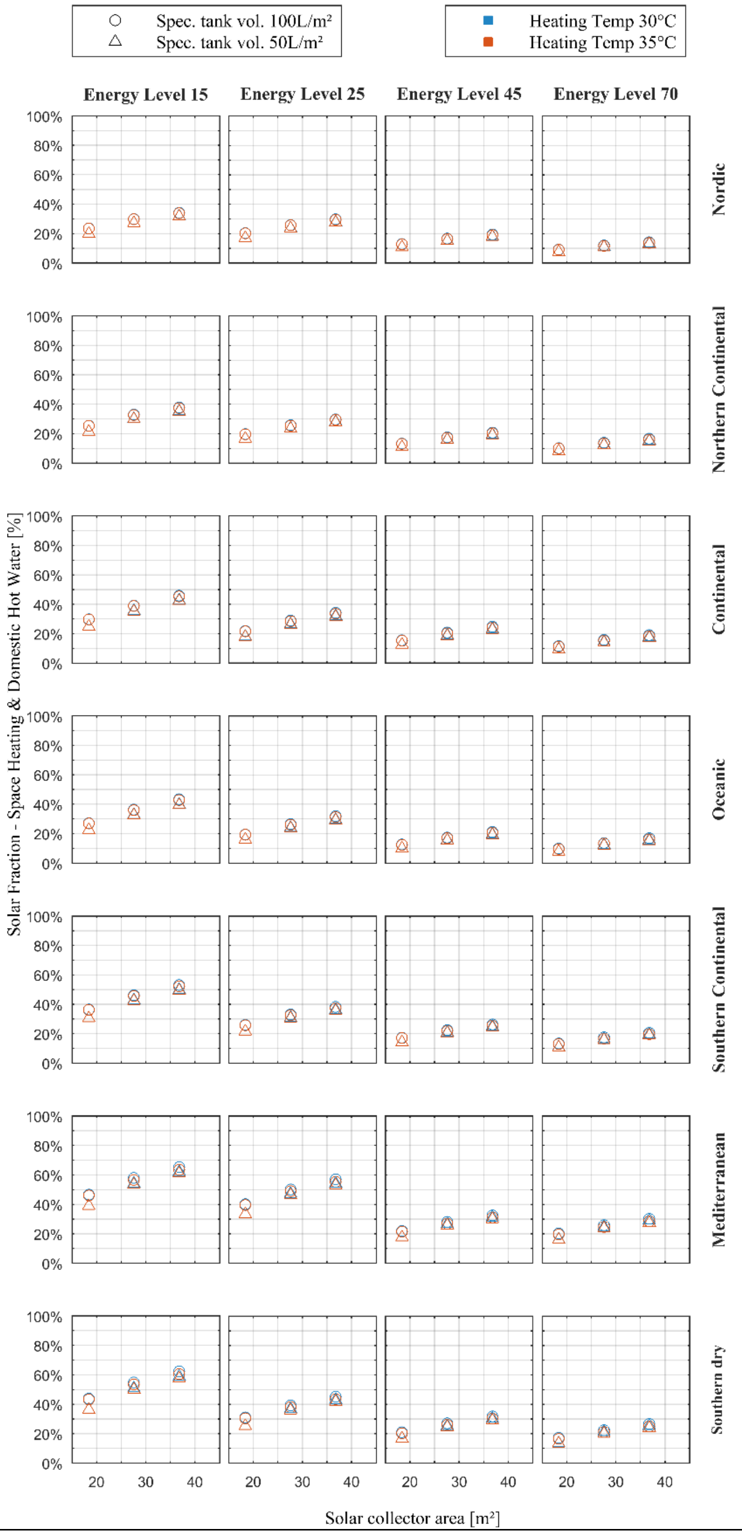

Figure 63 – Solar fraction for Domestic Hot Water and Space heating with solar collectors in the main façade.

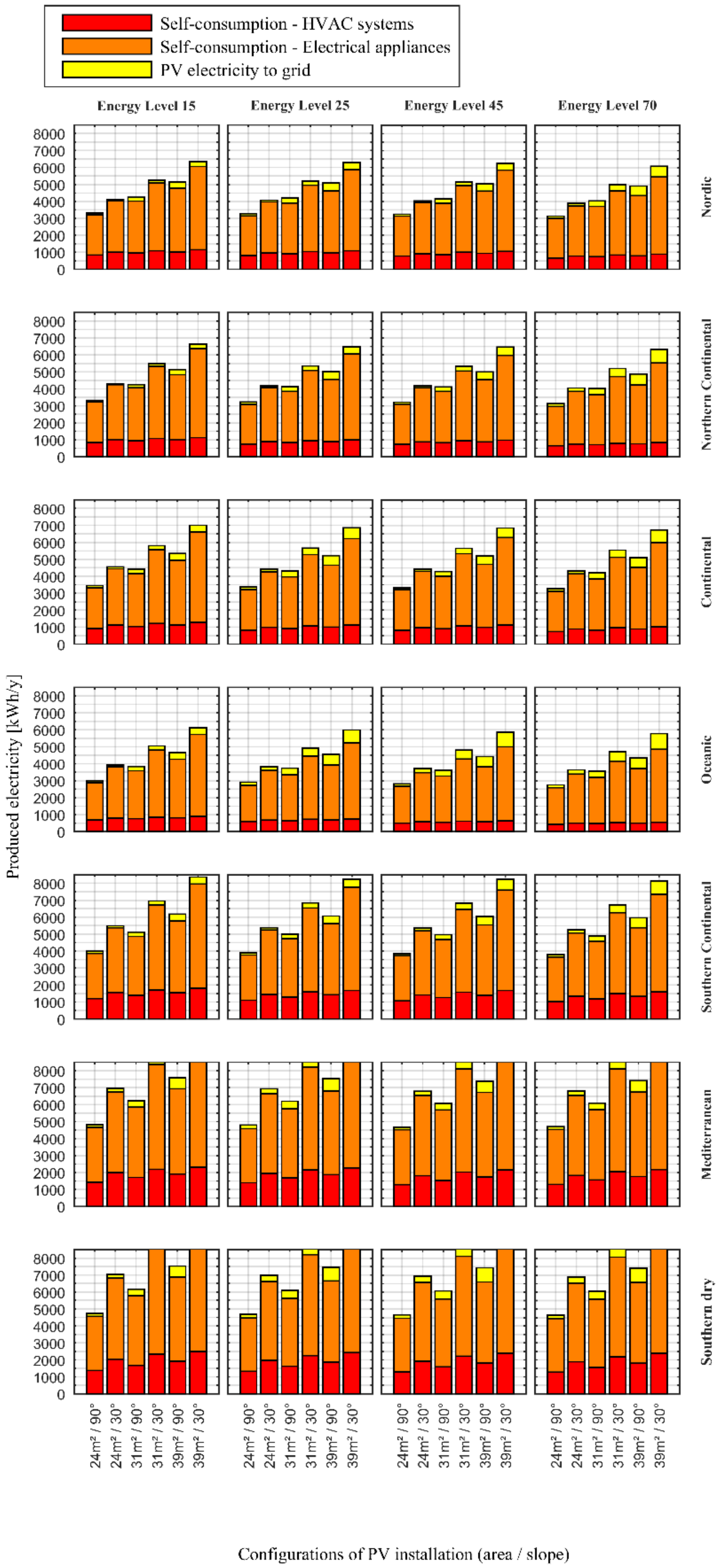

Figure 64 – Photovoltaic electricity production

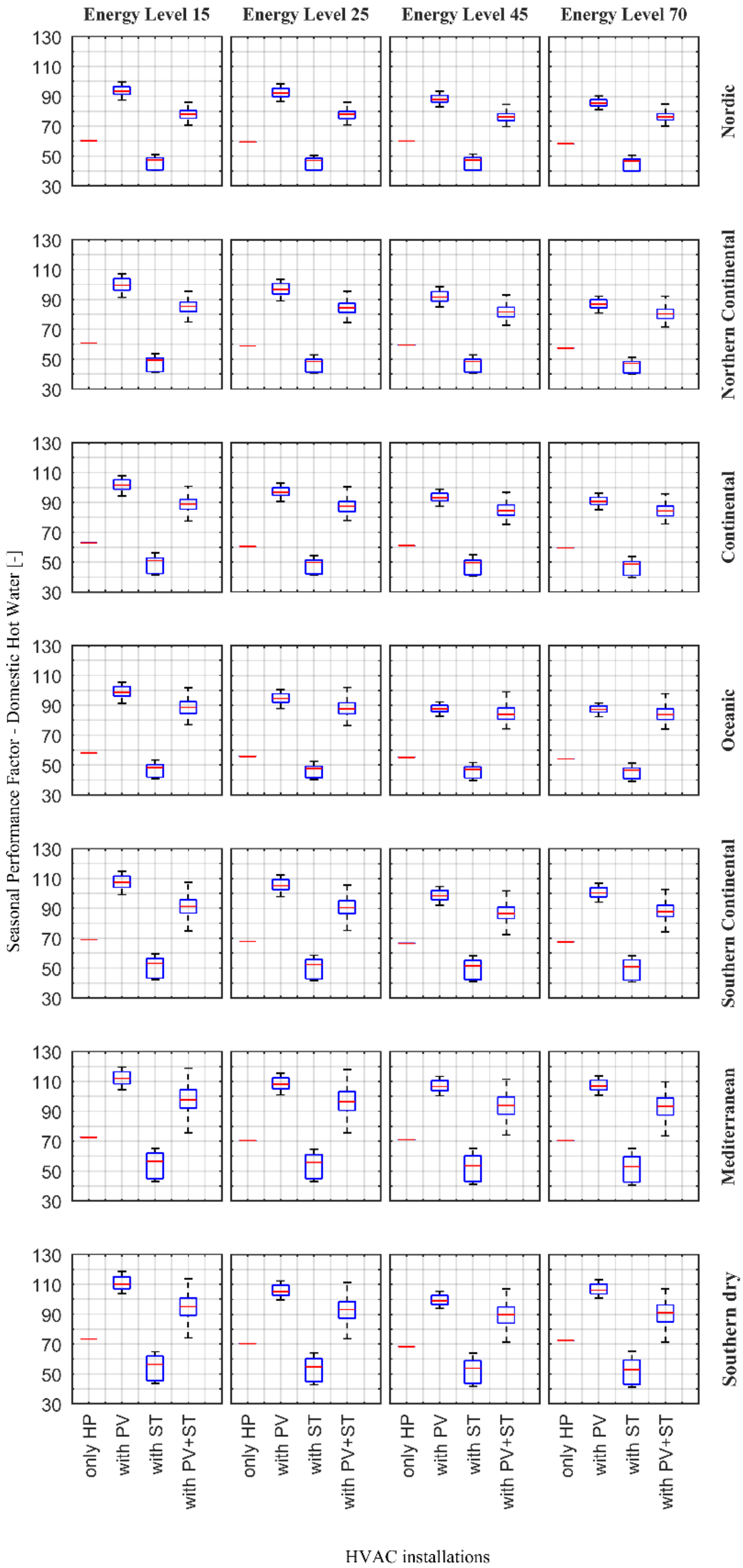

Figure 65 – Seasonal Performance Factor for Domestic Hot Water

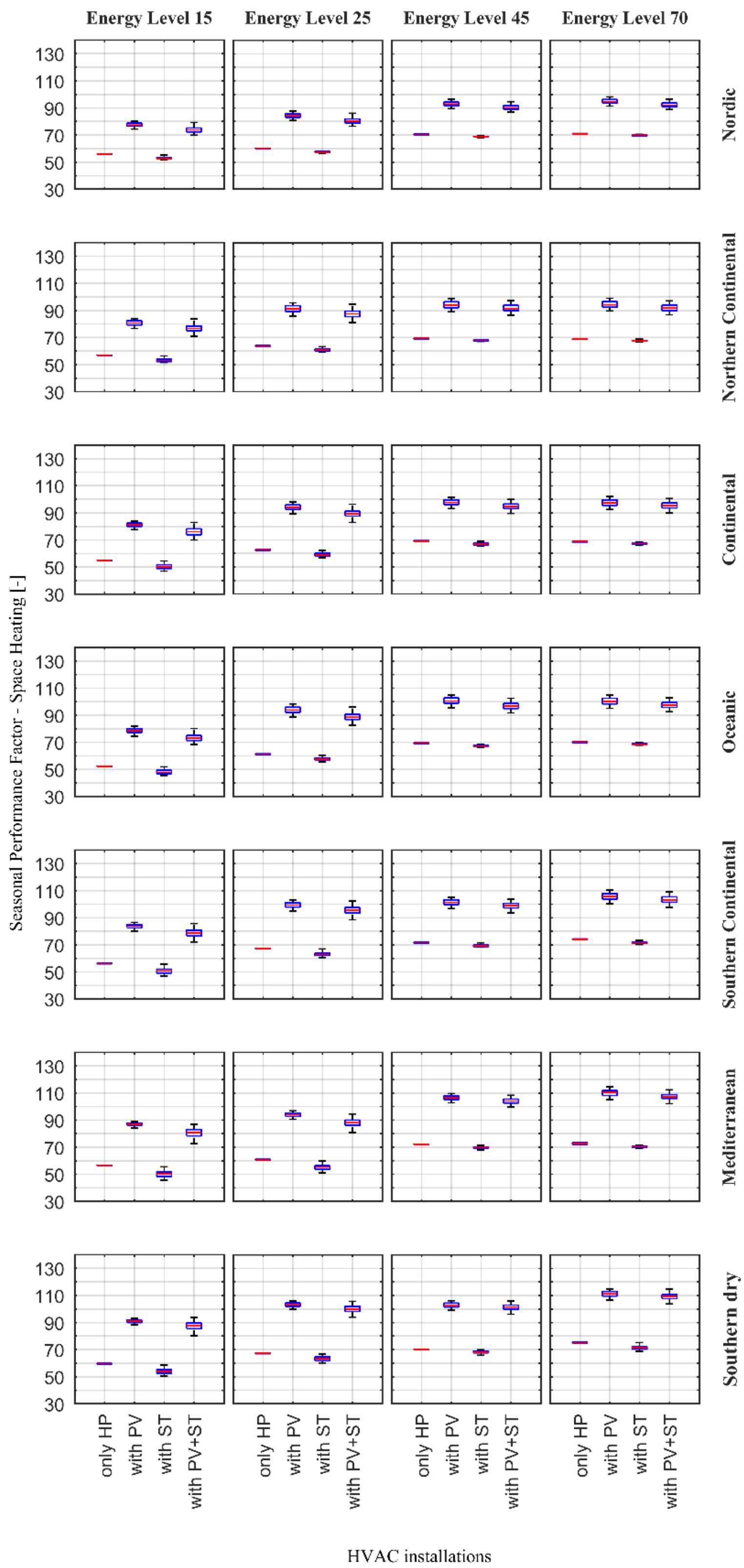

Figure 66 – Seasonal Performance Factor for Space Heating

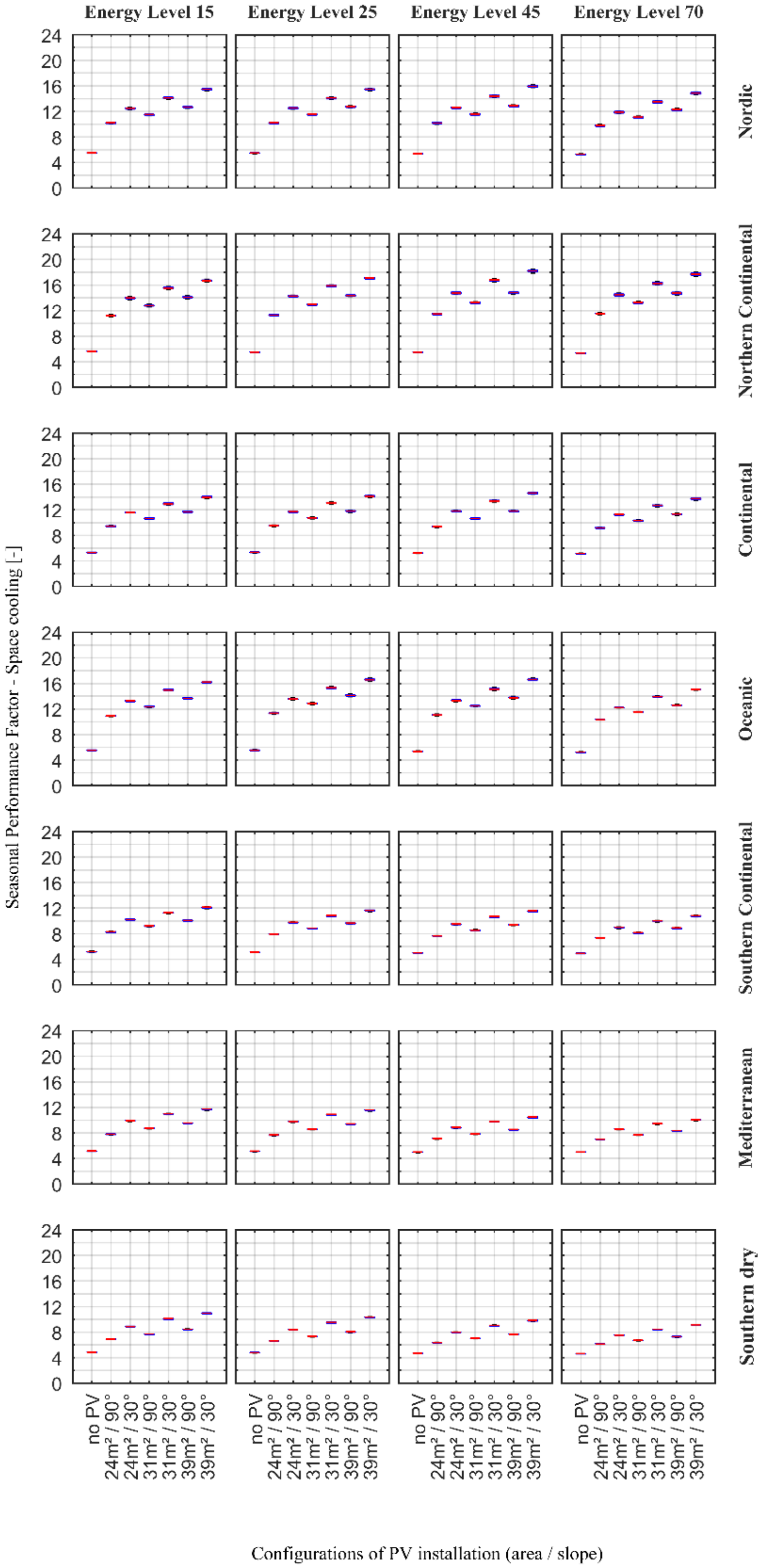

Figure 67 – Seasonal Performance Factor for Space Cooling

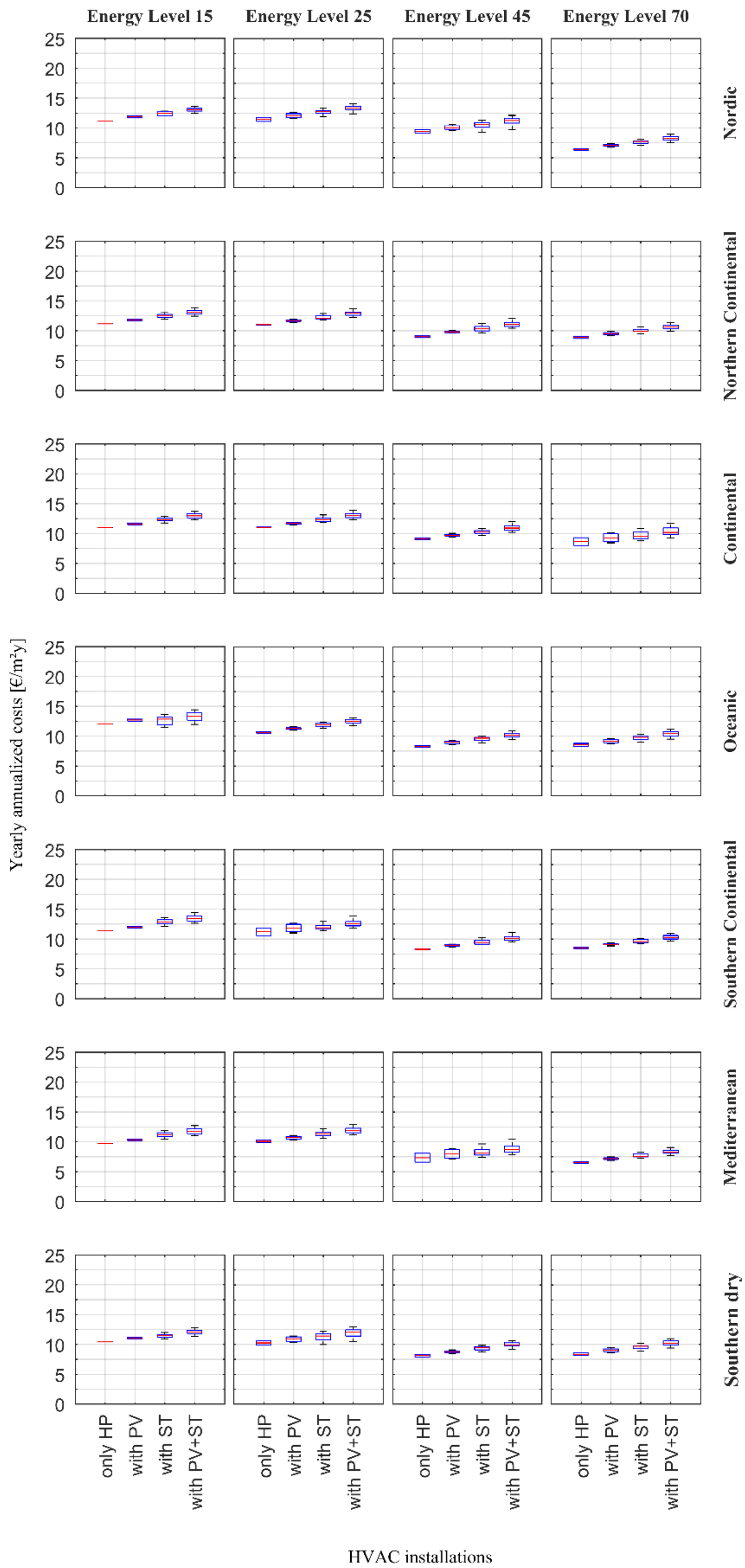

Figure 68 – Yearly annualised costs distribution for variants with solar systems

3.4 Small Multifamily Houses – Pellet boiler + radiant ceilings

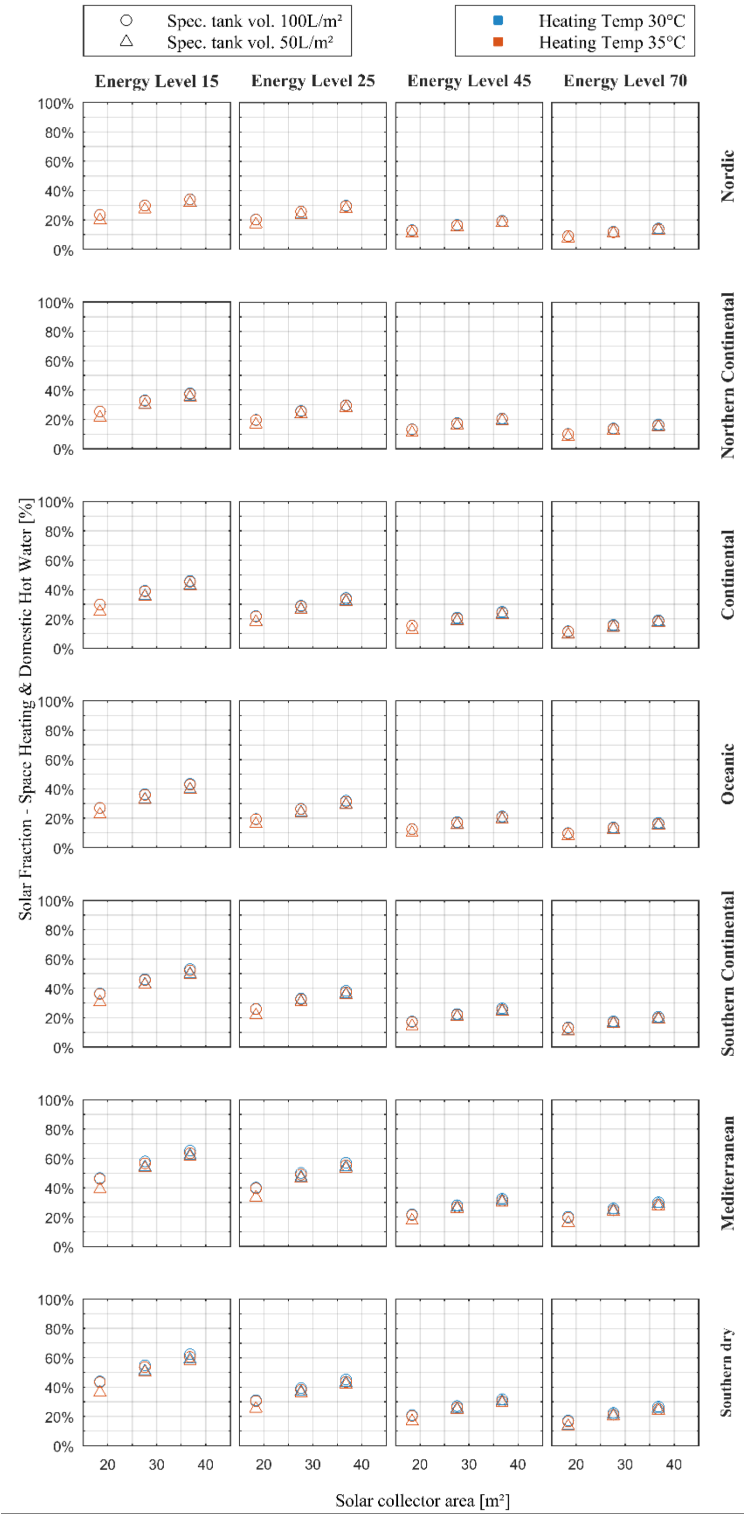

Figure 69 – Solar fraction for Domestic Hot Water and Space heating with solar collectors in the main façade.

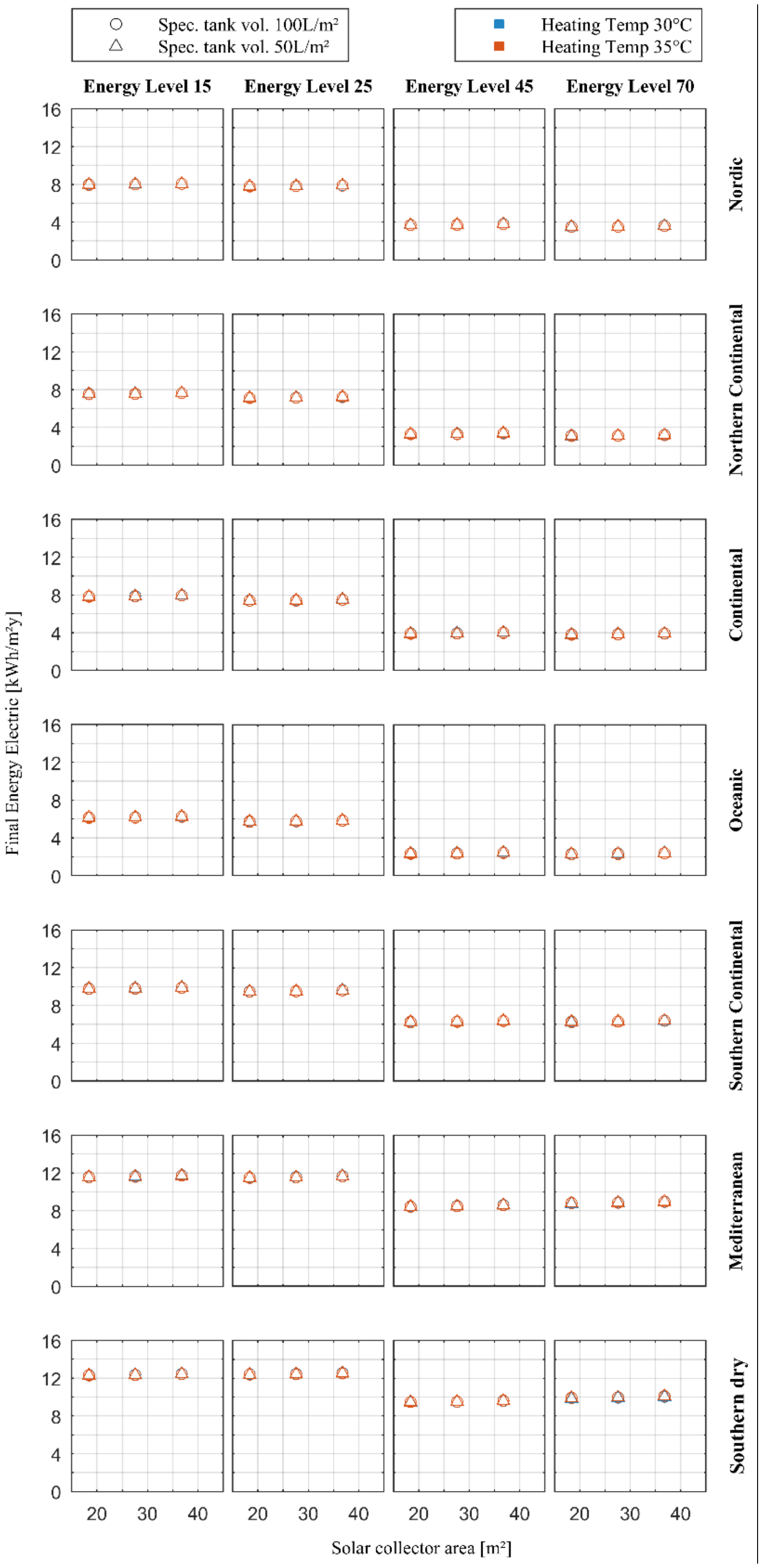

Figure 70 – Total final energy for several variants gas boiler and solar thermal system

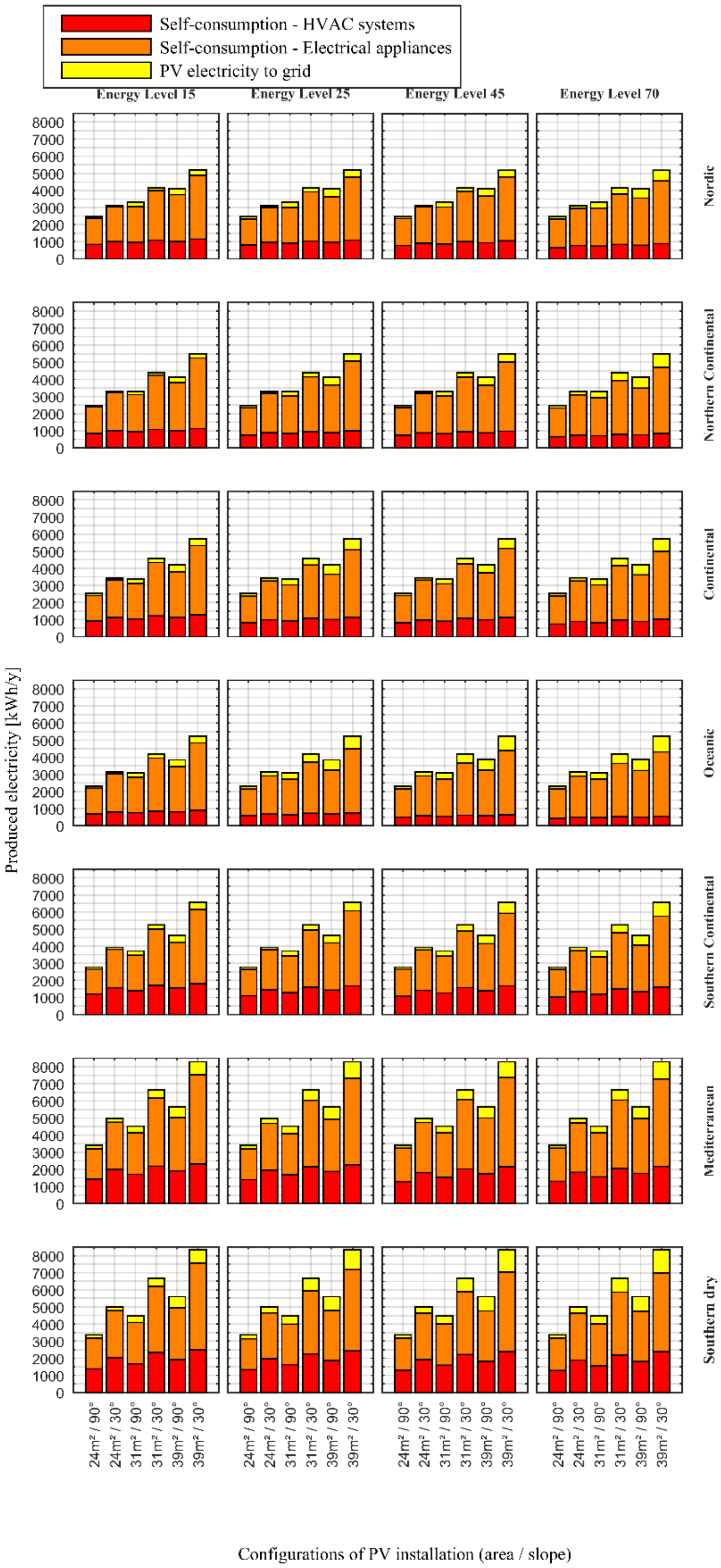

Figure 71 – Photovoltaic electricity production

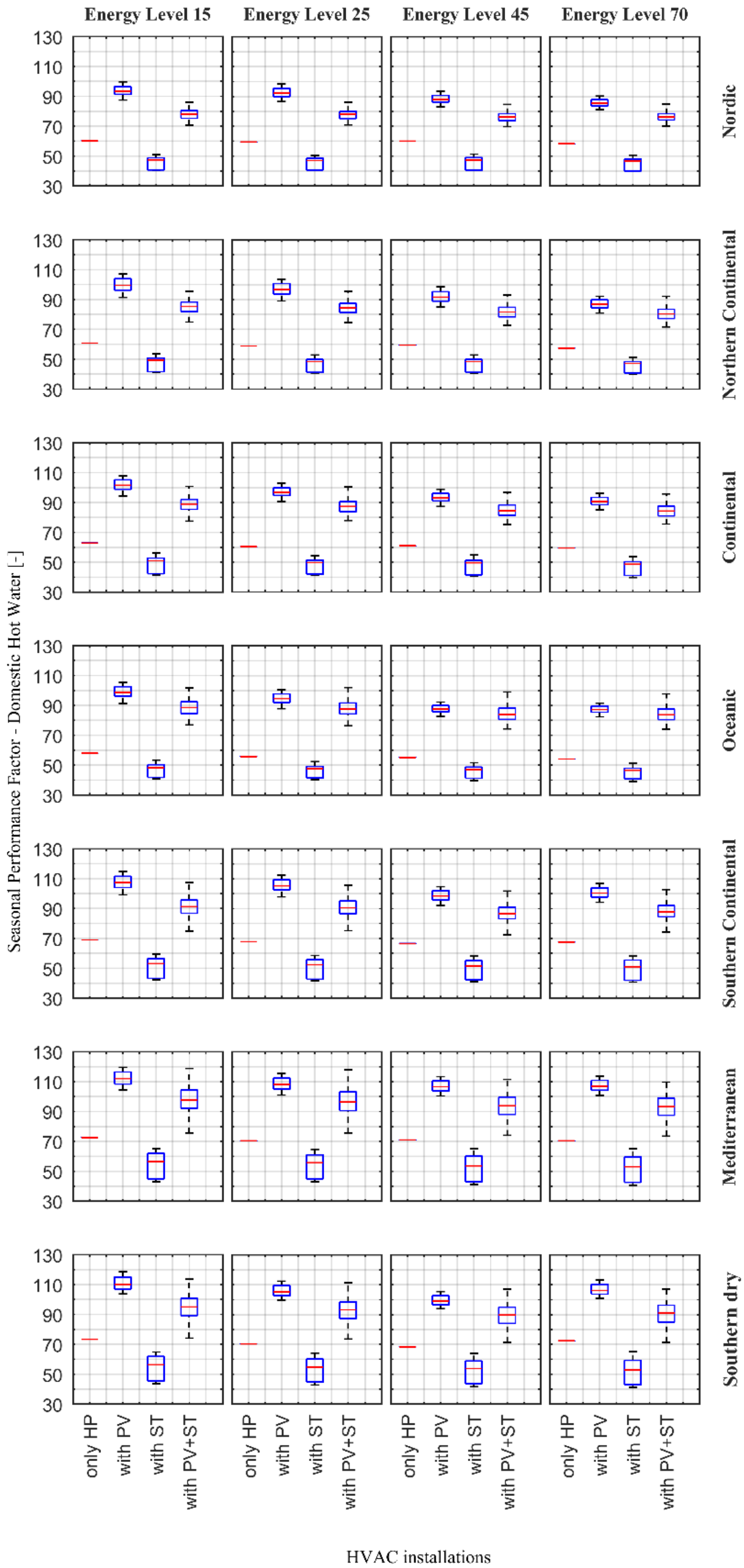

Figure 72 – Seasonal Performance Factor for Domestic Hot Water

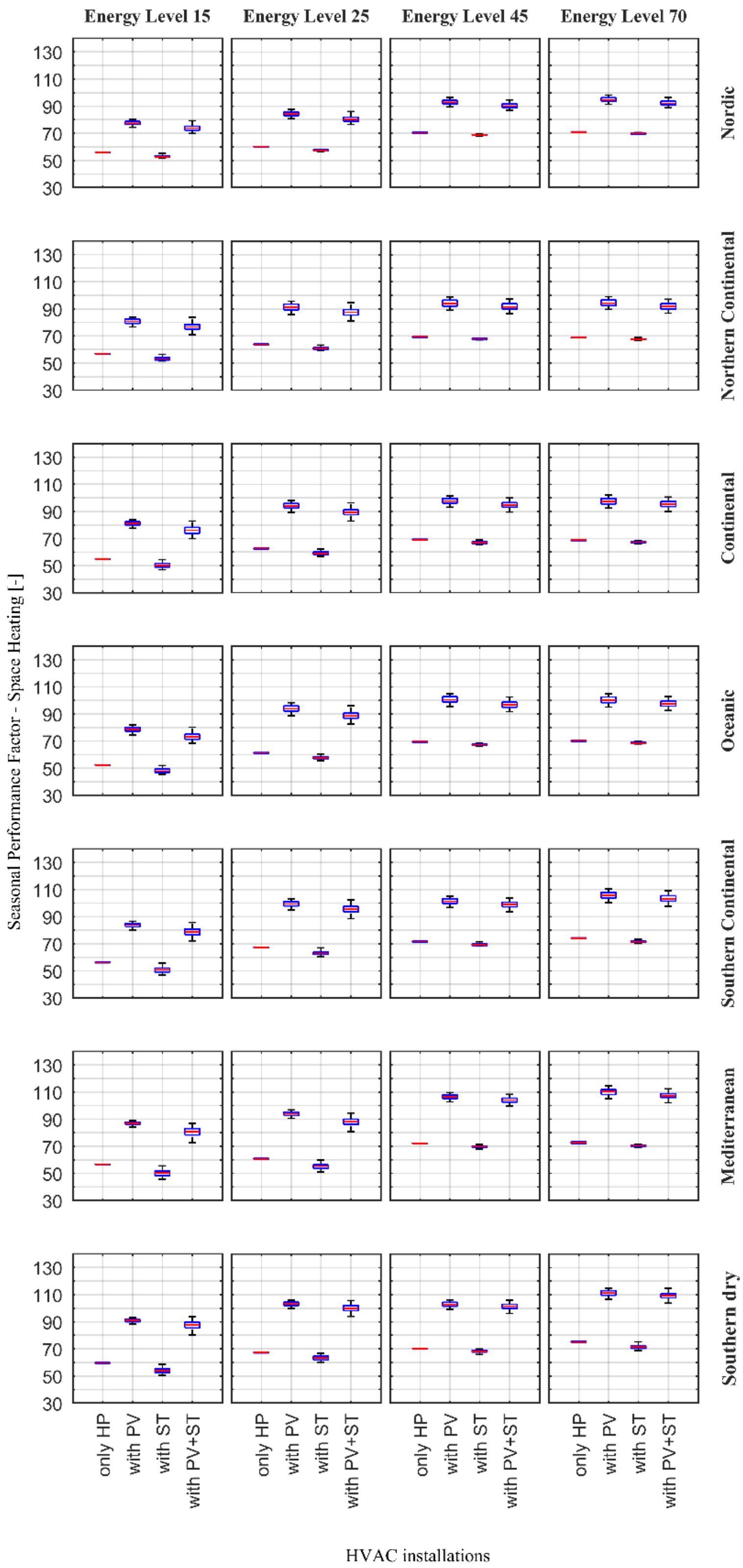

Figure 73 – Seasonal Performance Factor for Space Heating

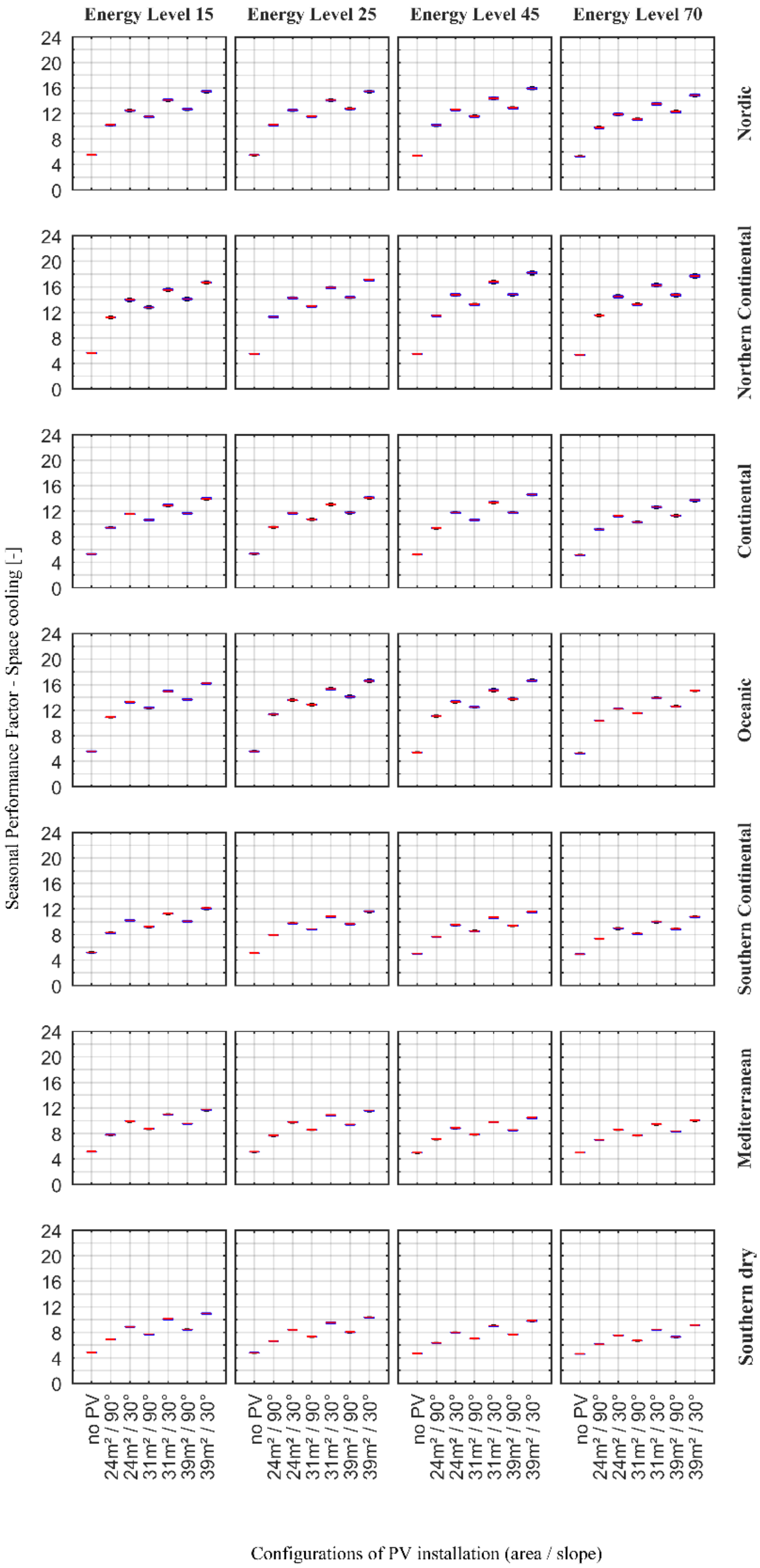

Figure 74 – Seasonal Performance Factor for Space Cooling

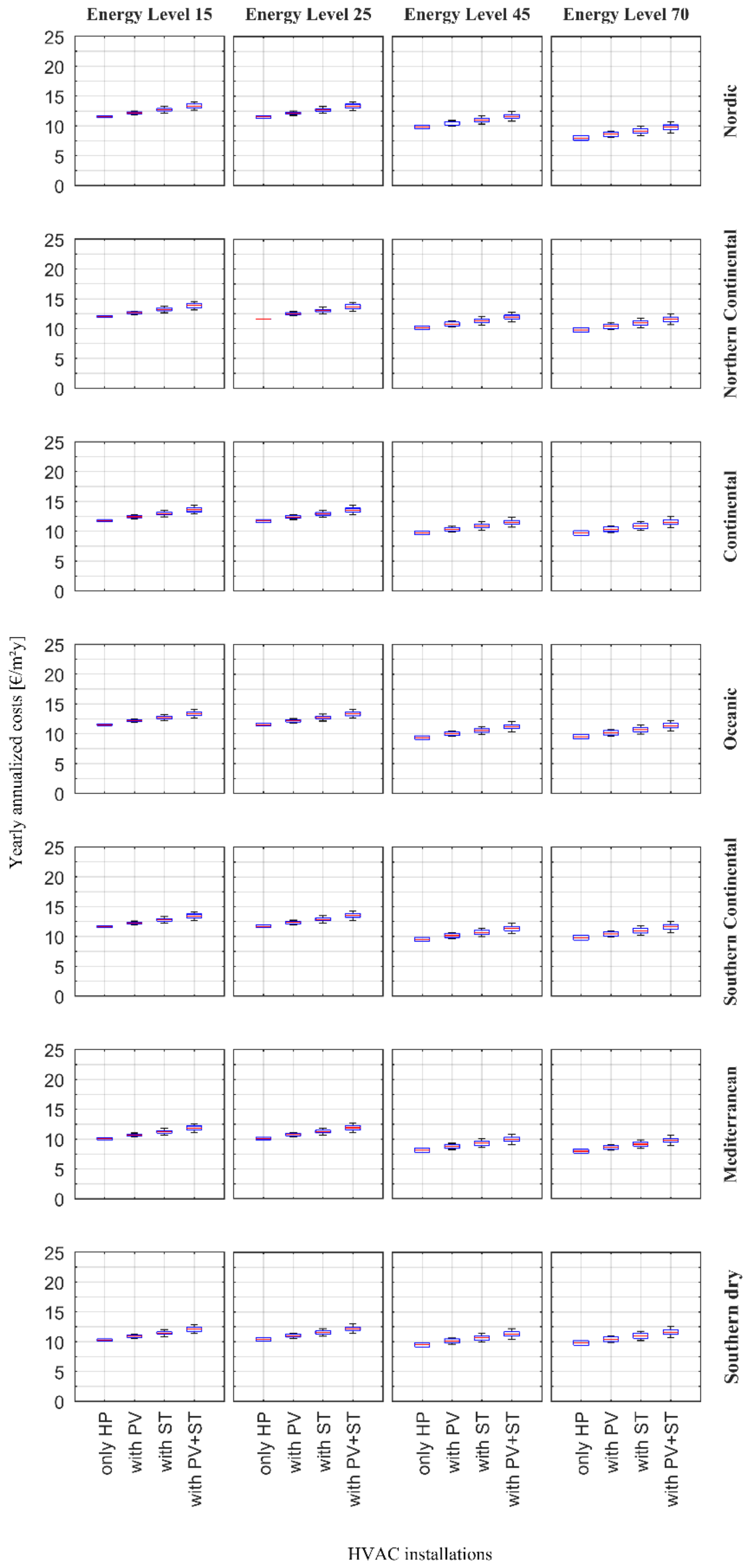

Figure 75 – Yearly annualised costs distribution for variants with solar systems

3.5 Small Multifamily Houses – Air to water heat pump + fan coils

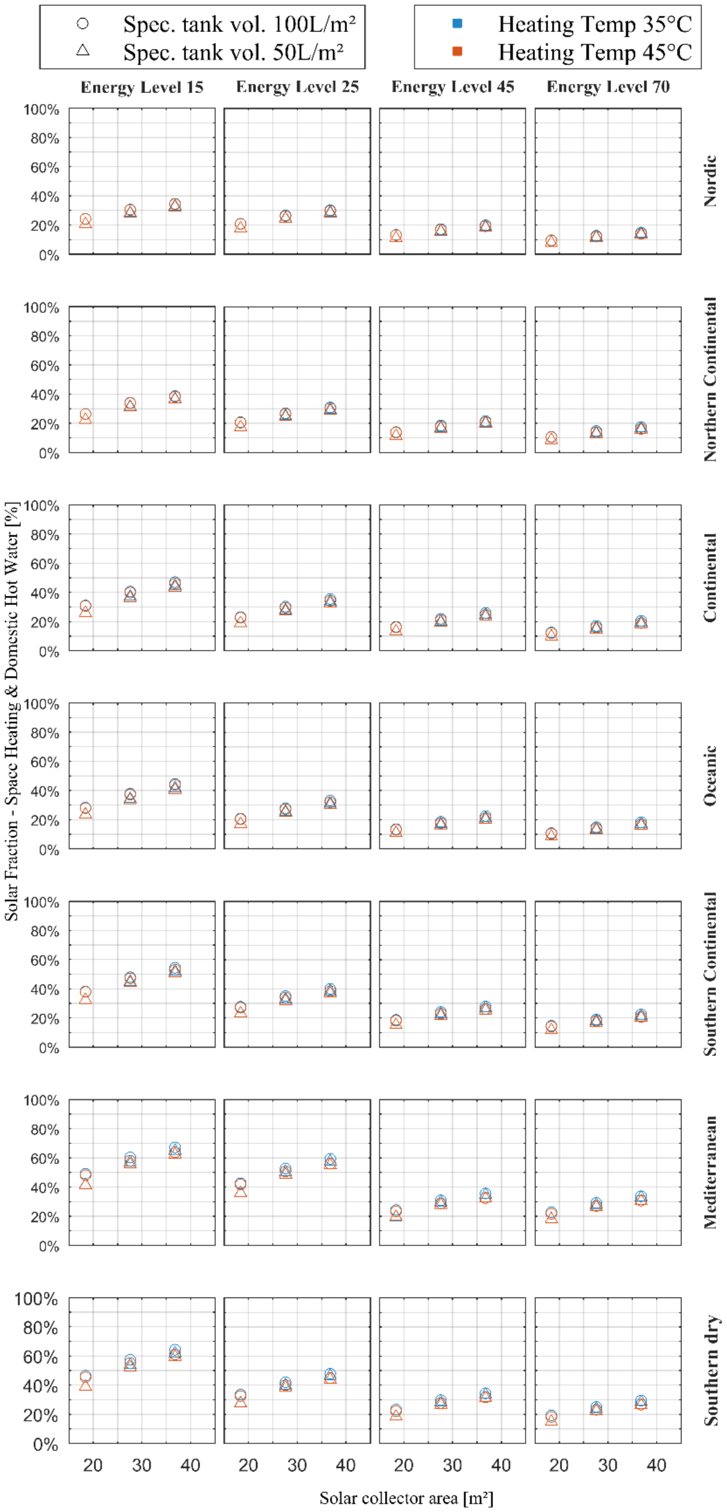

Figure 76 – Solar fraction for Domestic Hot Water and Space Heating with solar collectors in the main façade.

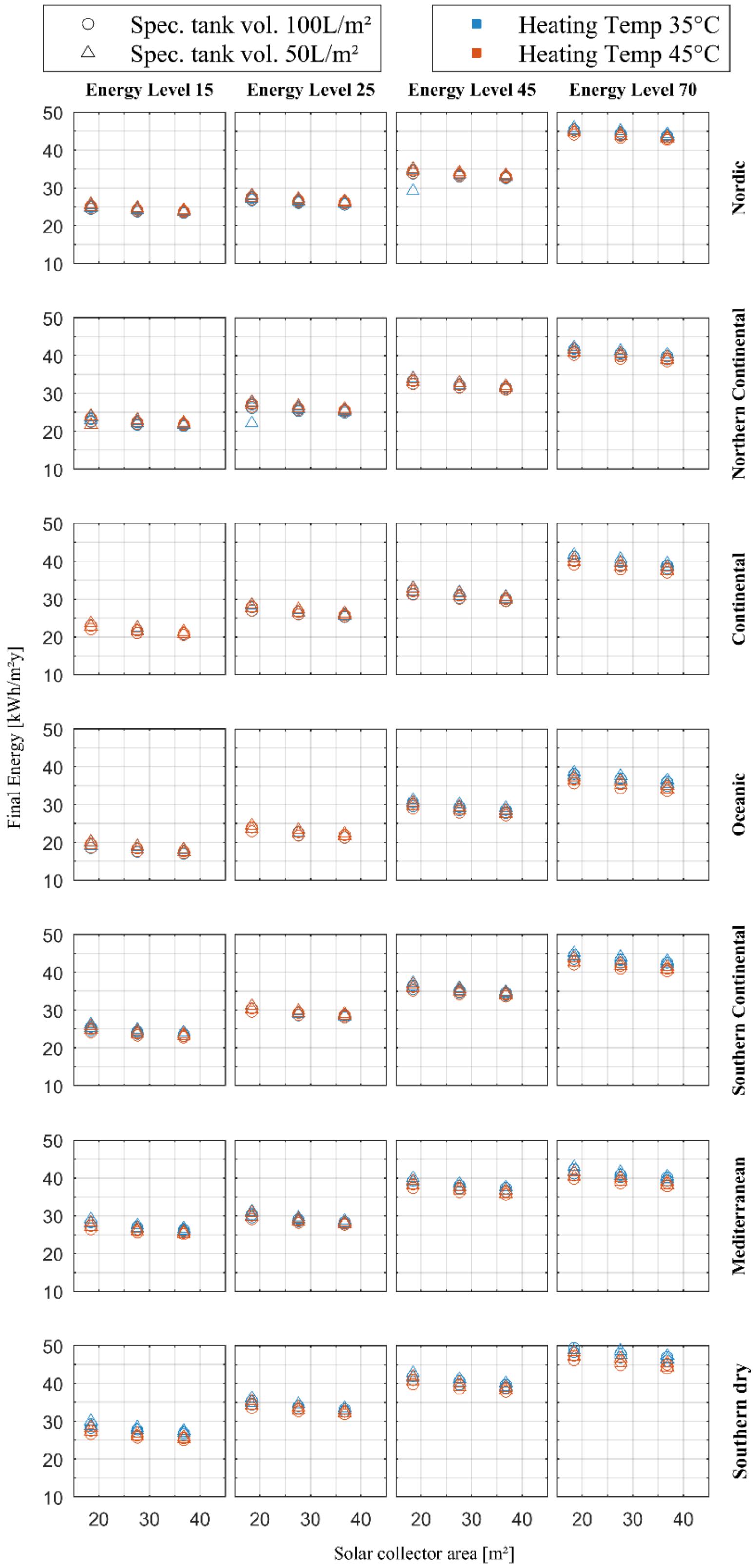

Figure 77 – Total final energy for several variants air-source heat pump and solar thermal system

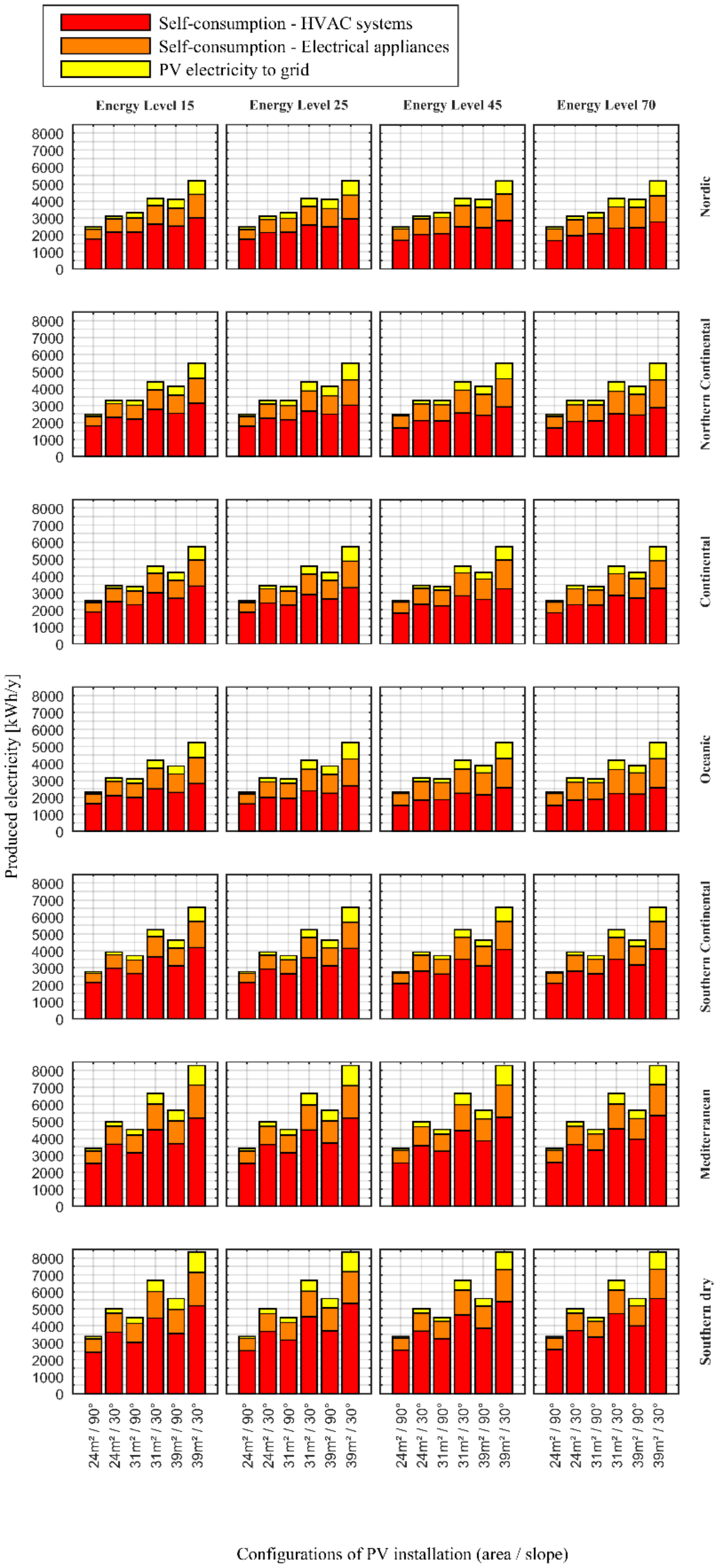

Figure 78 – Photovoltaic electricity production

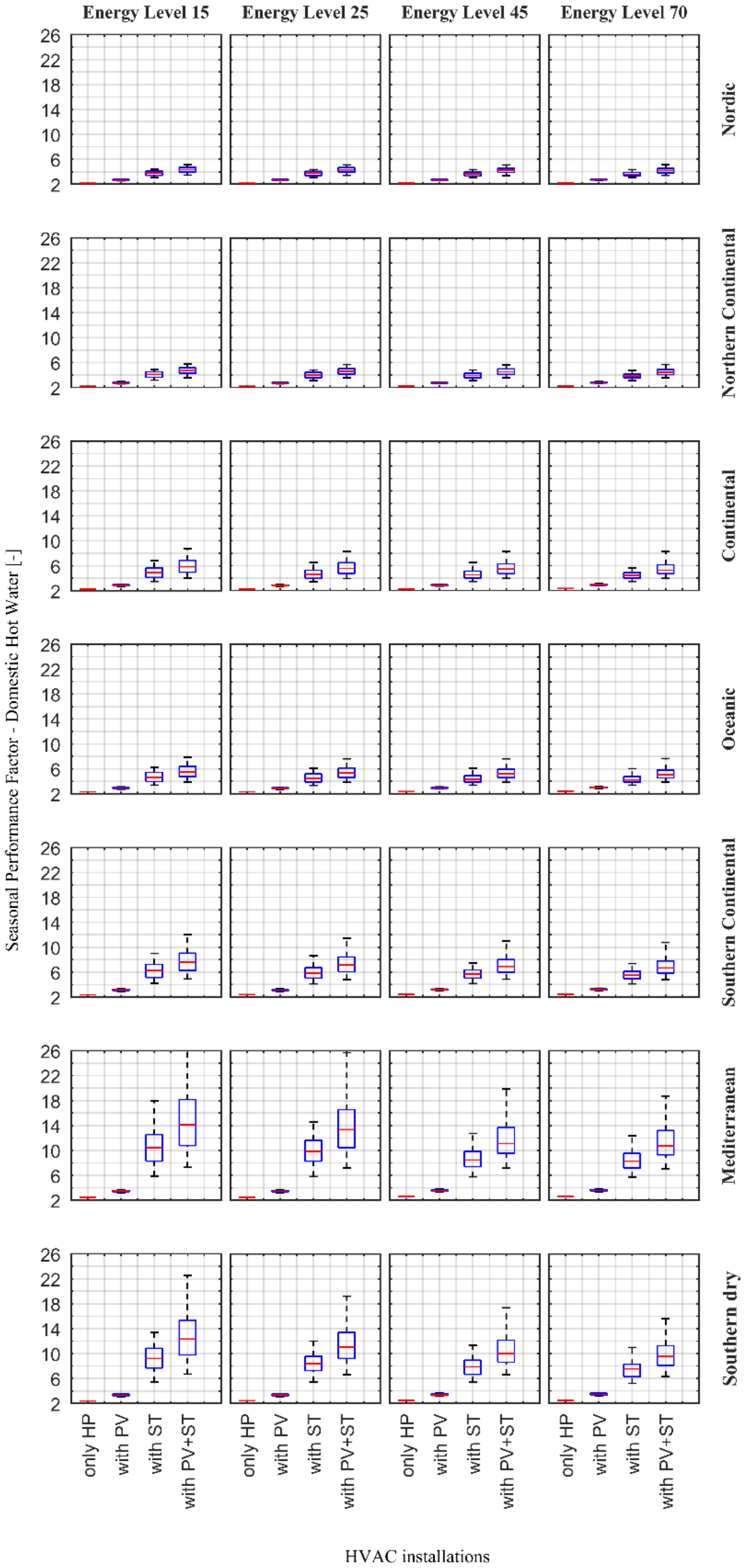

Figure 79 – Seasonal Performance Factor for Domestic Hot Water production

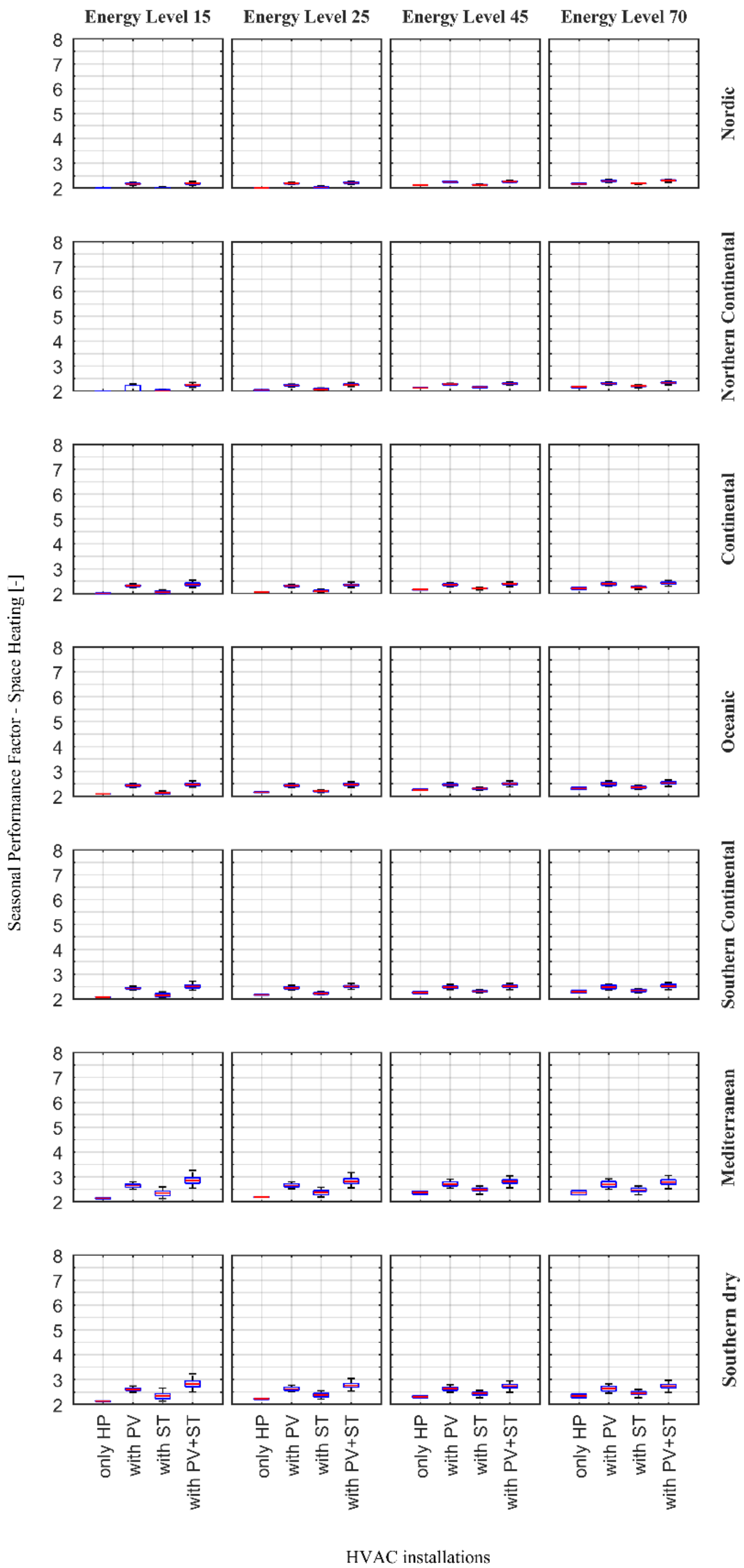

Figure 80 – Seasonal Performance Factor for Space Heating

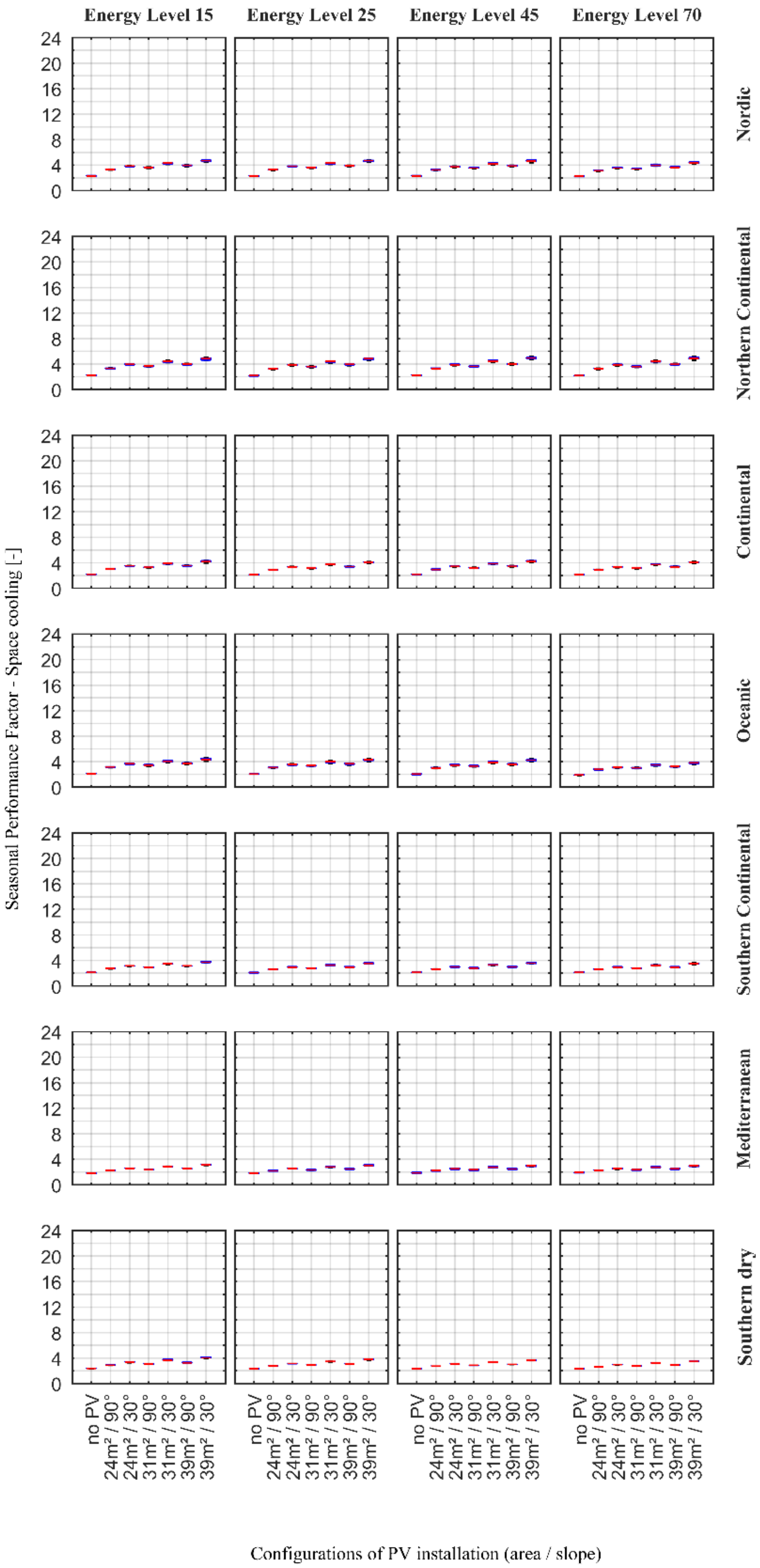

Figure 81 – Seasonal Performance Factor for Space Cooling

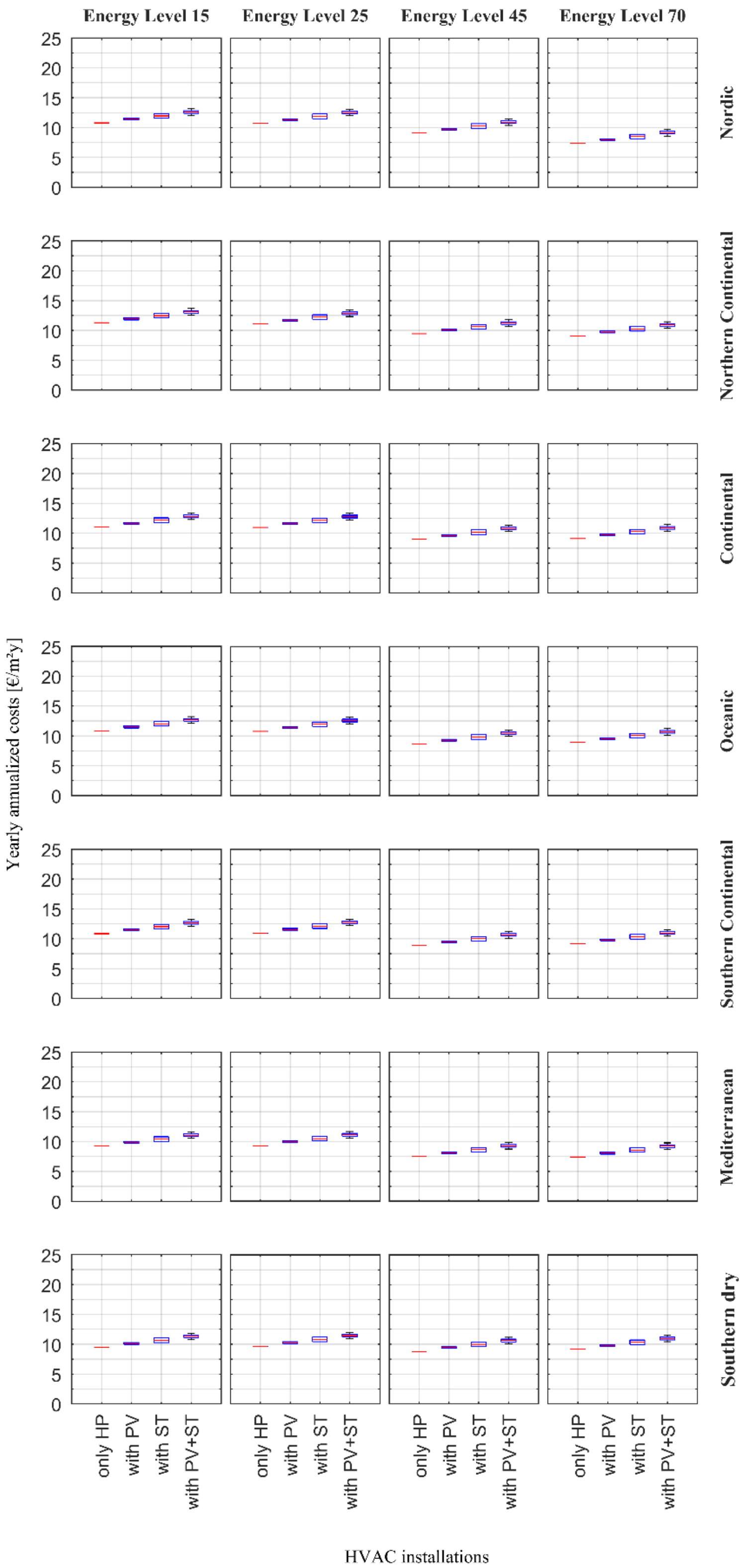

Figure 82 – Yearly annualised costs distribution for variants with solar systems

3.6 Small Multifamily Houses – Ground source heat pump + fan coils

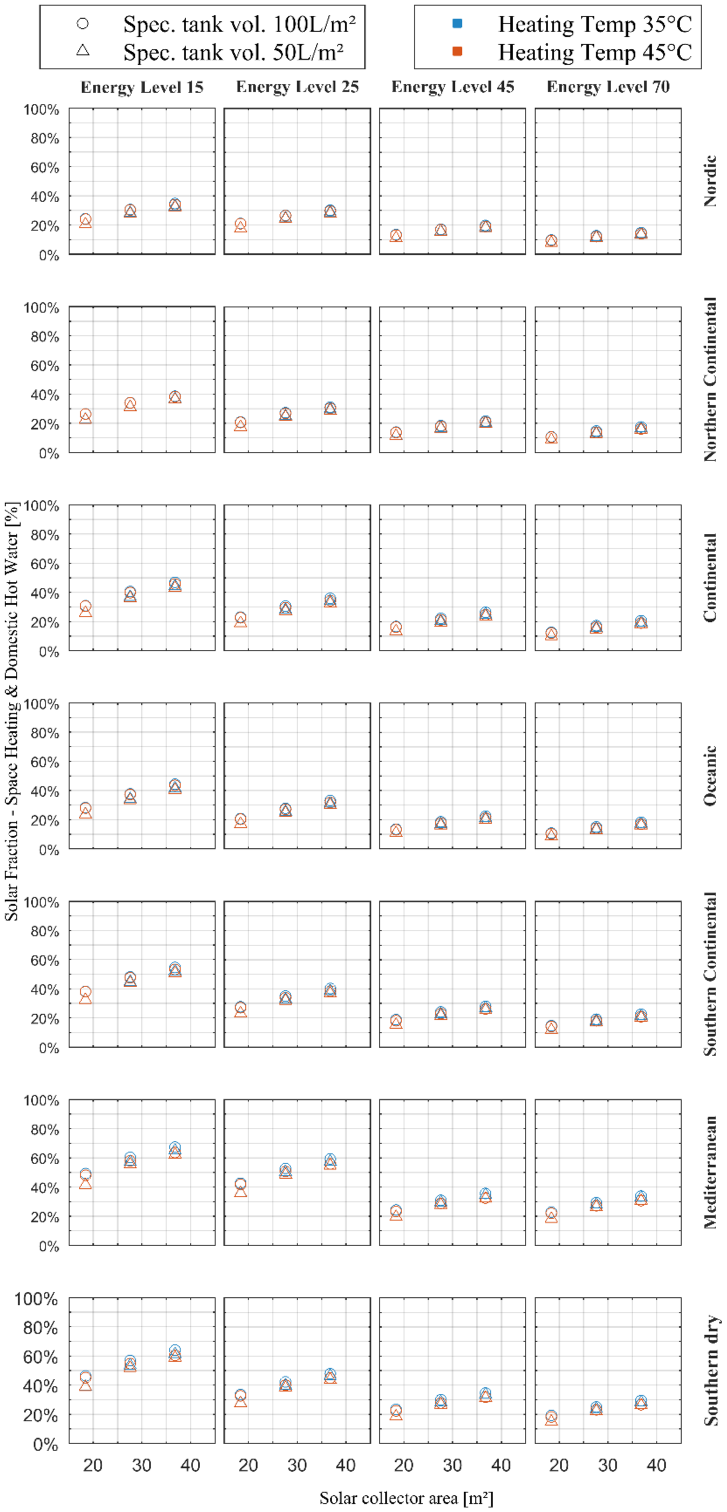

Figure 83 – Solar fraction for Domestic Hot Water and Space Heating with solar collectors in the main façade.

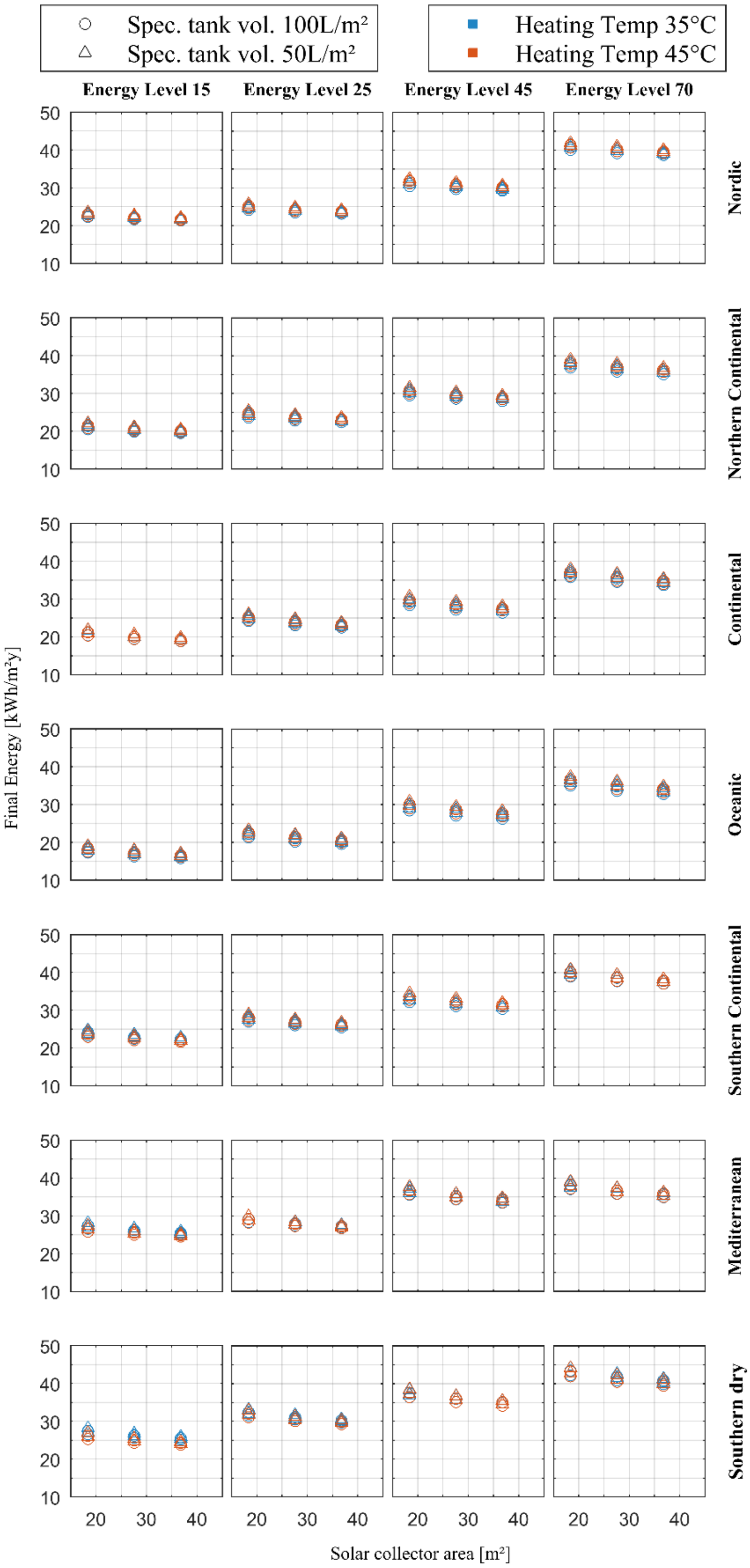

Figure 84 – Total final energy for several variants air-source heat pump and solar thermal system

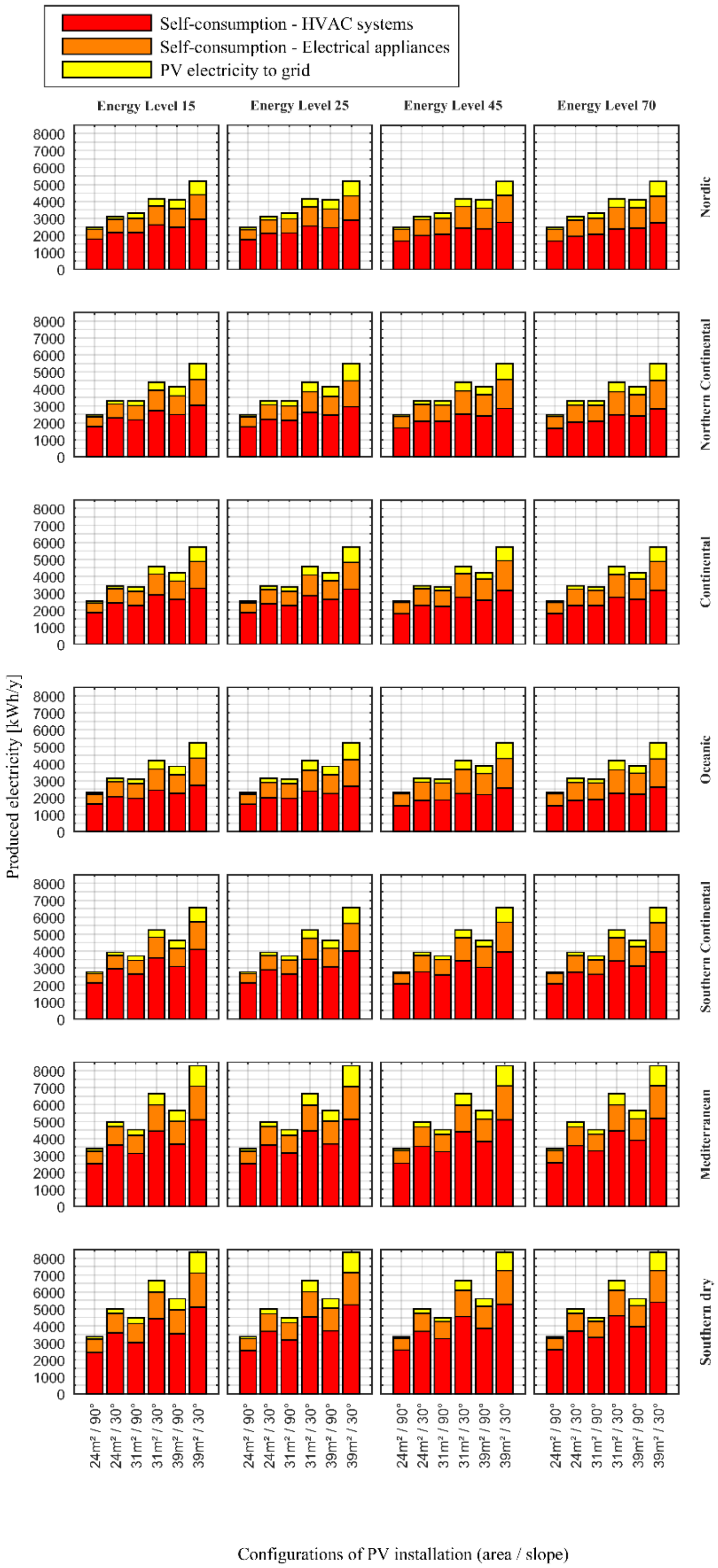

Figure 85 – Photovoltaic electricity production

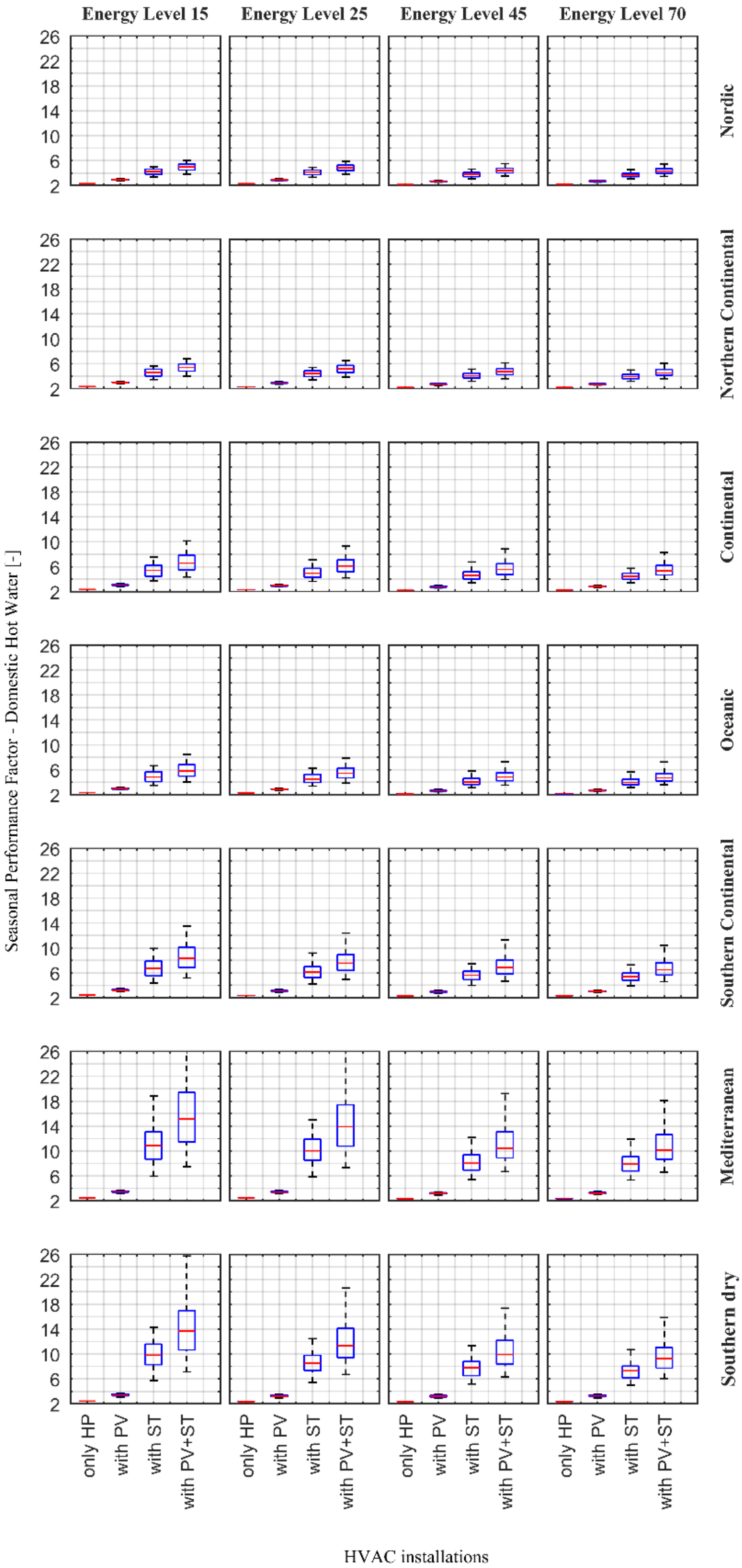

Figure 86 – Seasonal Performance Factor for Domestic Hot Water production

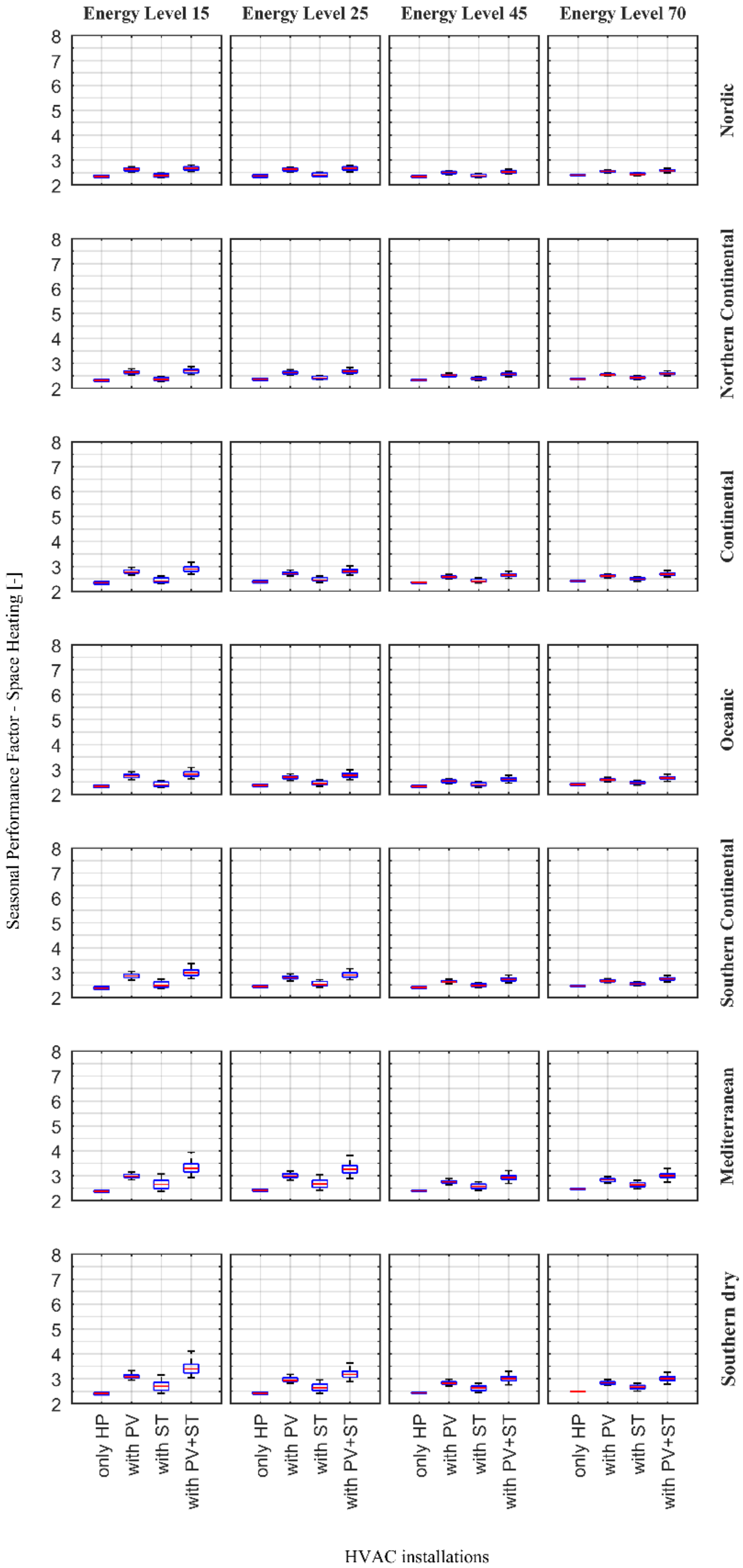

Figure 87 – Seasonal Performance Factor for Space Heating

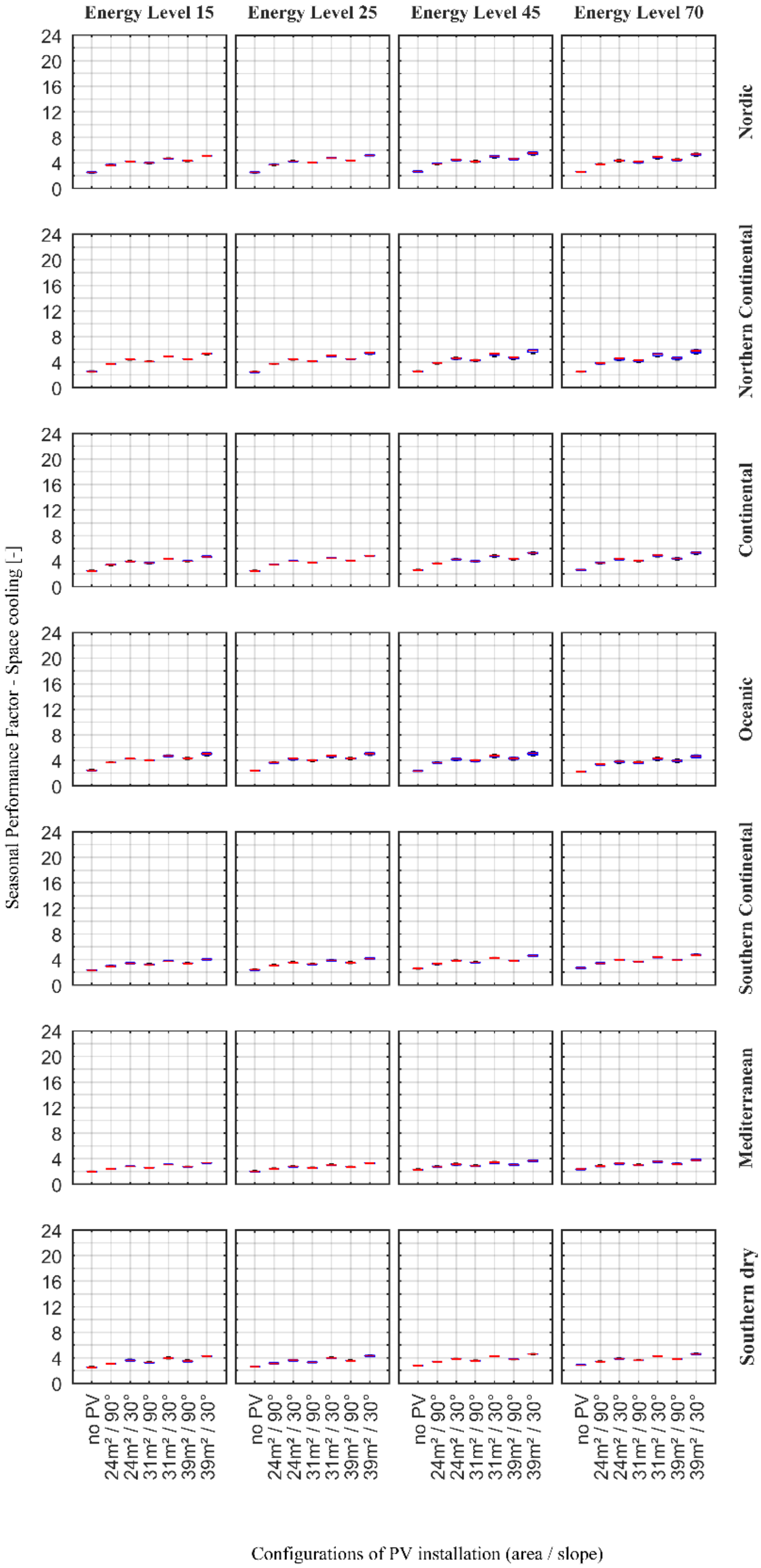

Figure 88 – Seasonal Performance Factor for Space Cooling

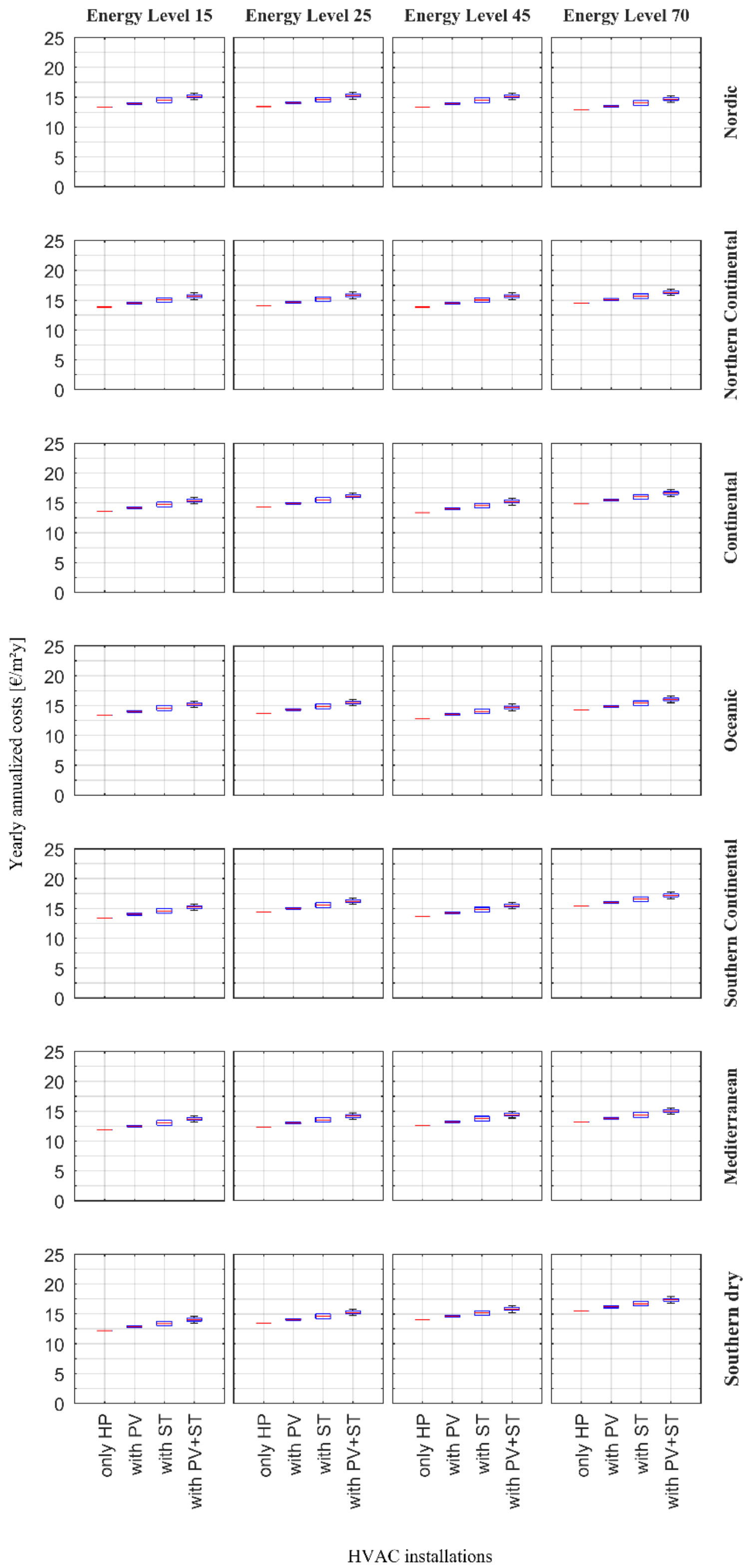

Figure 89 – Yearly annualised costs distribution for variants with solar systems

3.7 Small Multifamily Houses – Gas boiler + fan coils

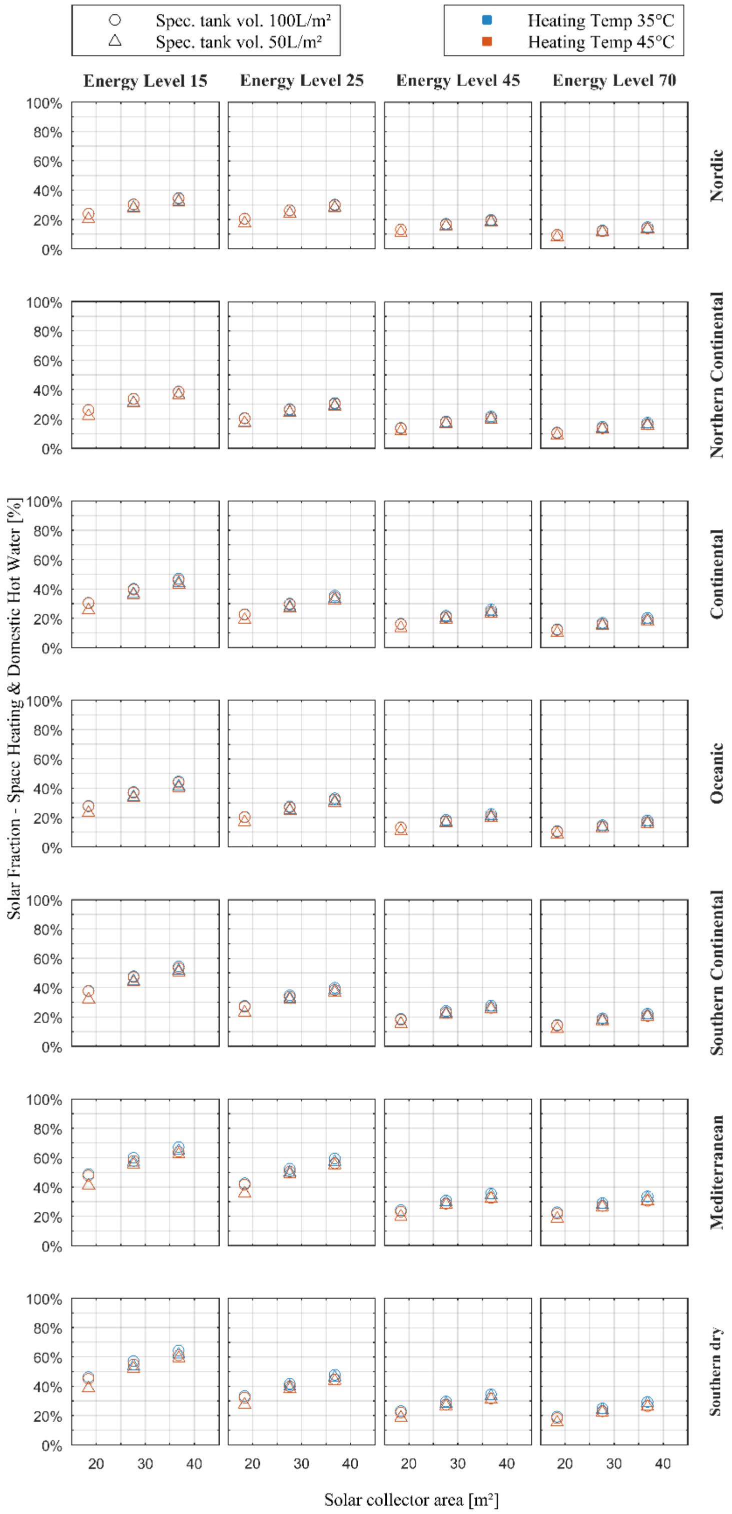

Figure 90 – Solar fraction for Domestic Hot Water and Space Heating with solar collectors in the main façade.

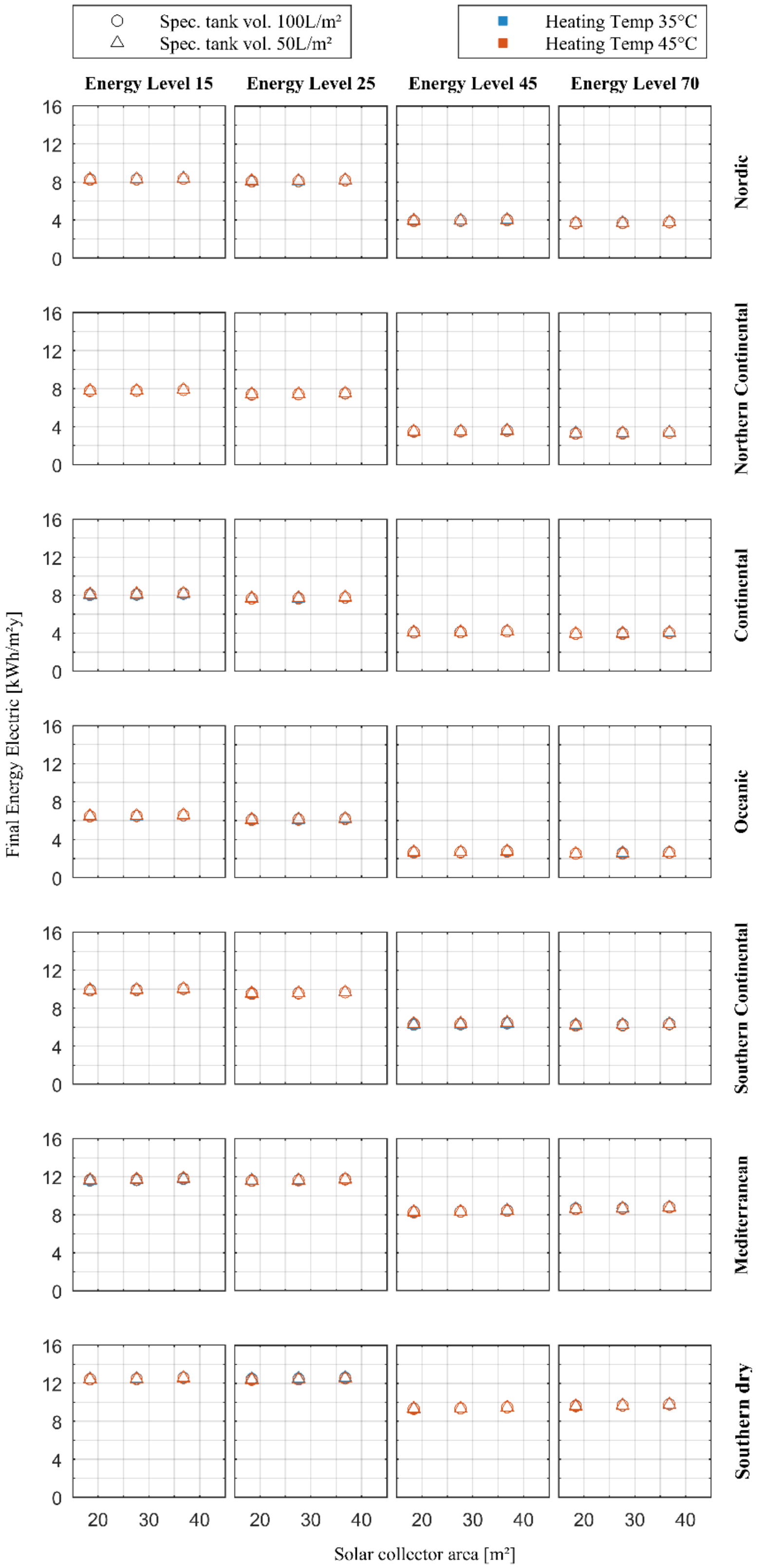

Figure 91 – Total final energy for several variants of gas boiler and solar thermal system

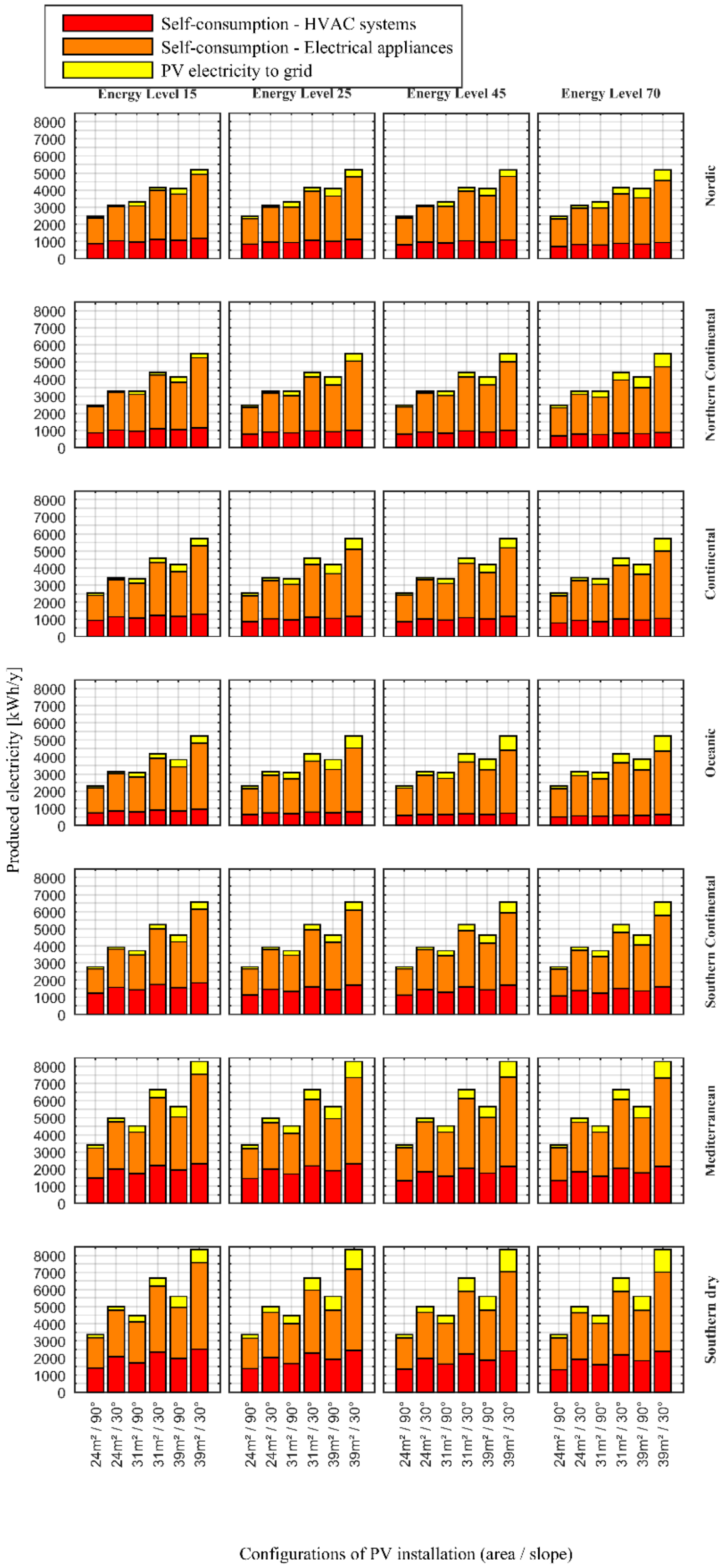

Figure 92 – Photovoltaic electricity production

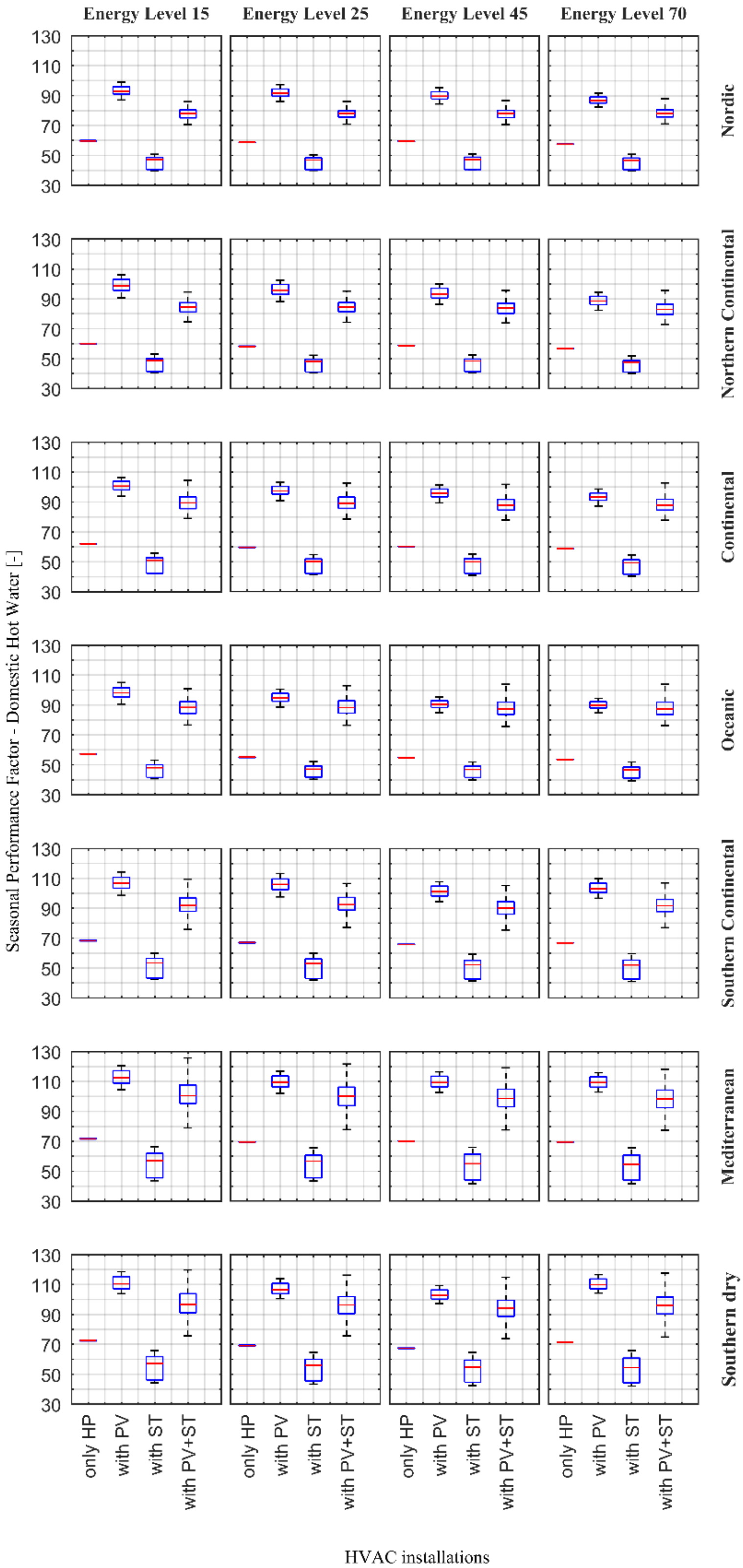

Figure 93 – Seasonal Performance Factor for Domestic Hot Water production

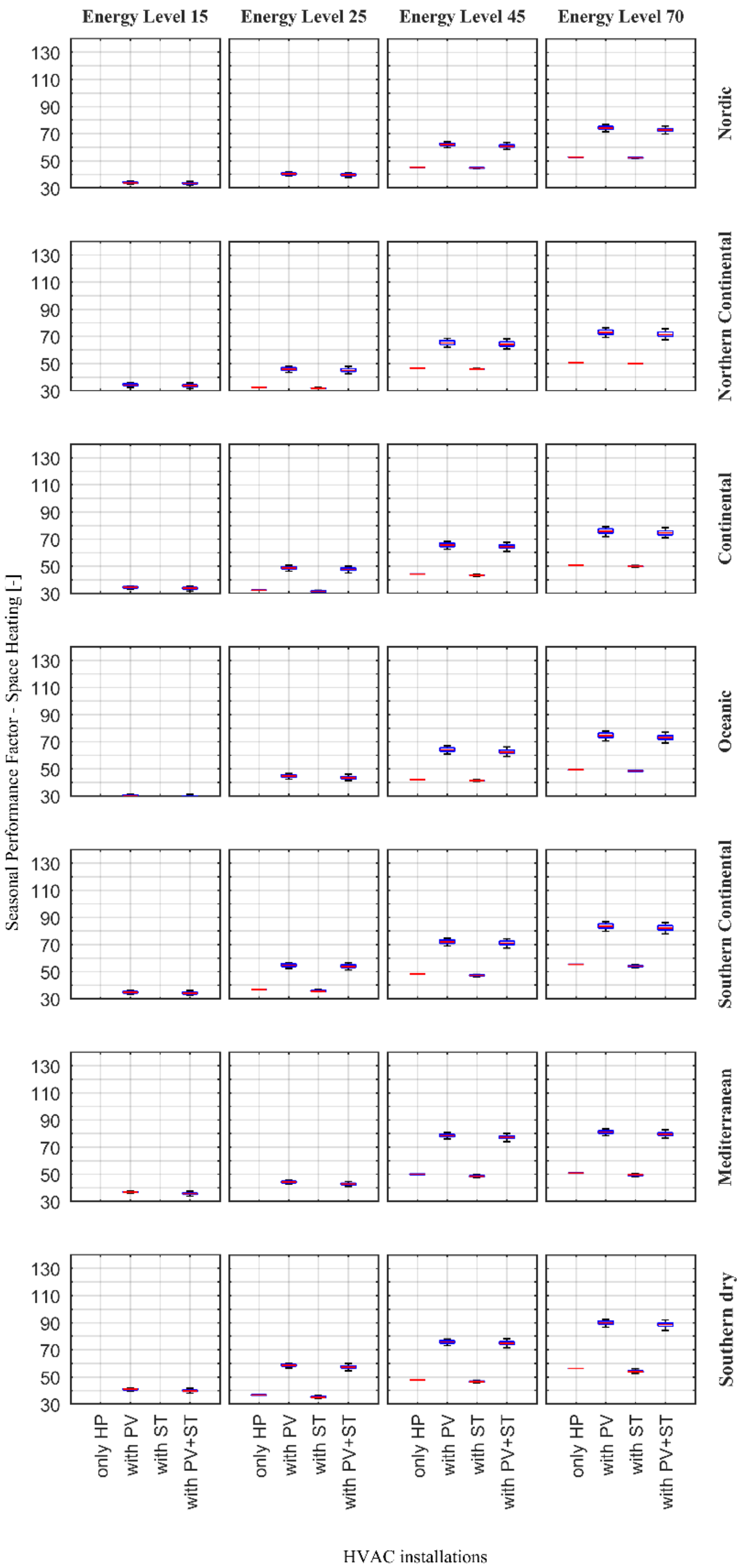

Figure 94 – Seasonal Performance Factor for Space Heating

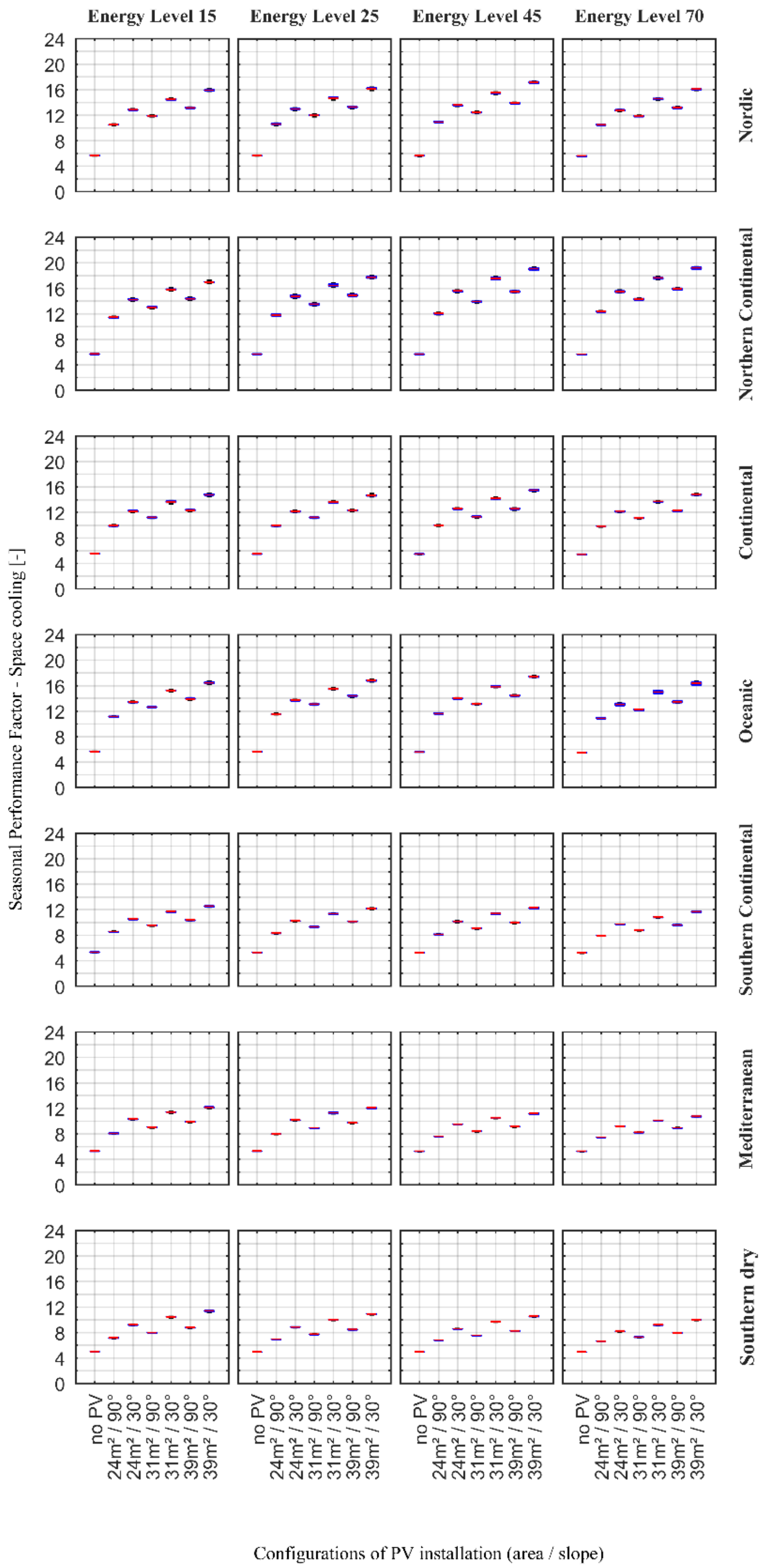

Figure 95 – Seasonal Performance Factor for Space Cooling

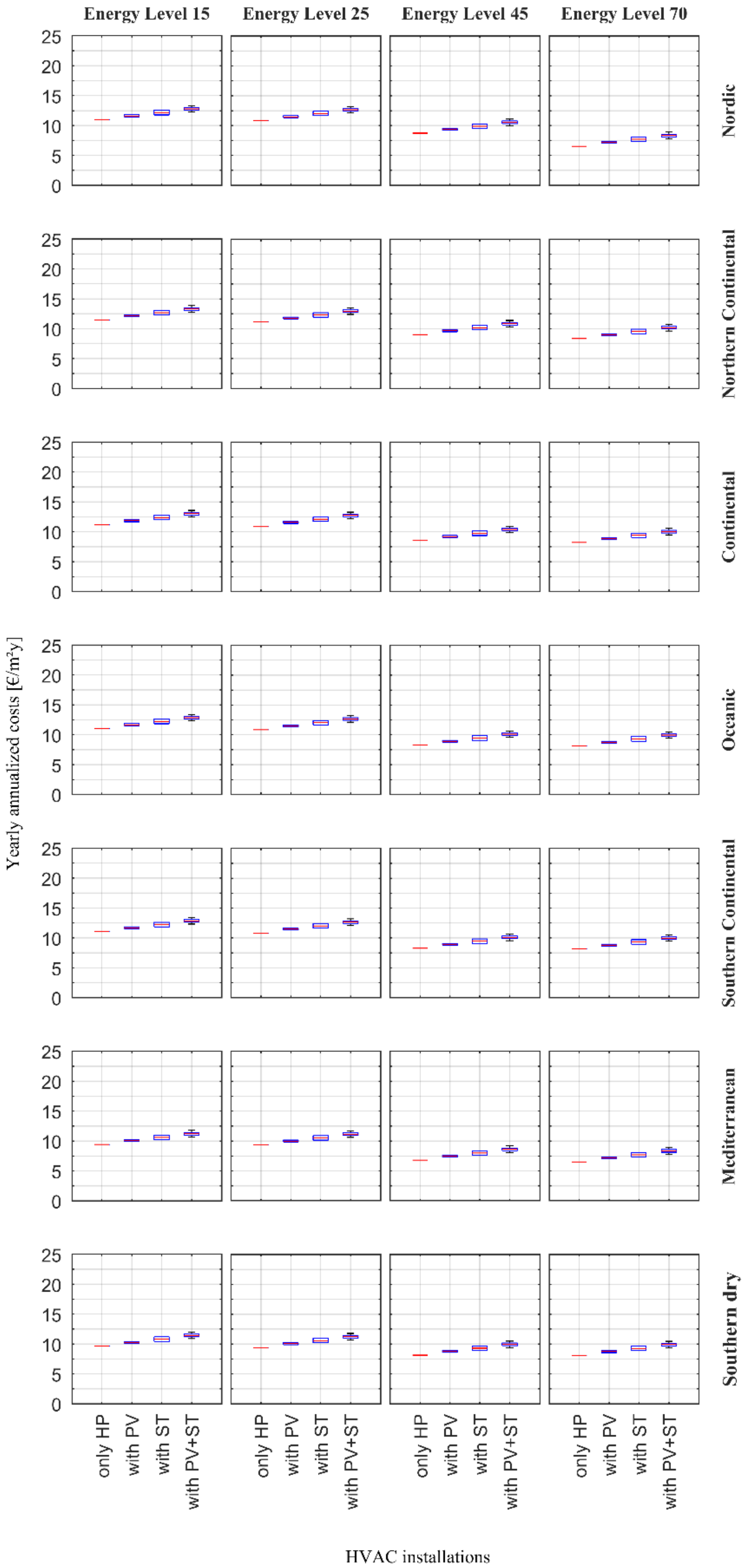

Figure 96 – Yearly annualised costs distribution for variants with solar systems

3.8 Small Multifamily Houses – Pellet boiler + fan coils

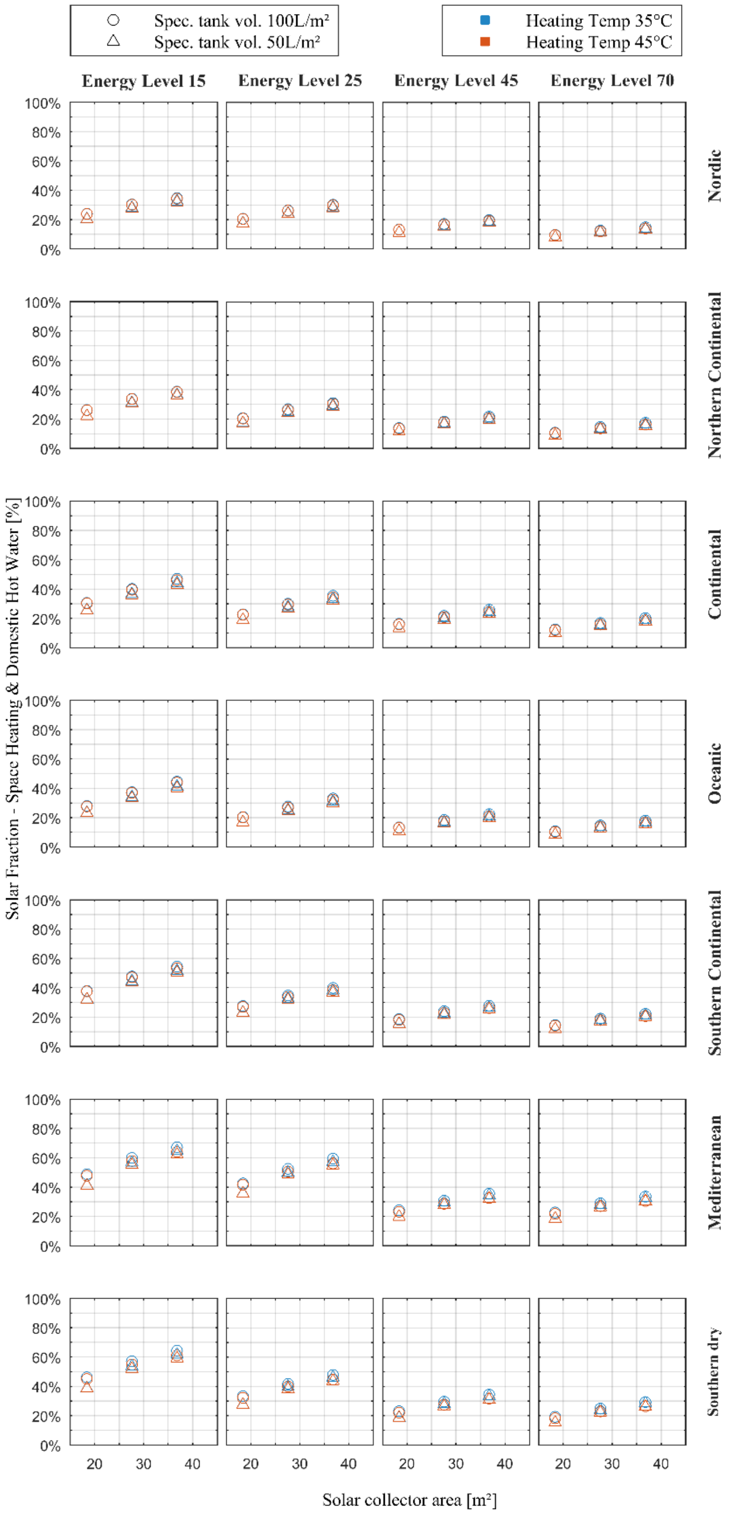

Figure 97 – Solar fraction for Domestic Hot Water and Space Heating with solar collectors in the main façade.

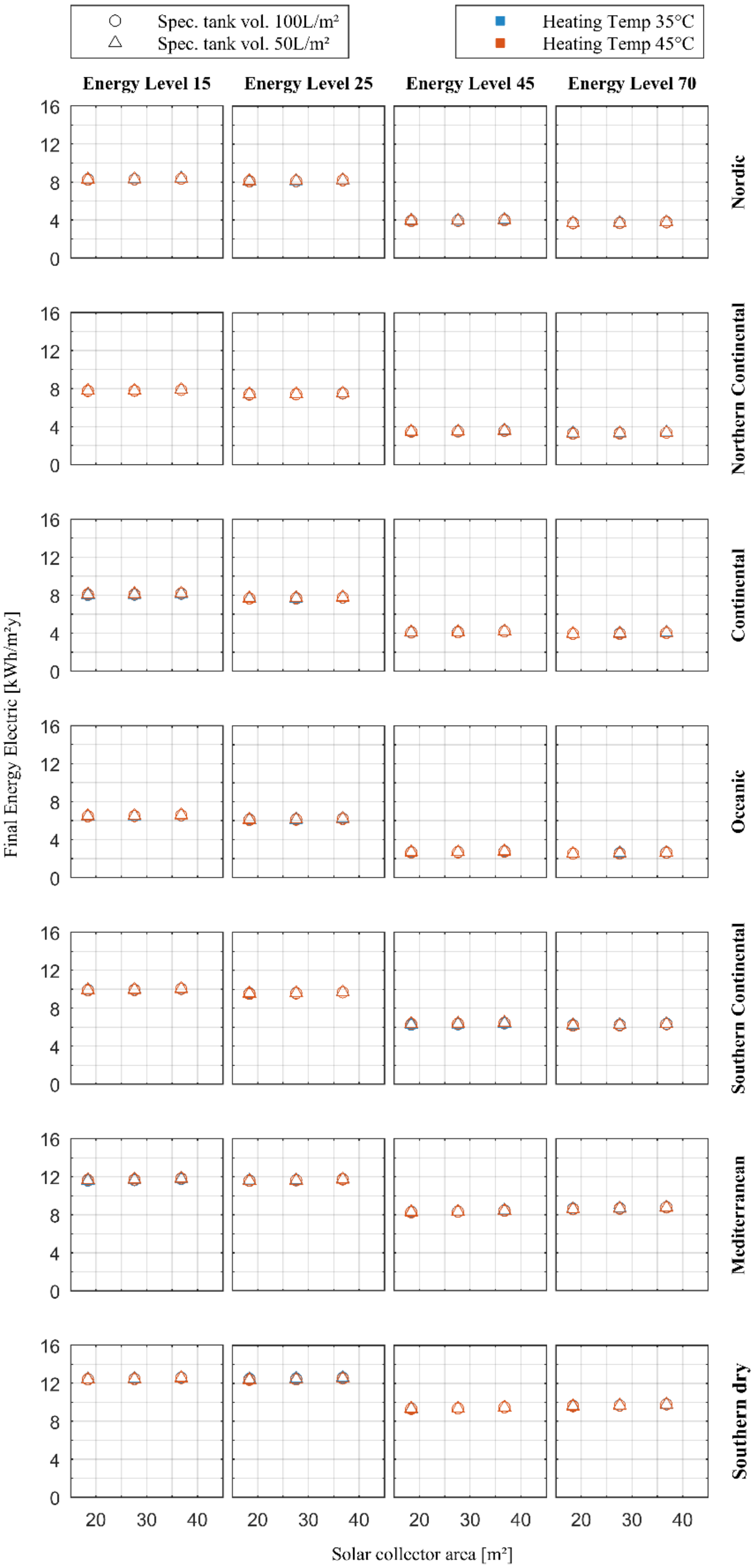

Figure 98 – Total final energy for several variants of gas boiler and solar thermal system

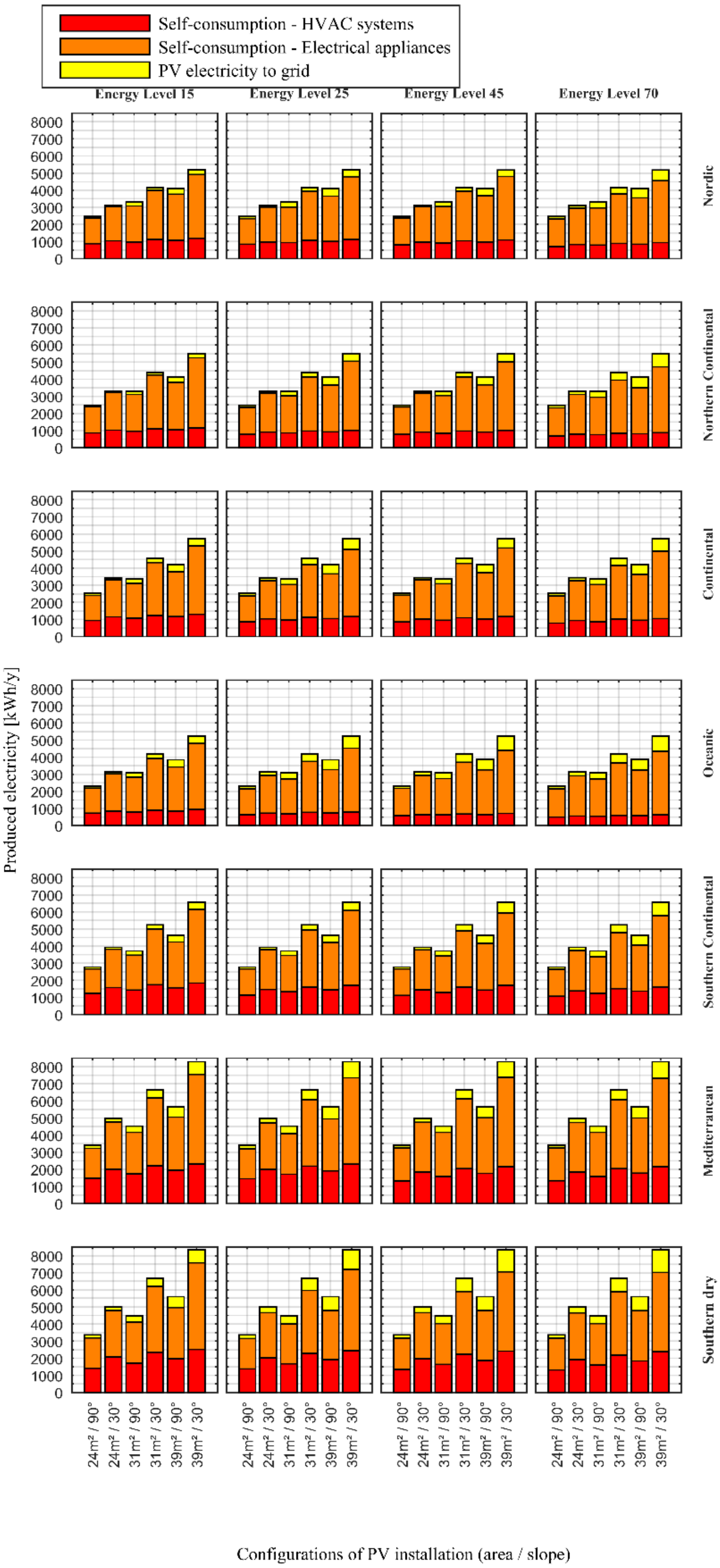

Figure 99 – Photovoltaic electricity production

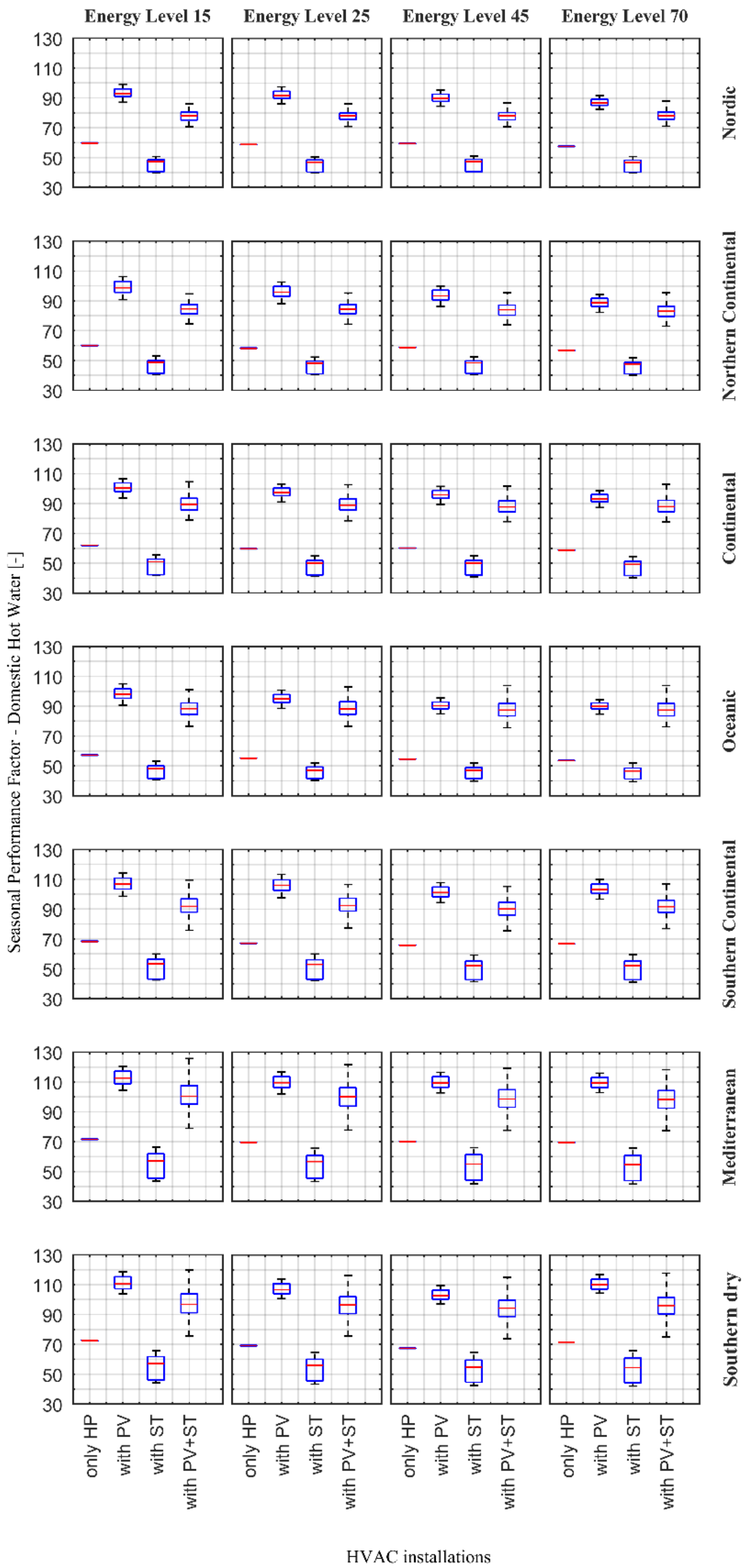

Figure 100 – Seasonal Performance Factor for Domestic Hot Water production

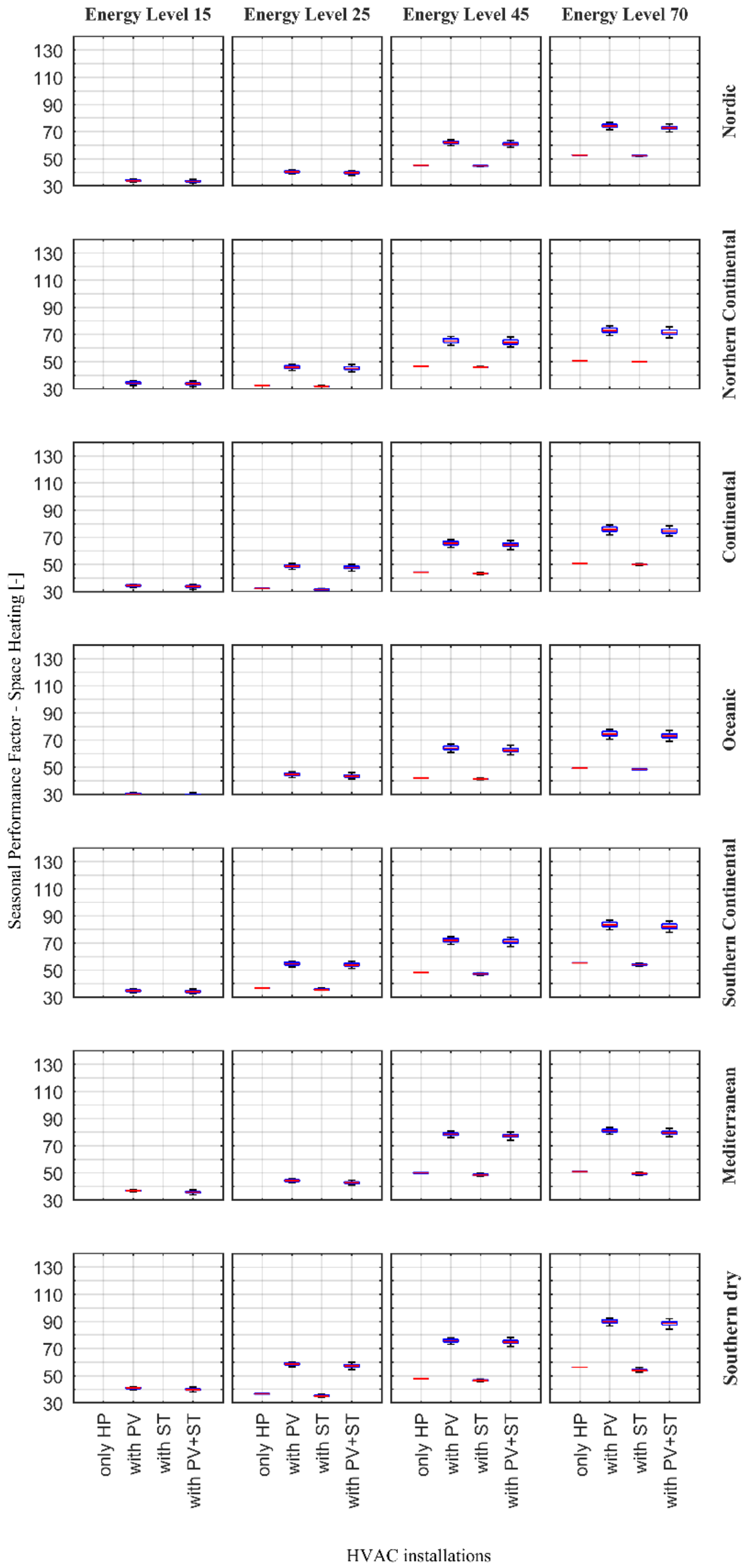

Figure 101 – Seasonal Performance Factor for Space Heating

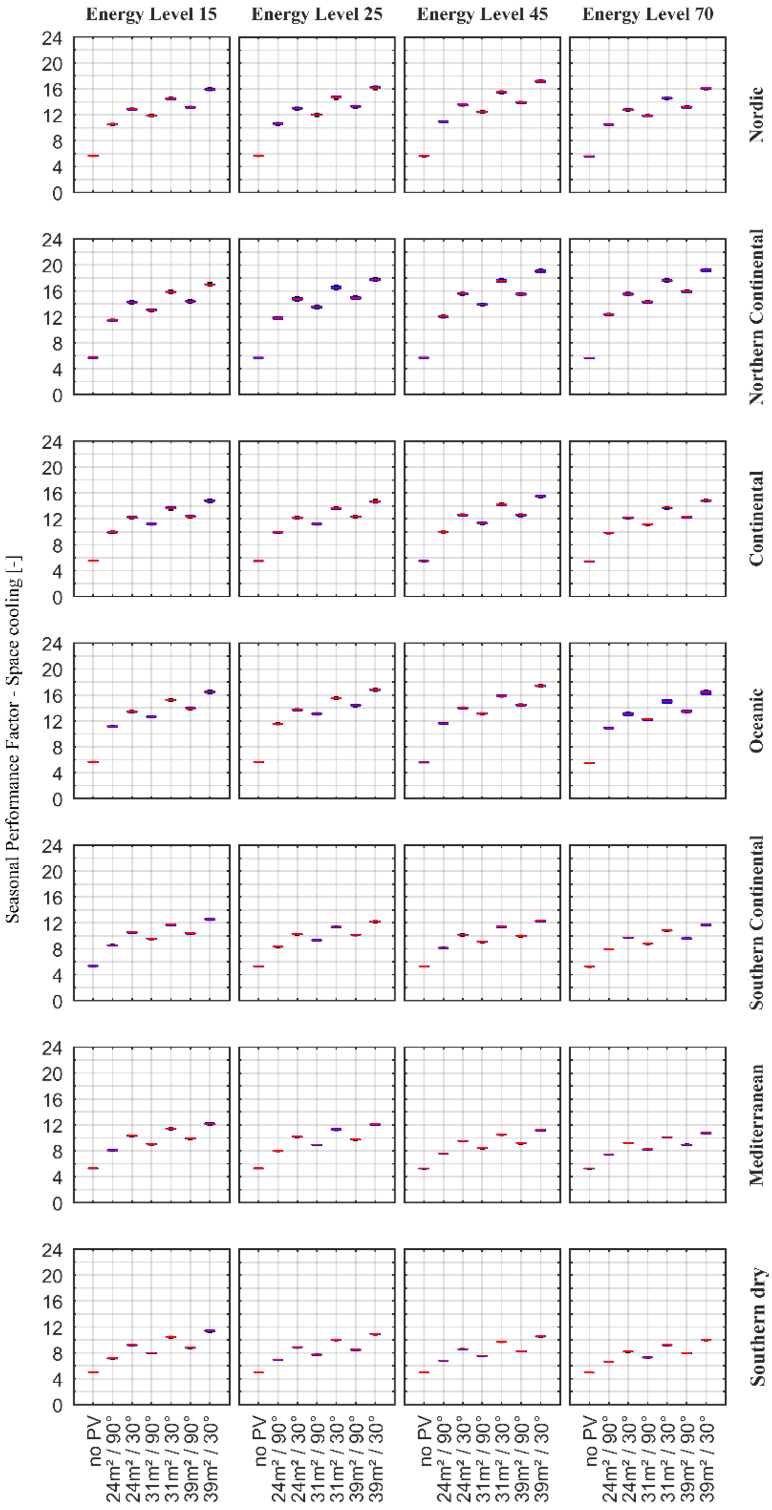

Figure 102 – Seasonal Performance Factor for Space Cooling

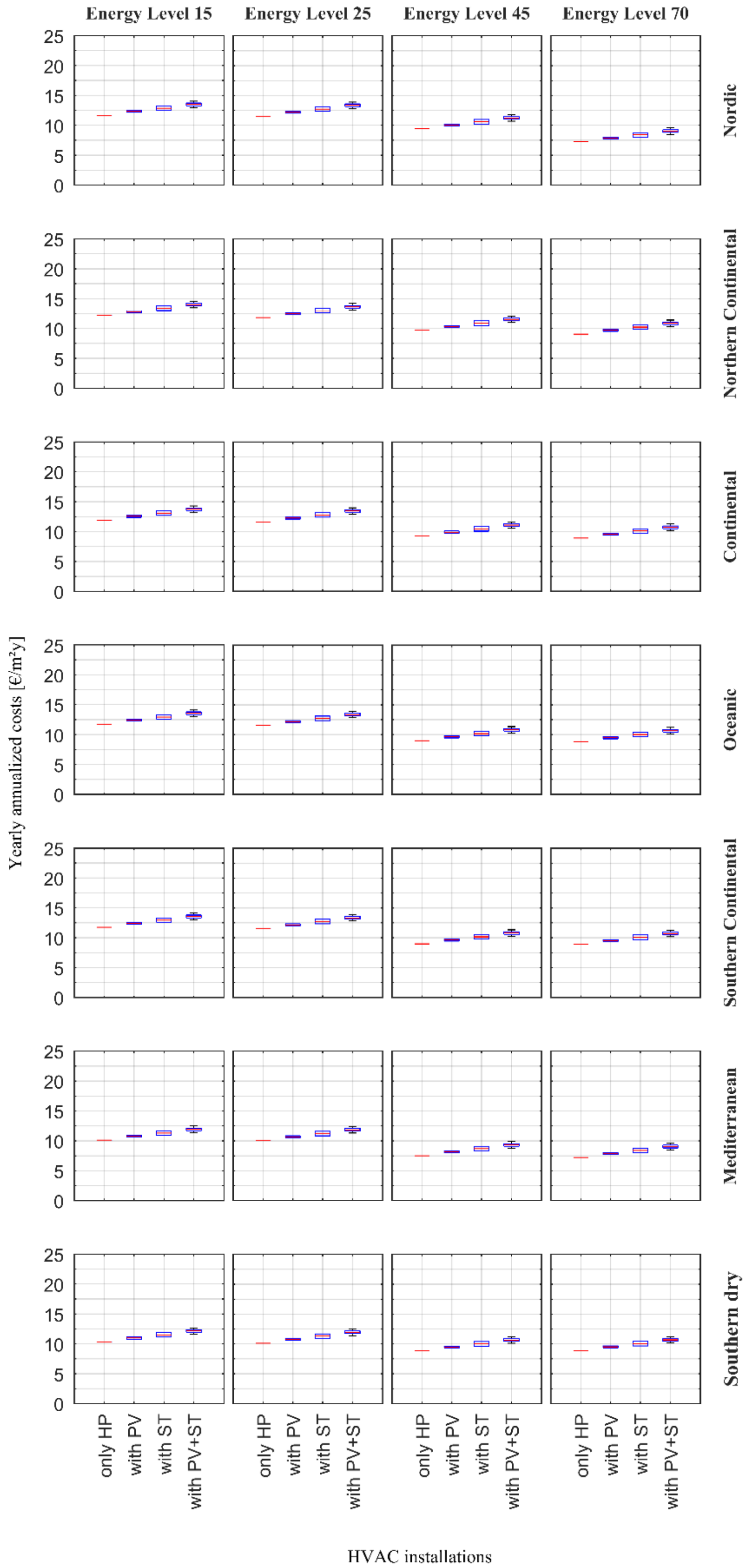

Figure 103 – Yearly annualised costs distribution for variants with solar systems

3.9 Small Multifamily Houses – Air to water heat pump + radiators

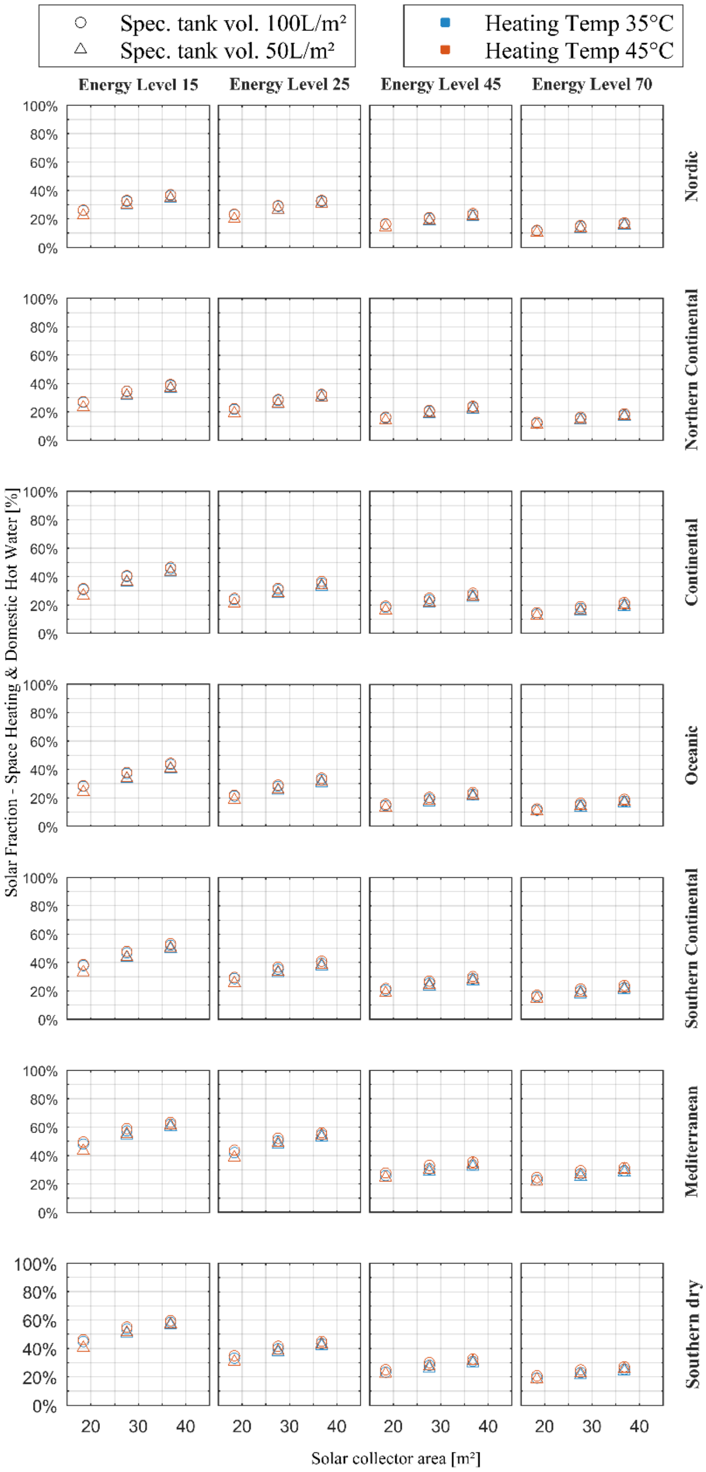

Figure 104 – Solar fraction for Domestic Hot Water and Space Heating with solar collectors in the main façade.

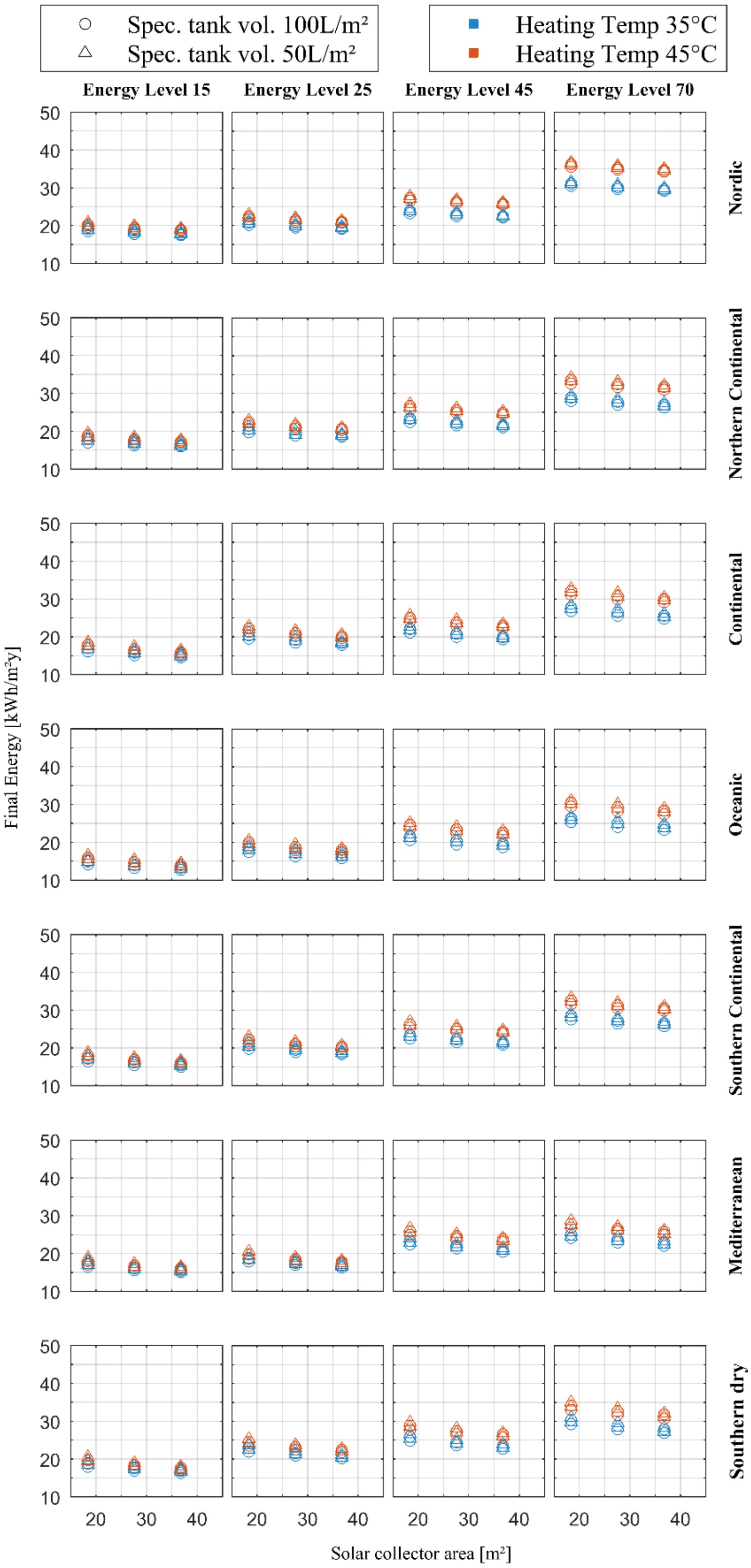

Figure 105 – Total final energy for several variants air-source heat pump and solar thermal system

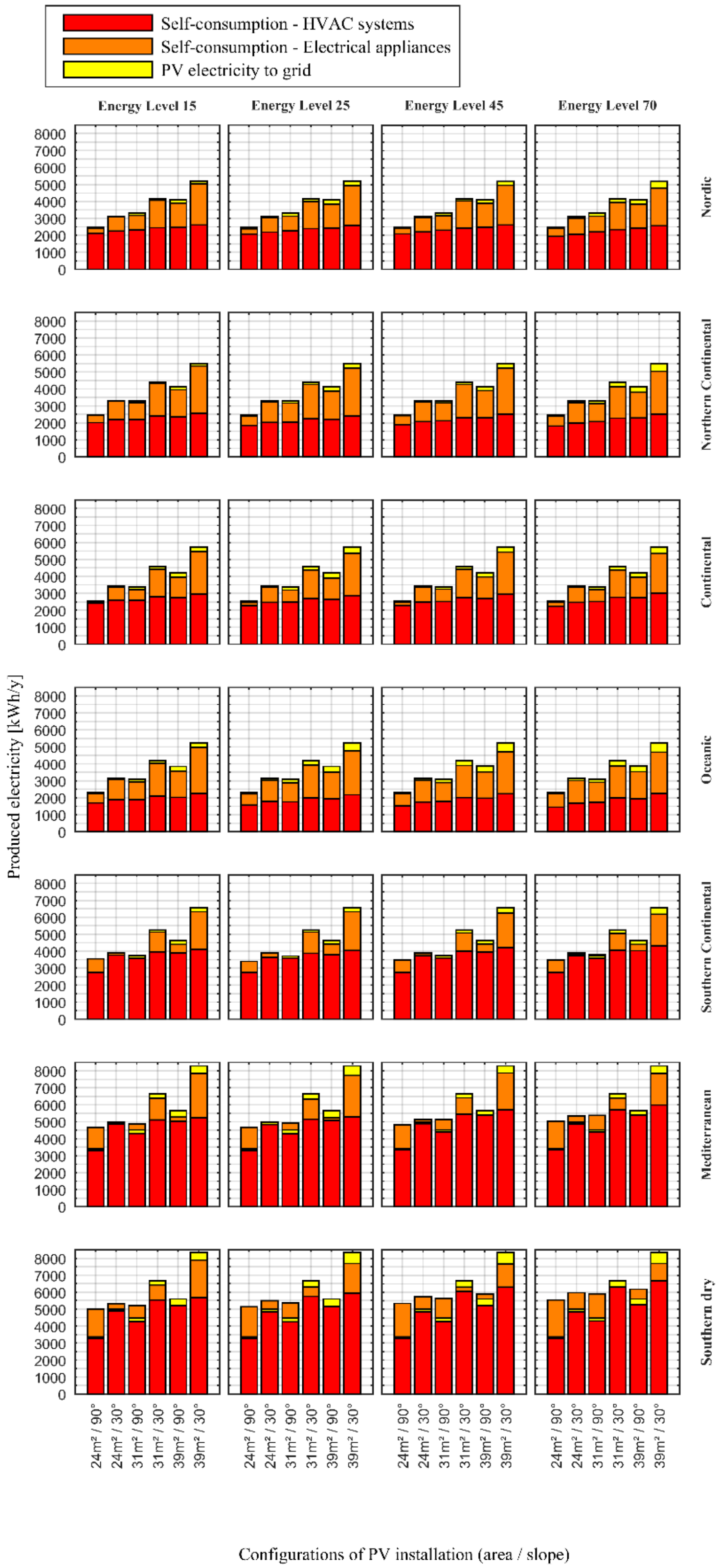

Figure 106 – Photovoltaic electricity production

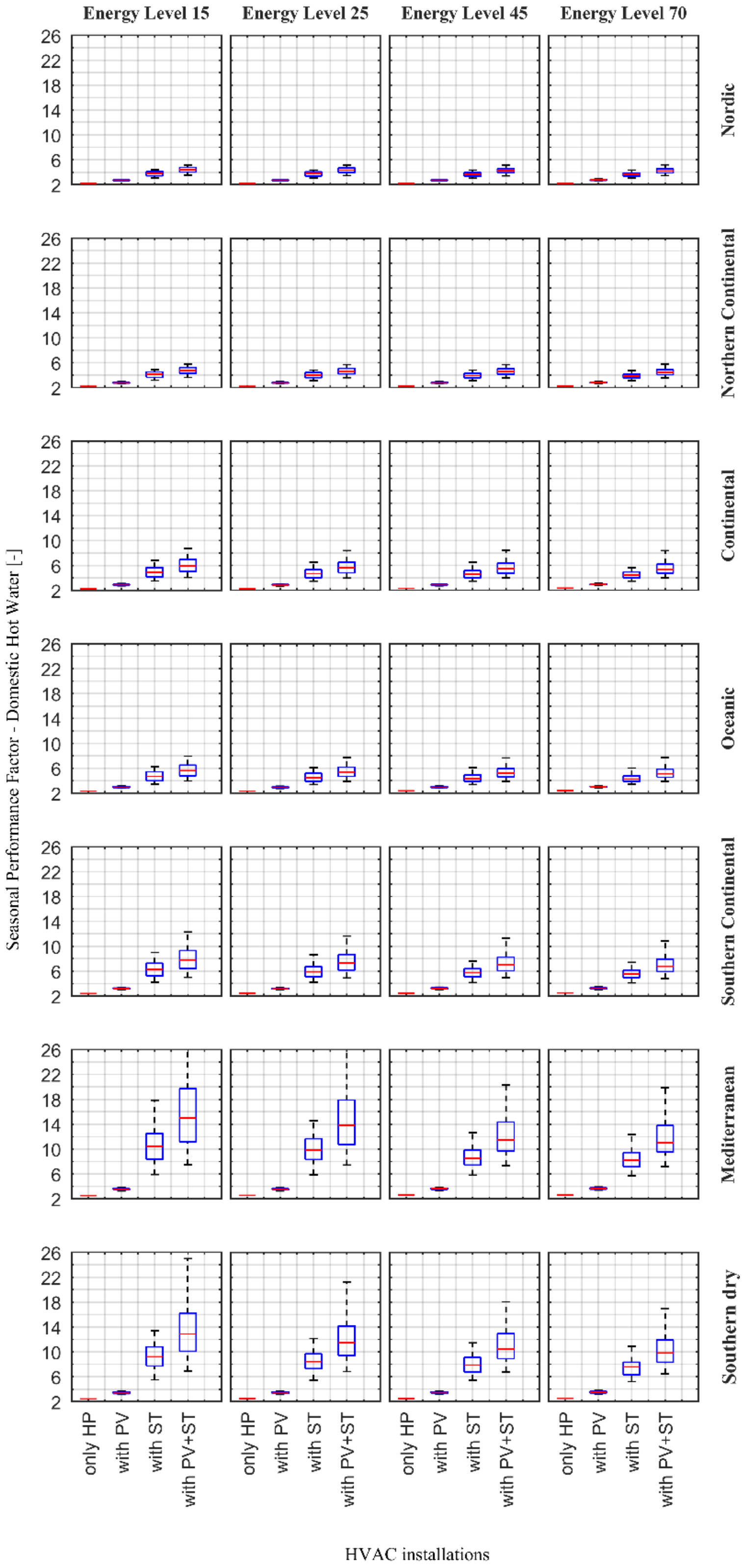

Figure 107 – Seasonal Performance Factor for Domestic Hot Water production

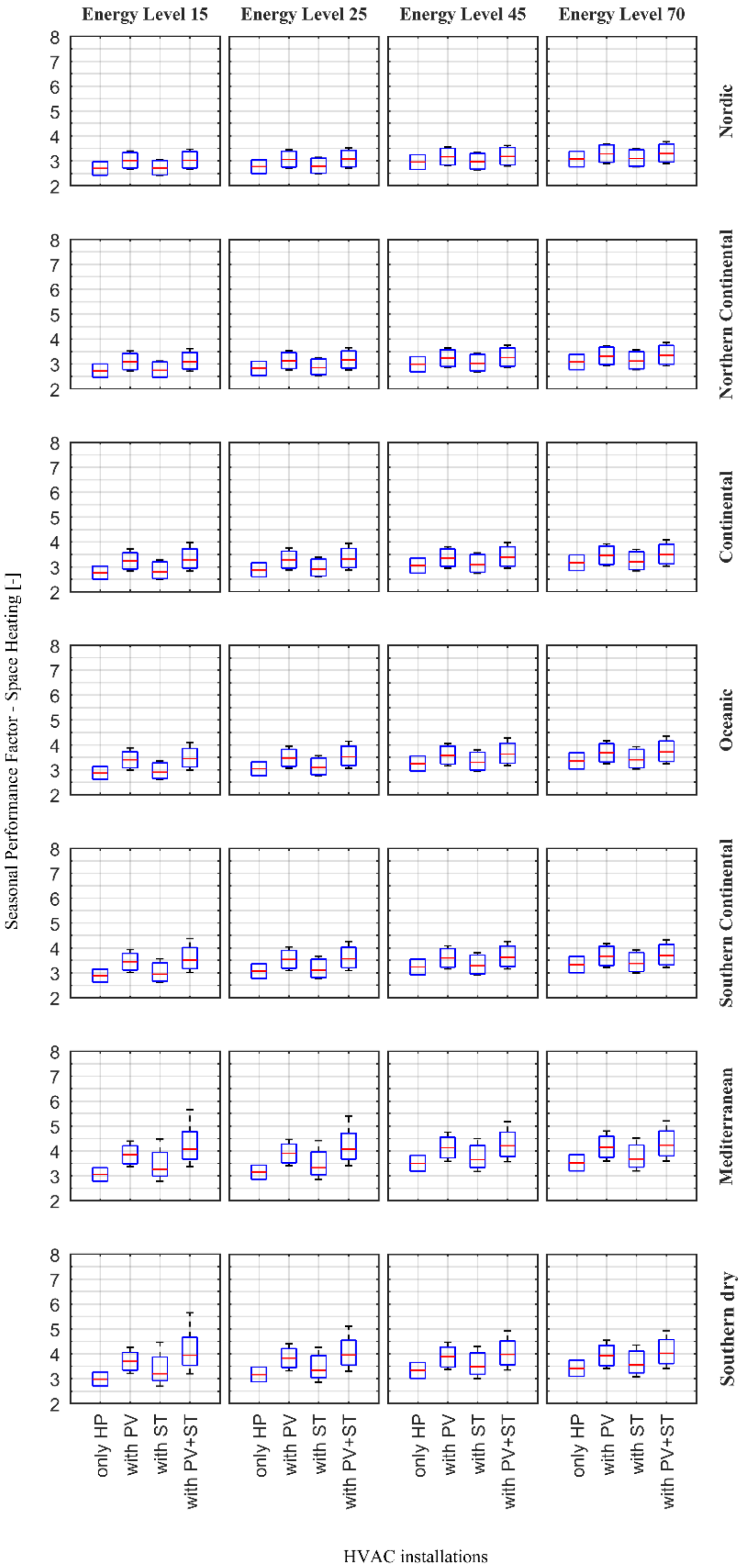

Figure 108 – Seasonal Performance Factor for Space Heating

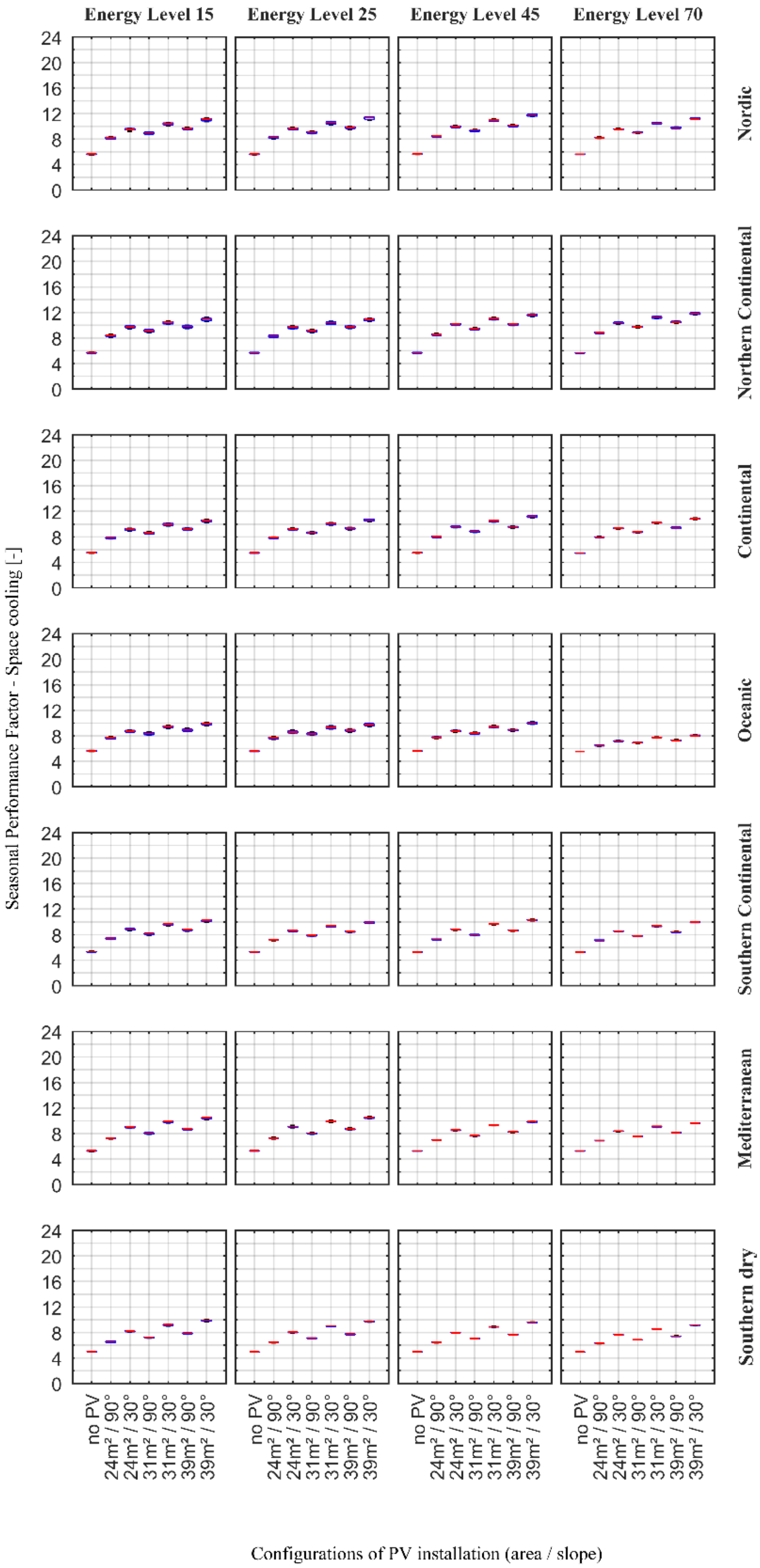

Figure 109 – Seasonal Performance Factor for Space Cooling

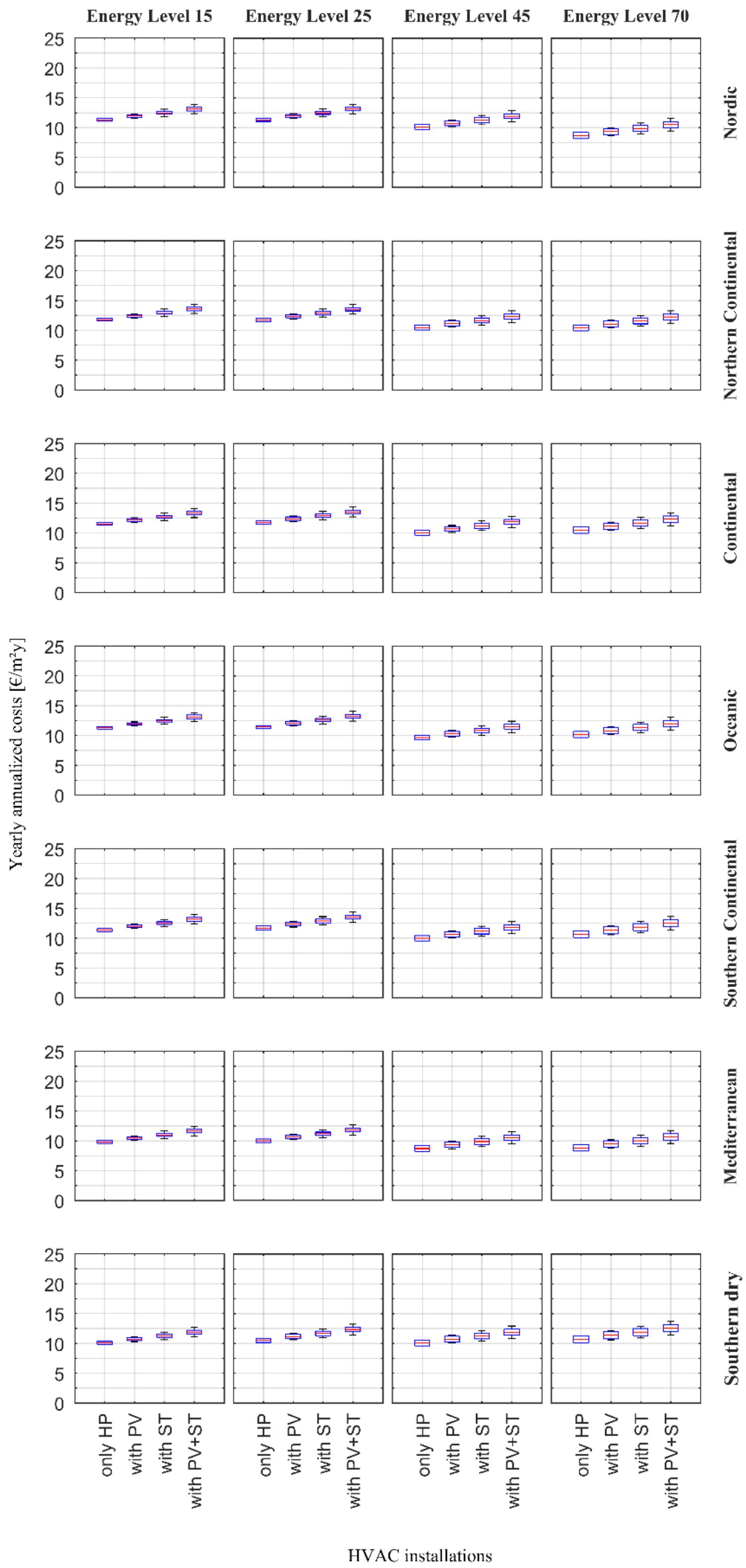

Figure 110 – Yearly annualised costs distribution for variants with solar systems

3.10 Small Multifamily Houses – Ground source heat pump + radiators

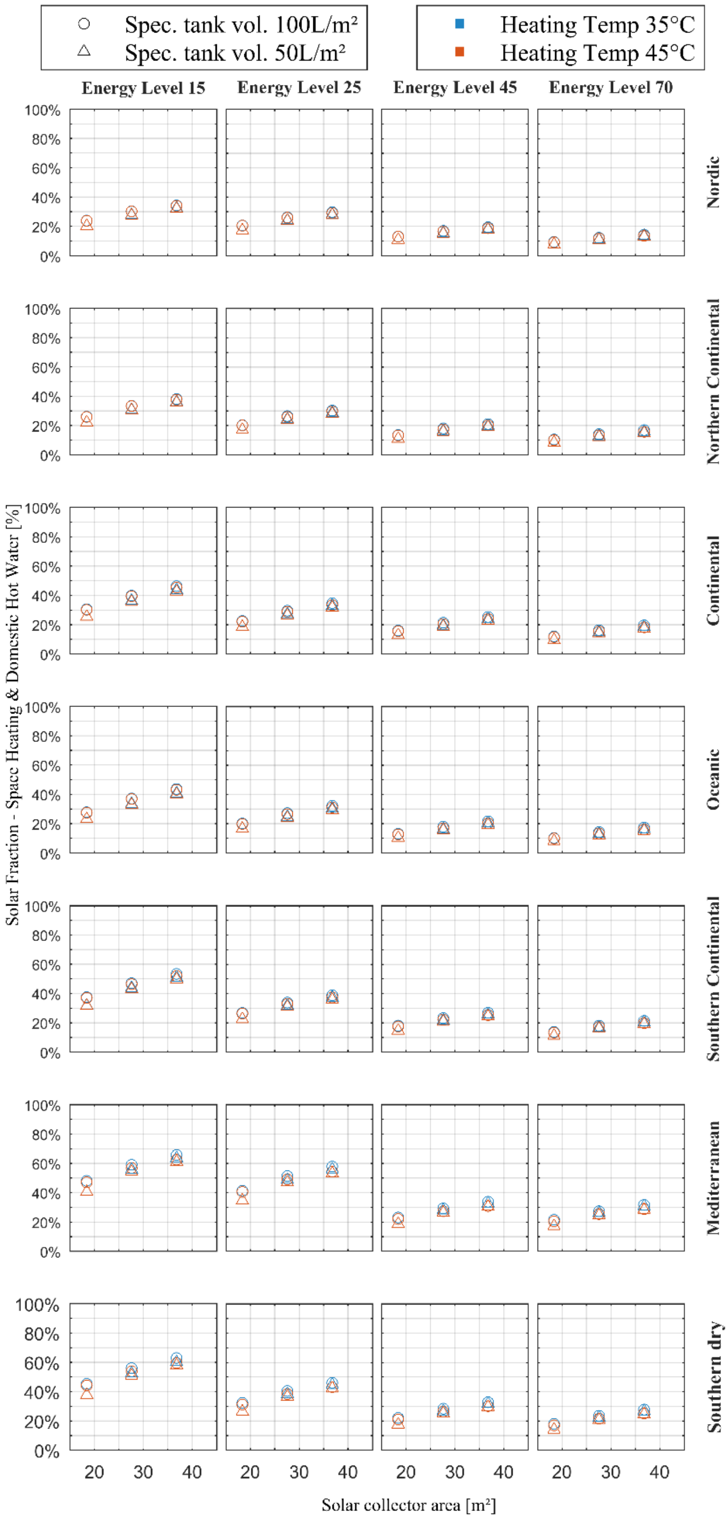

Figure 111 – Solar fraction for Domestic Hot Water and Space Heating with solar collectors in the main façade.

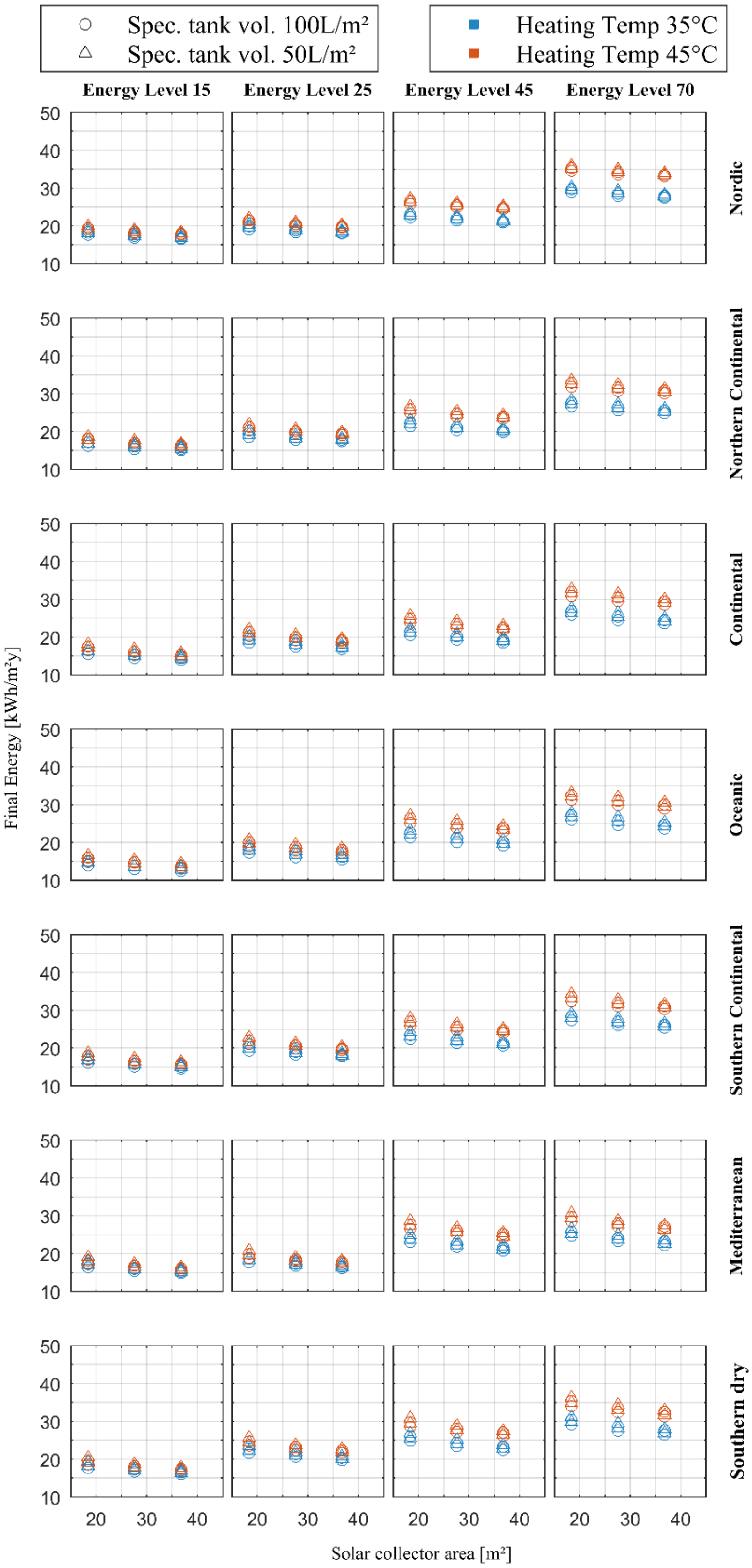

Figure 112 – Total final energy for several variants air-source heat pump and solar thermal system

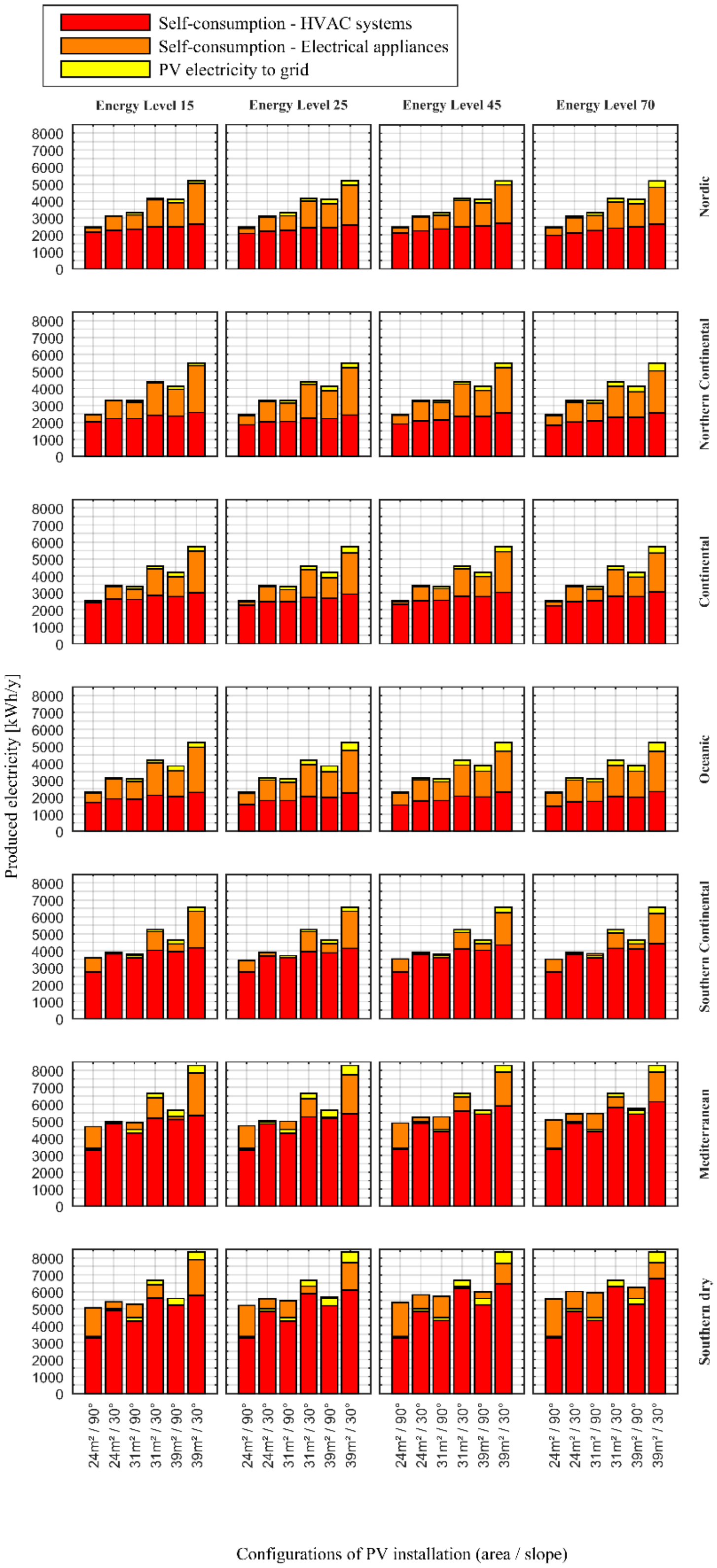

Figure 113 – Photovoltaic electricity production

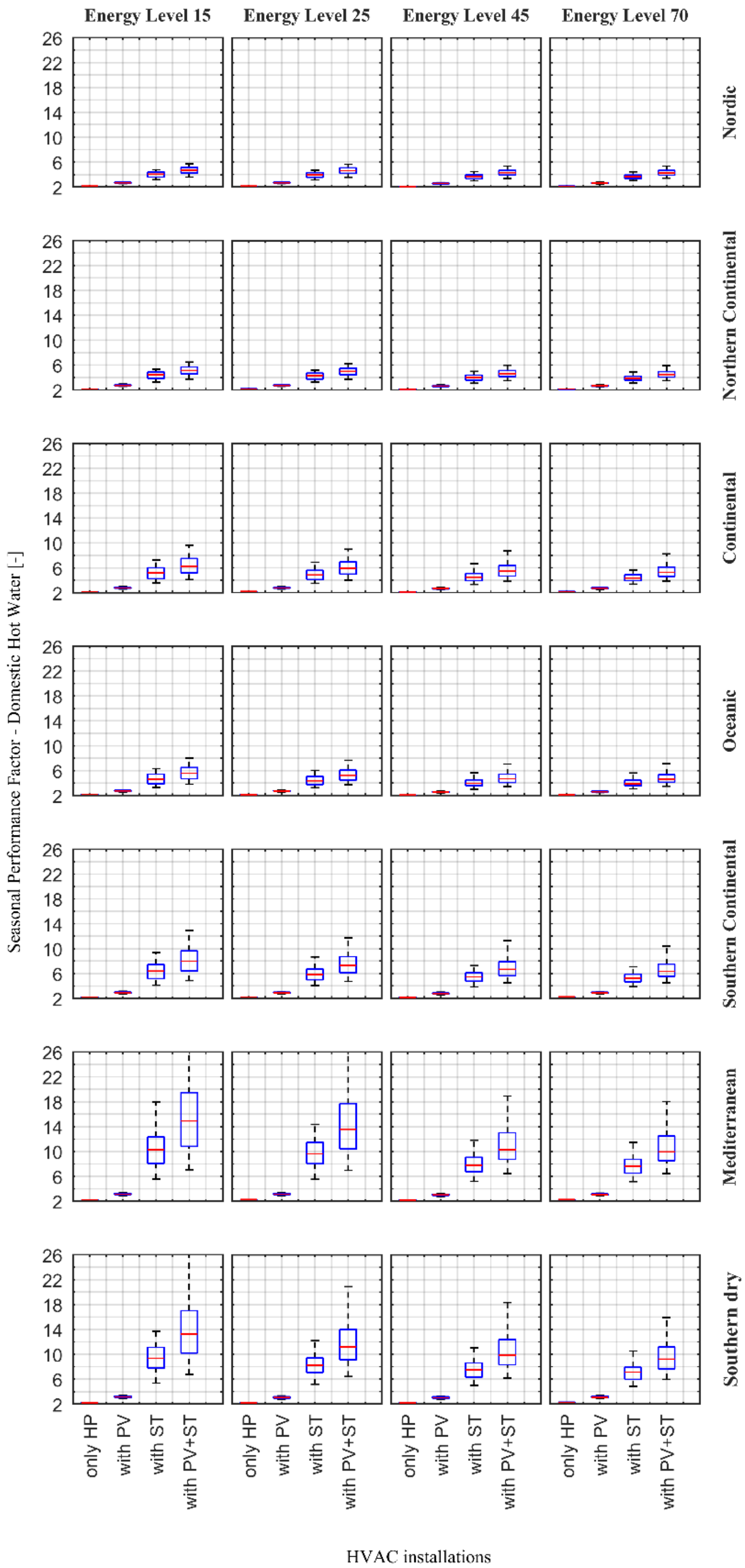

Figure 114 – Seasonal Performance Factor for Domestic Hot Water production

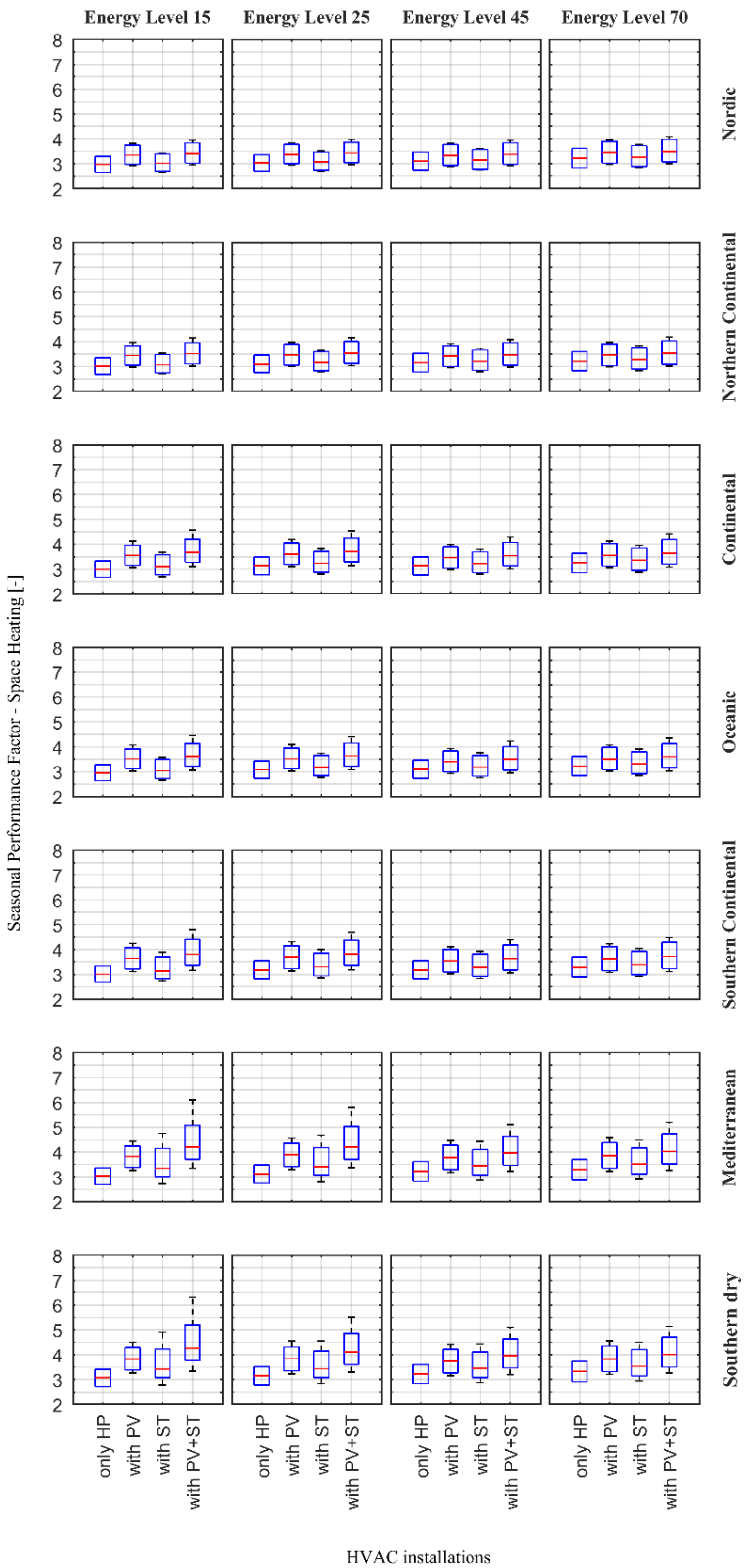

Figure 115 – Seasonal Performance Factor for Space Heating

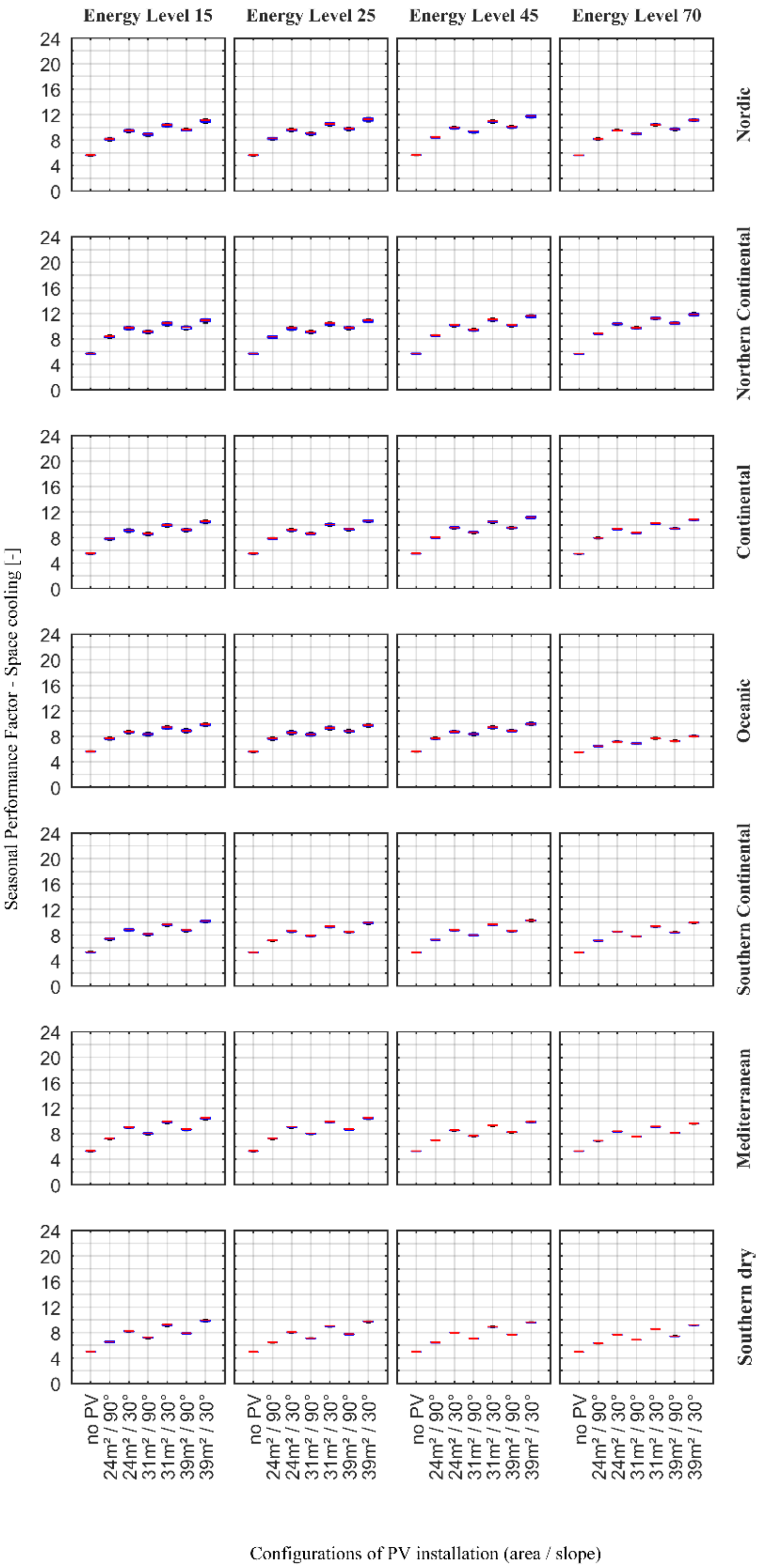

Figure 116 – Seasonal Performance Factor for Space Cooling

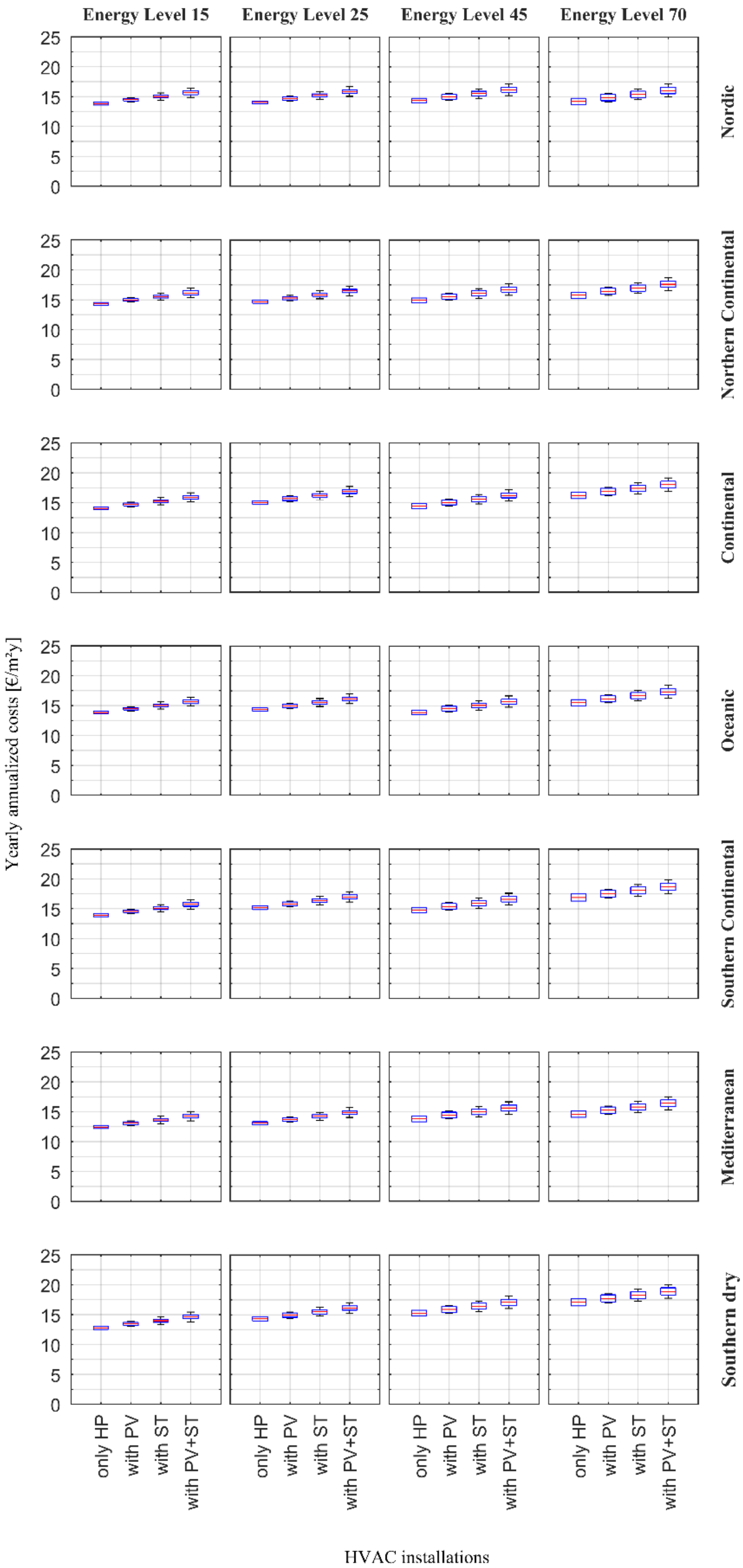

Figure 117 – Yearly annualised costs distribution for variants with solar systems

3.11 Small Multifamily Houses – Gas Boiler with Radiators

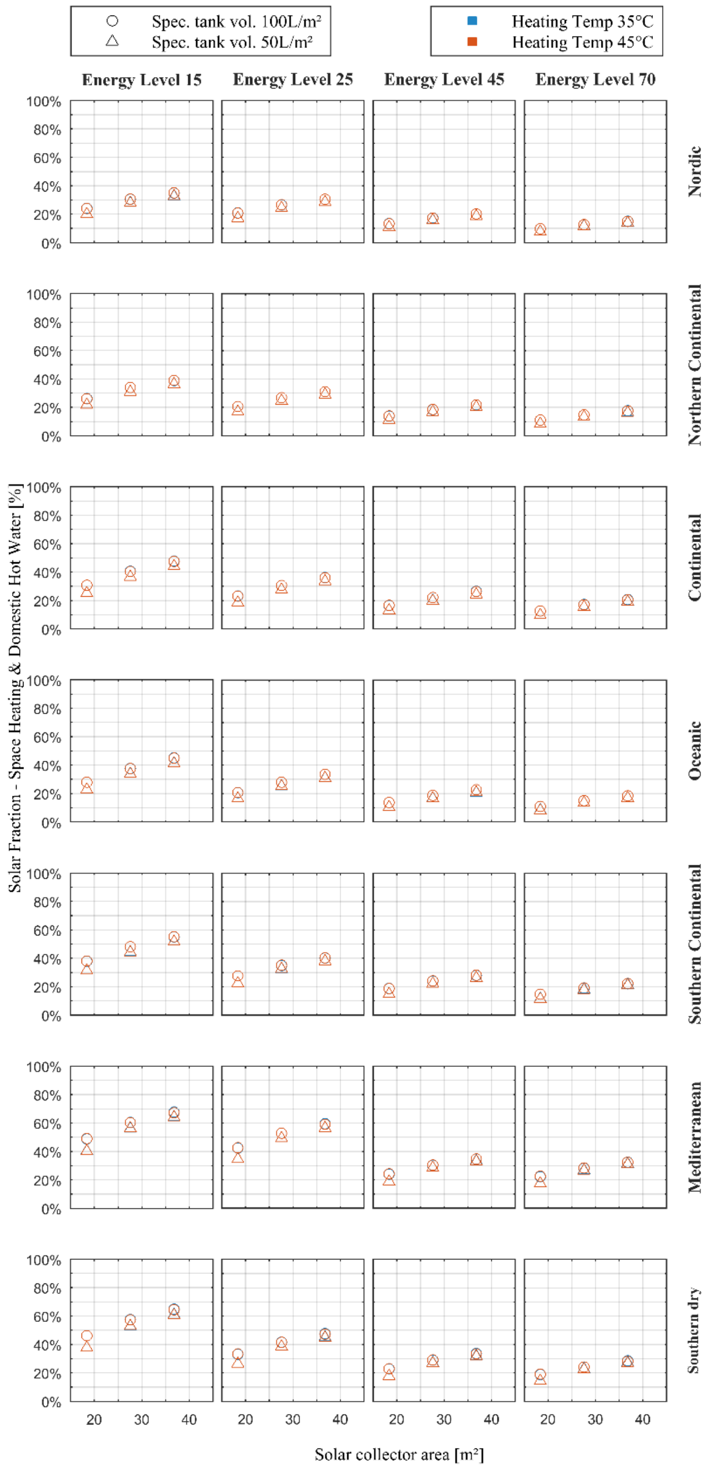

Figure 118 – Solar fraction for Domestic Hot Water and space heating with solar collectors in the main façade.

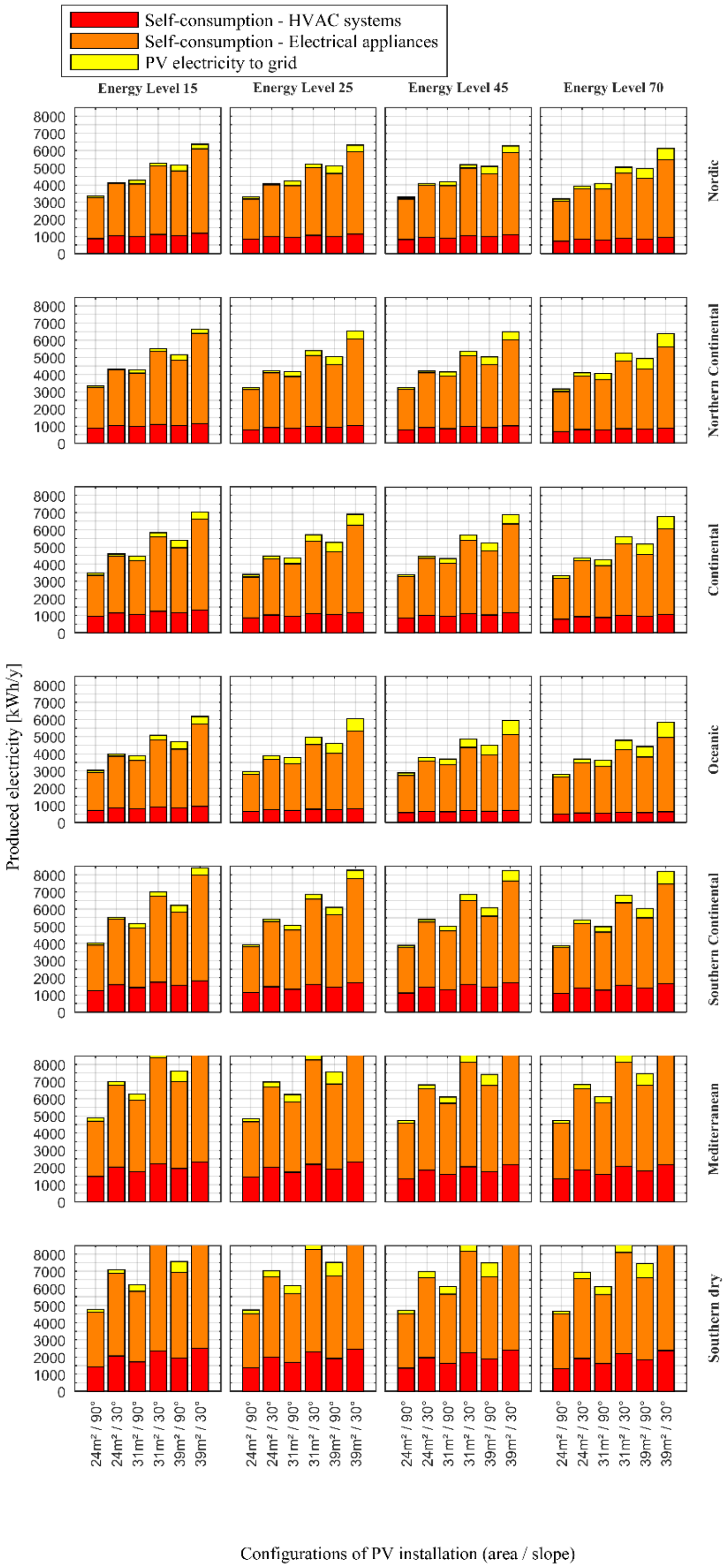

Figure 119 – Photovoltaic electricity production

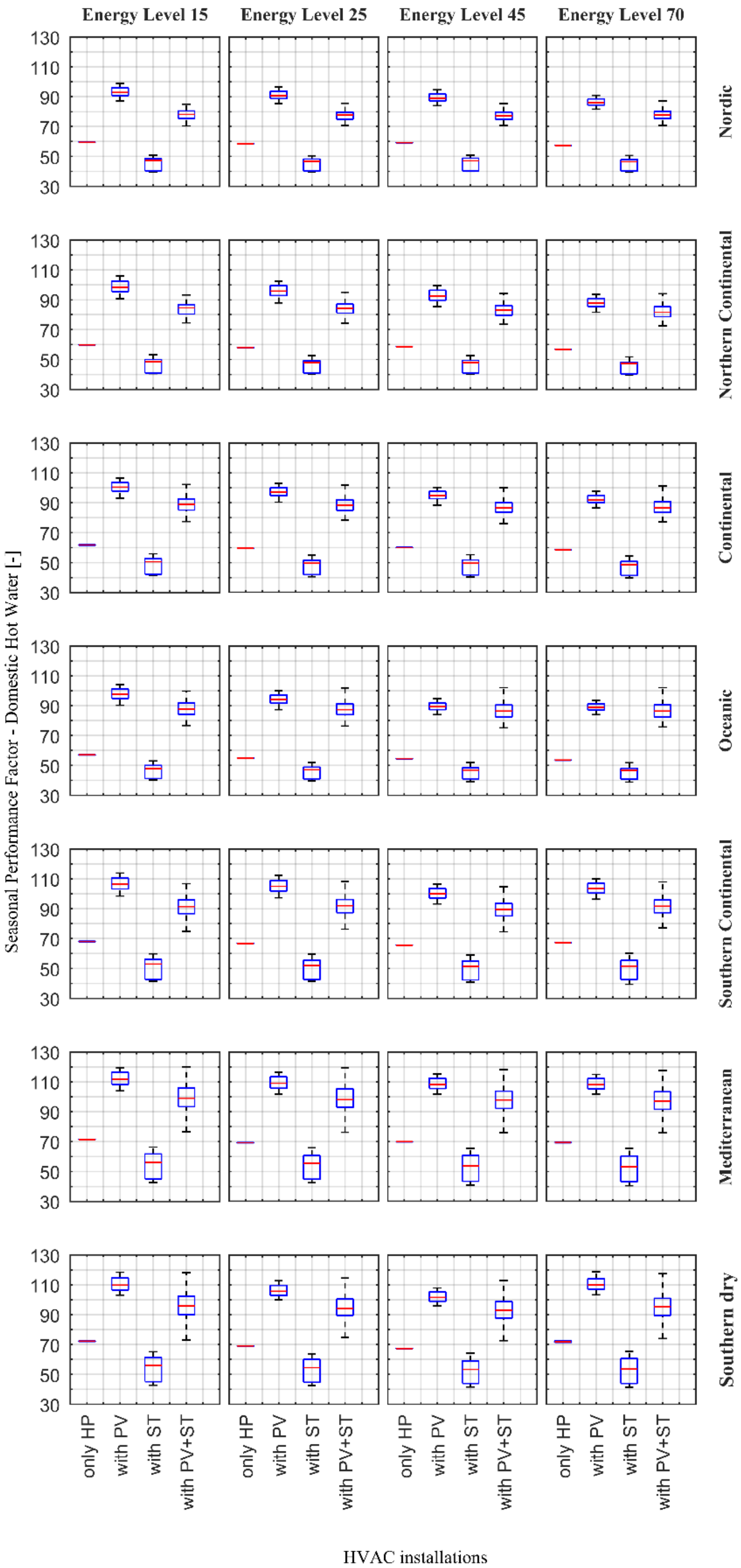

Figure 120 – Seasonal Performance Factor for Domestic Hot Water Production

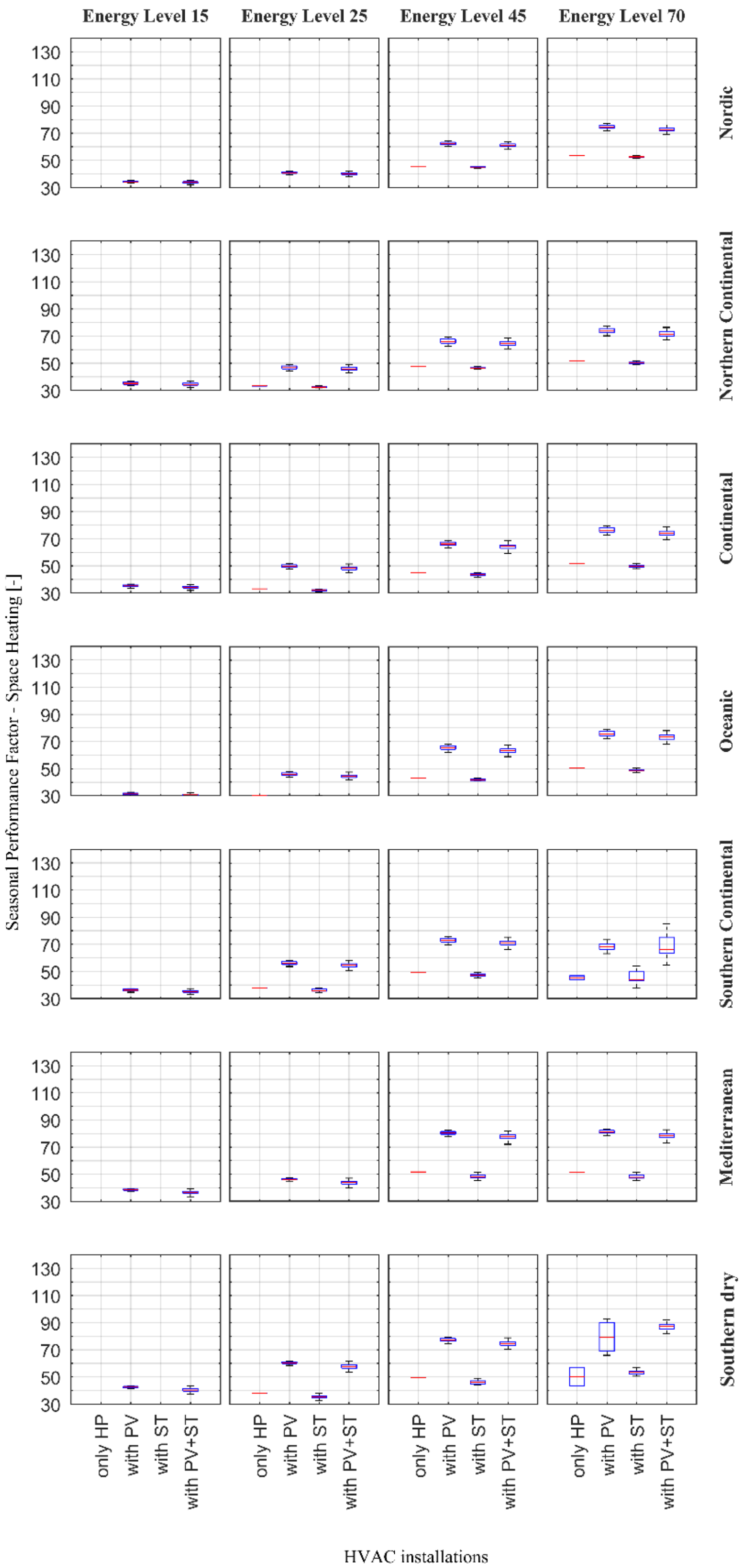

Figure 121 – Seasonal Performance Factor for Space Heating

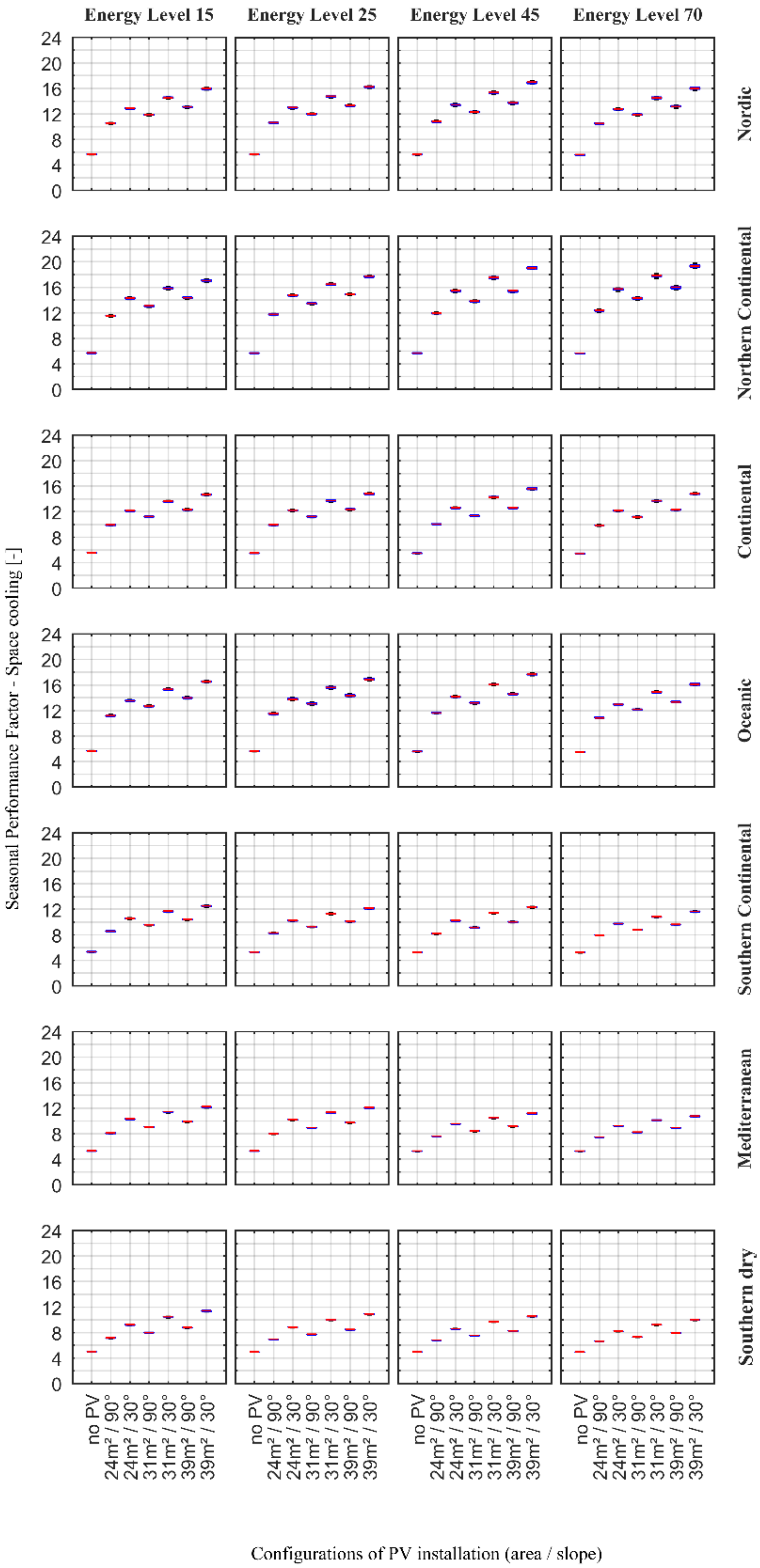

Figure 122 – Seasonal Performance Factor for Space Cooling

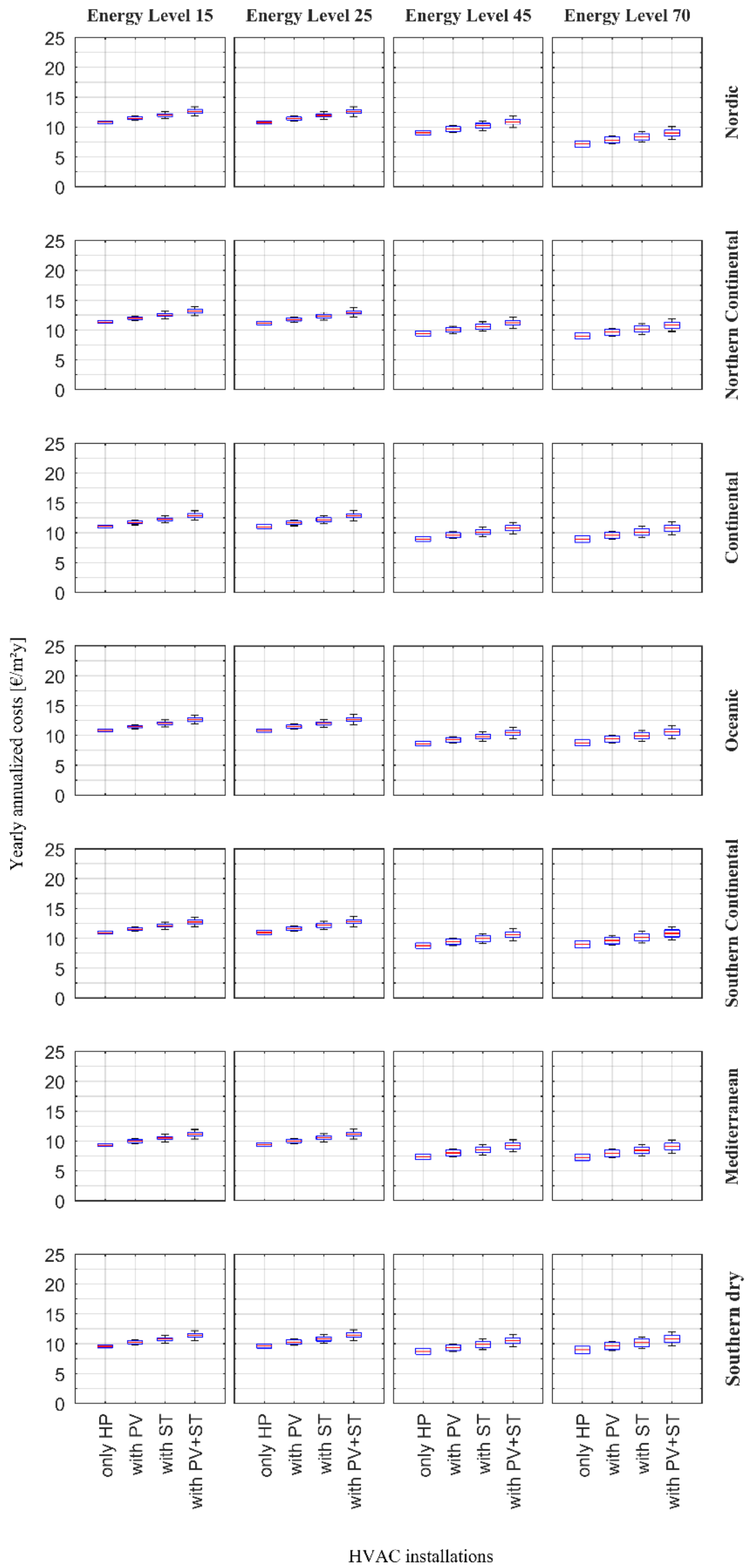

Figure 123 – Yearly annualised costs distribution for variants with solar systems

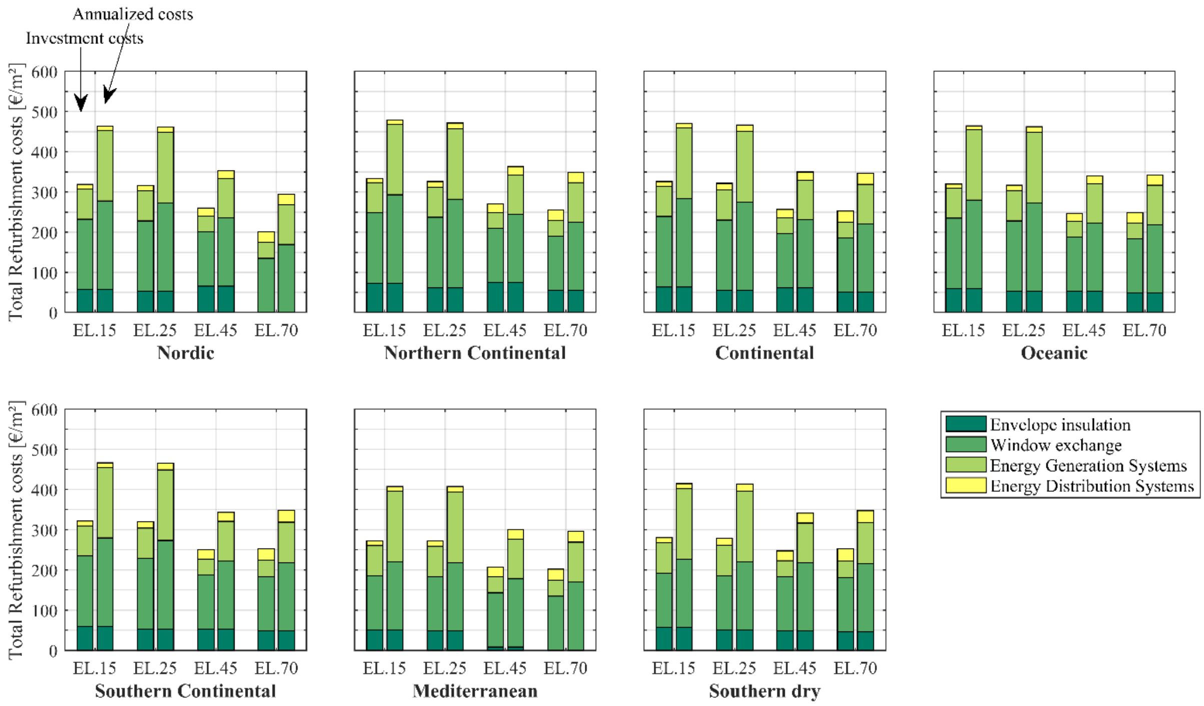

Figure 124 - Investment costs distribution (first year investment and annualized costs) without solar systems (35 °C water distribution temperature)

3.12 Small Multifamily Houses – Pellet Boiler with Radiators

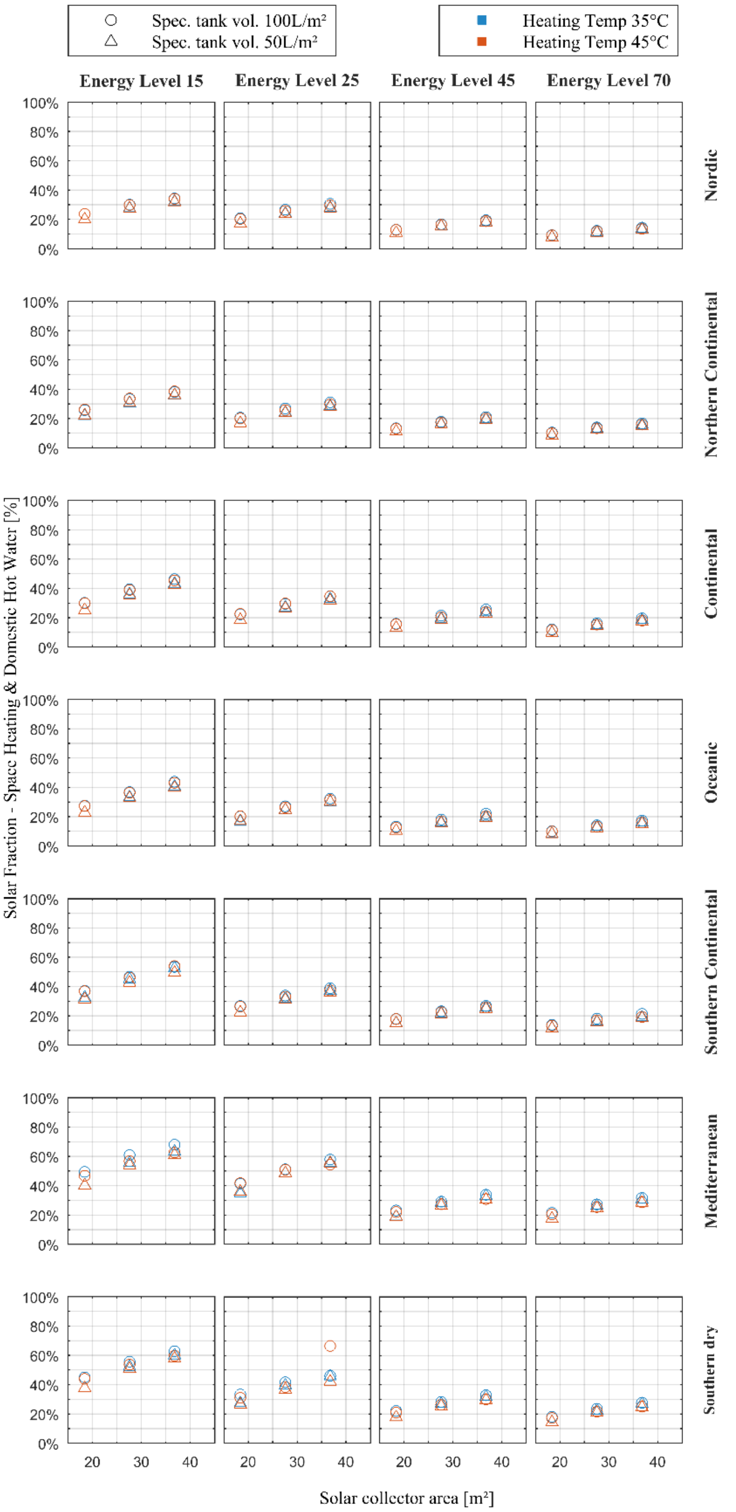

Figure 125 – Solar fraction for Domestic Hot Water and Space Heating with solar collectors in the main façade.

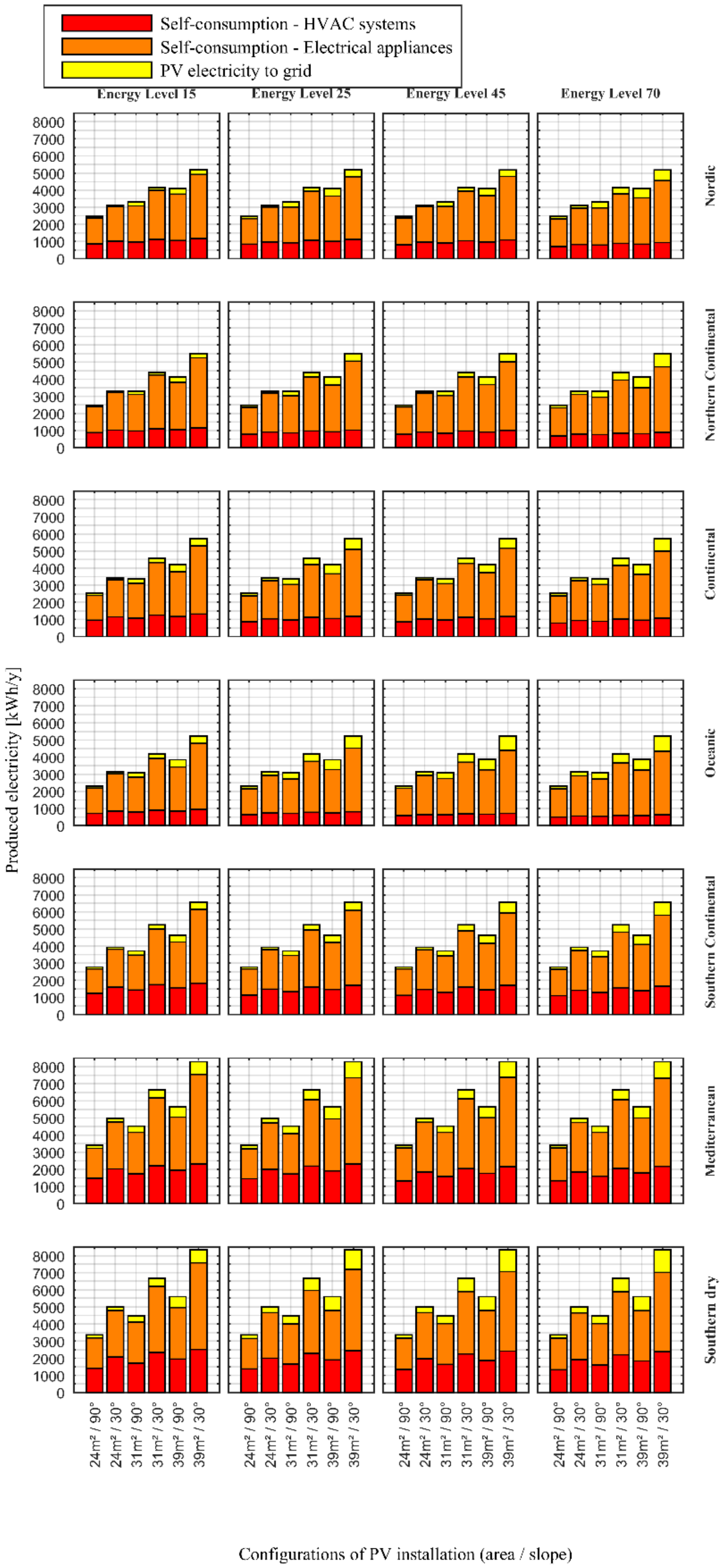

Figure 126 – Photovoltaic electricity production

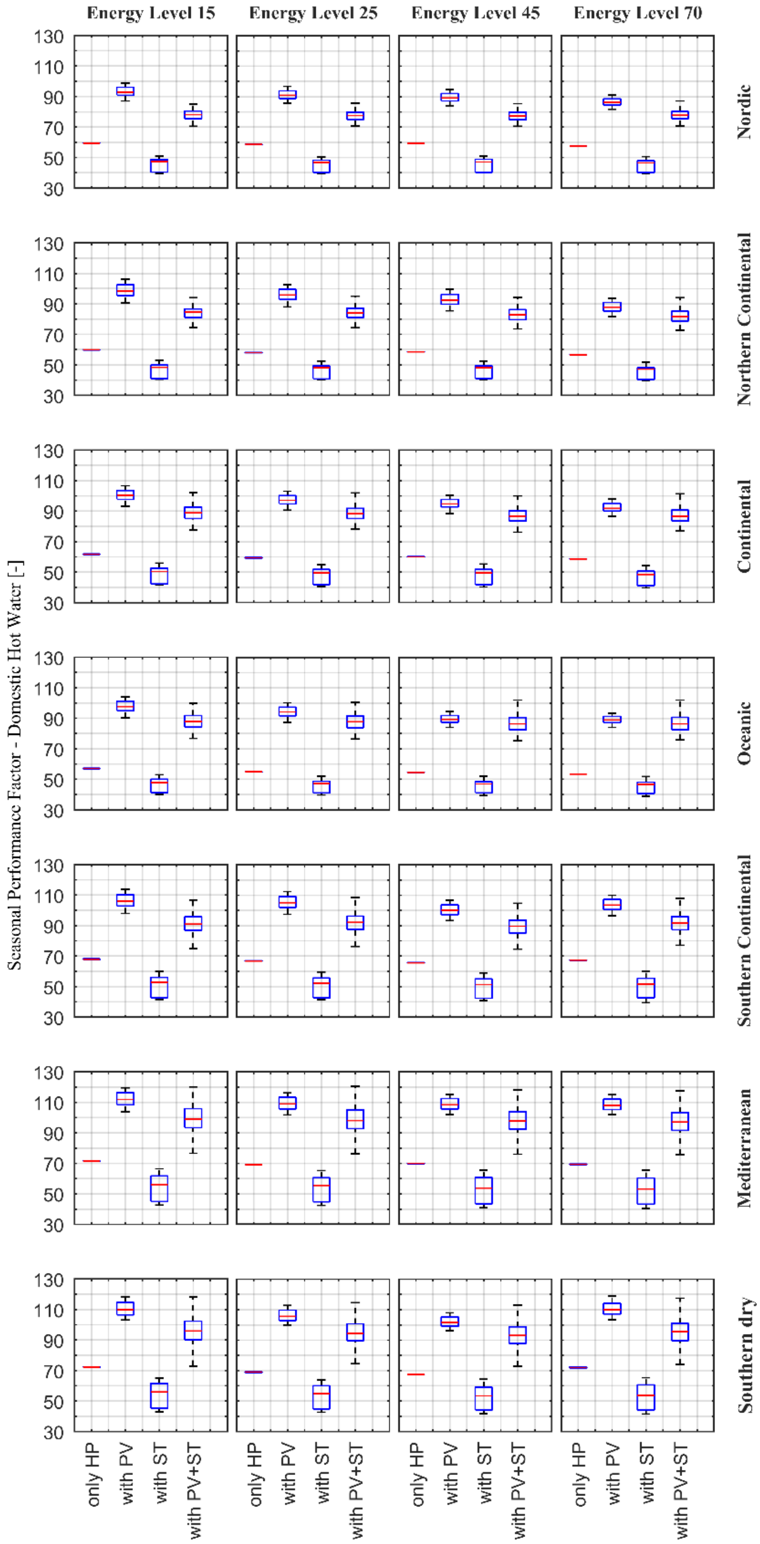

Figure 127 – Seasonal Performance Factor for Domestic Hot Water Production

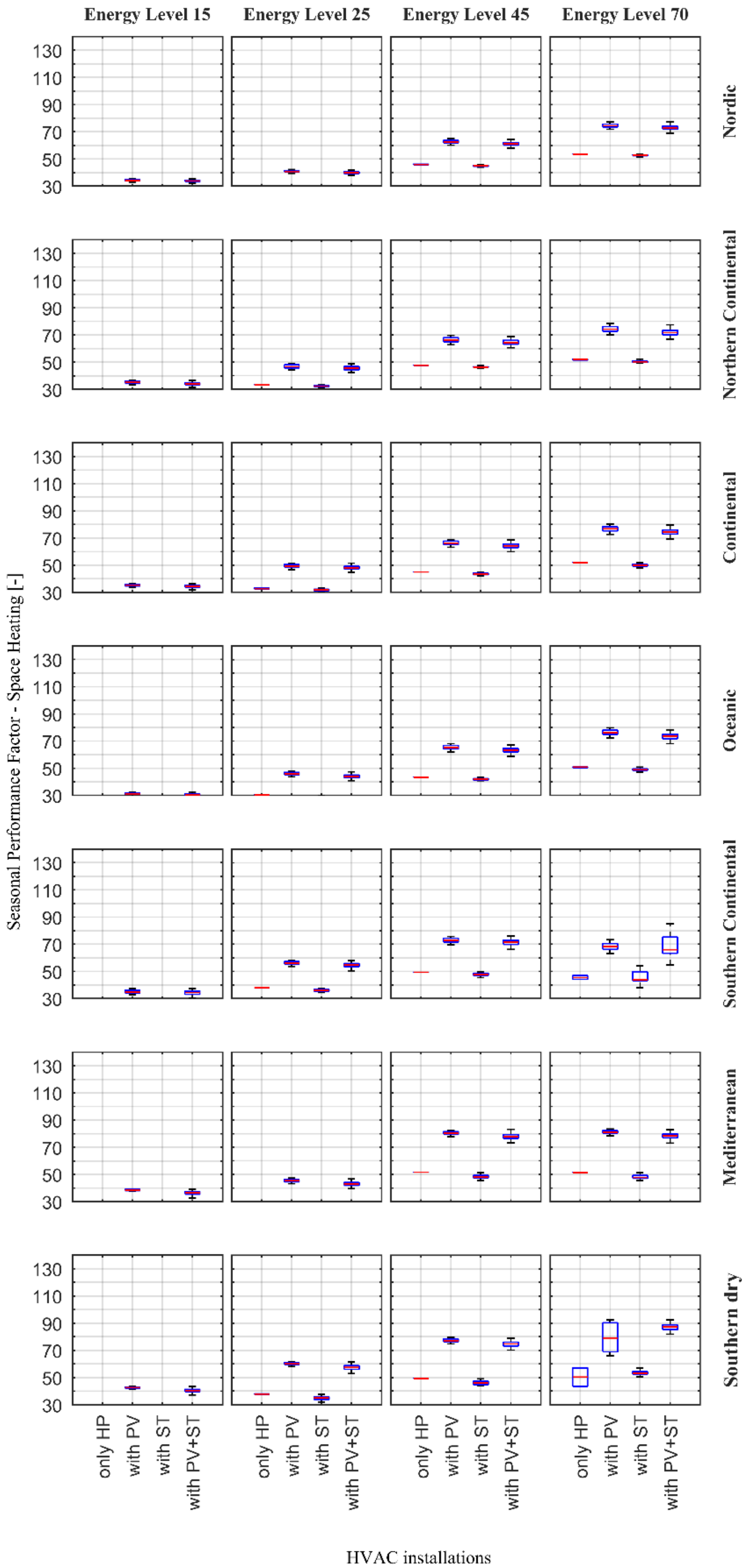

Figure 128 – Seasonal Performance Factor for Space Heating

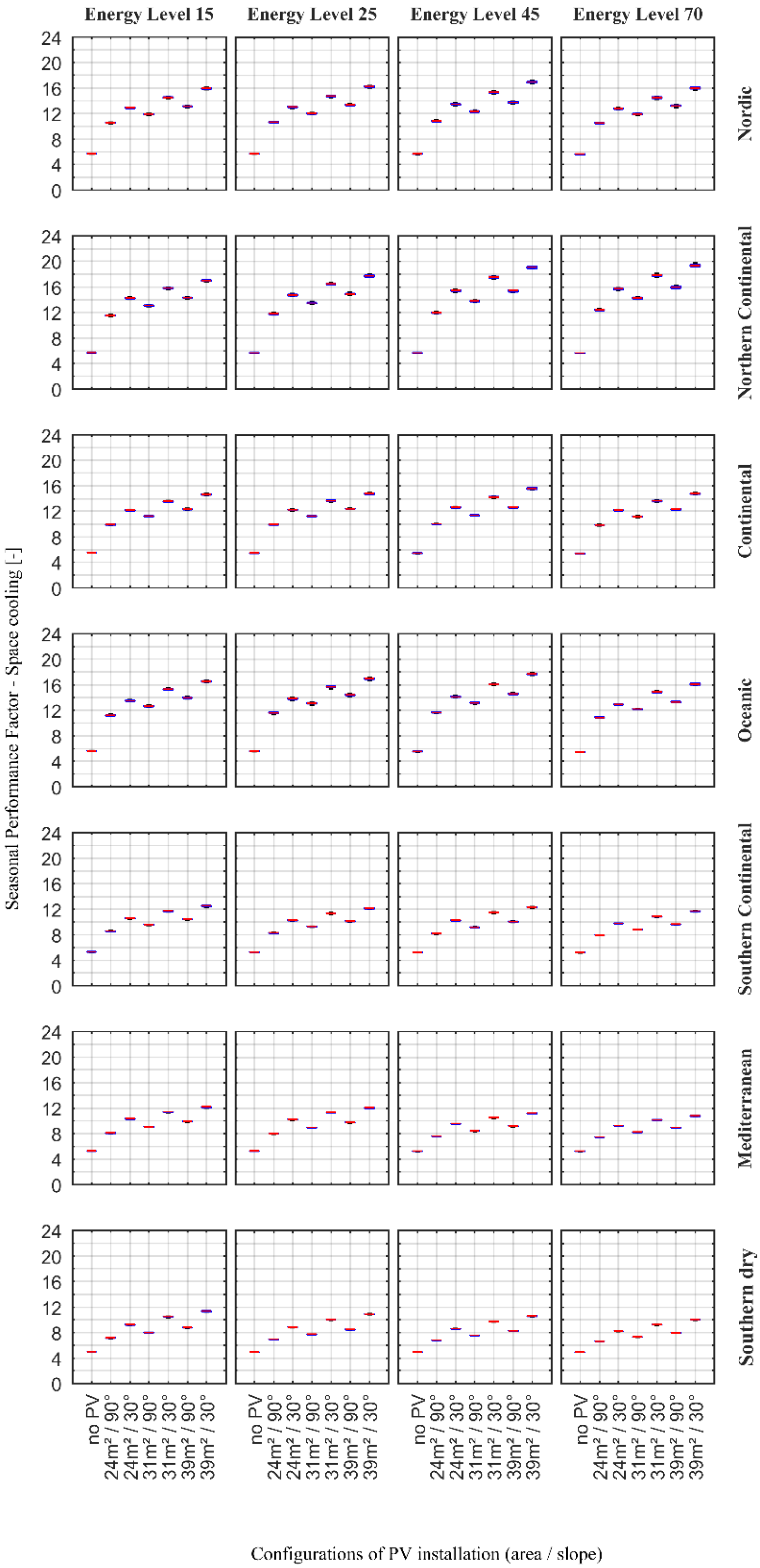

Figure 129 – Seasonal Performance Factor for Space Cooling

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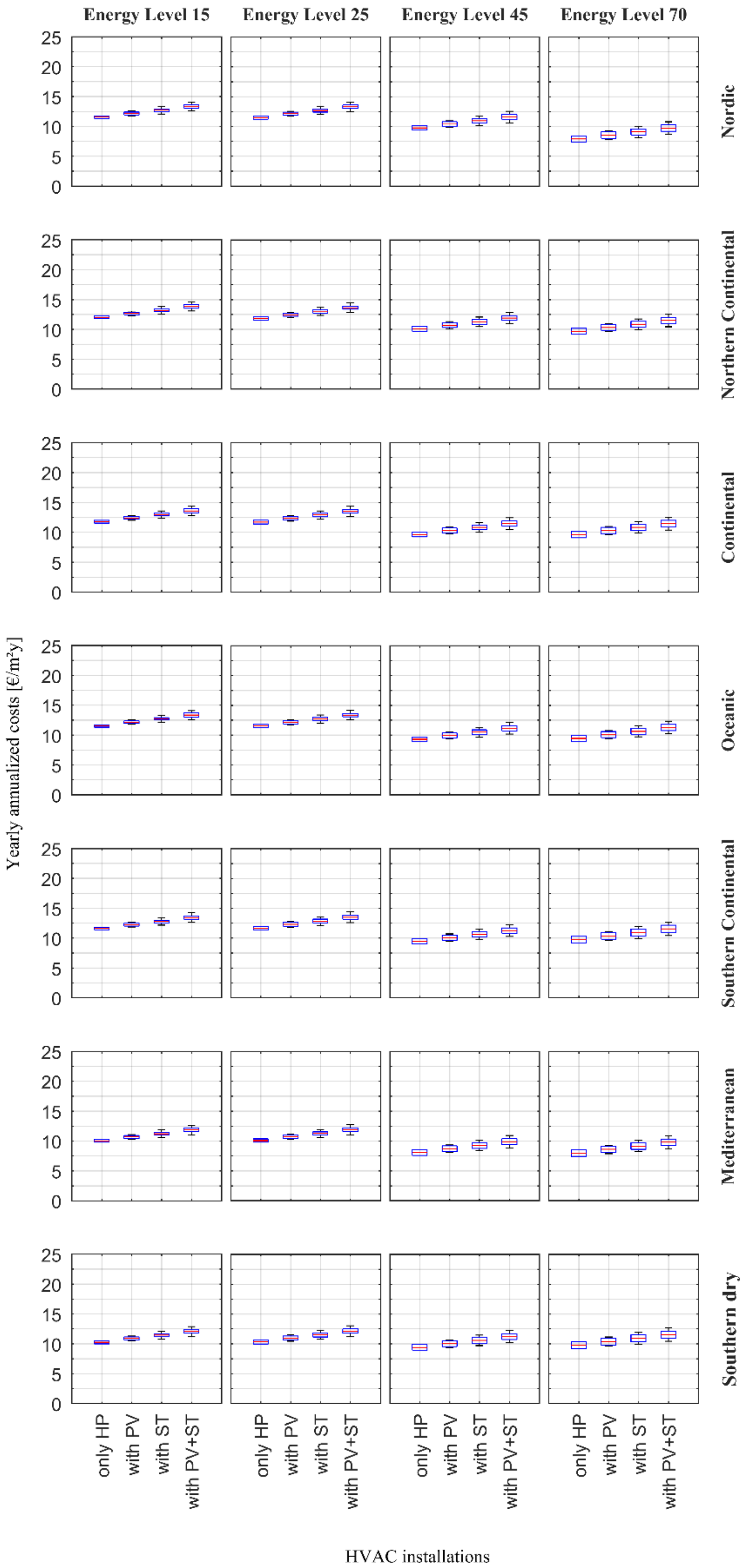

Figure 130 – Yearly annualised costs distribution for variants with solar systems

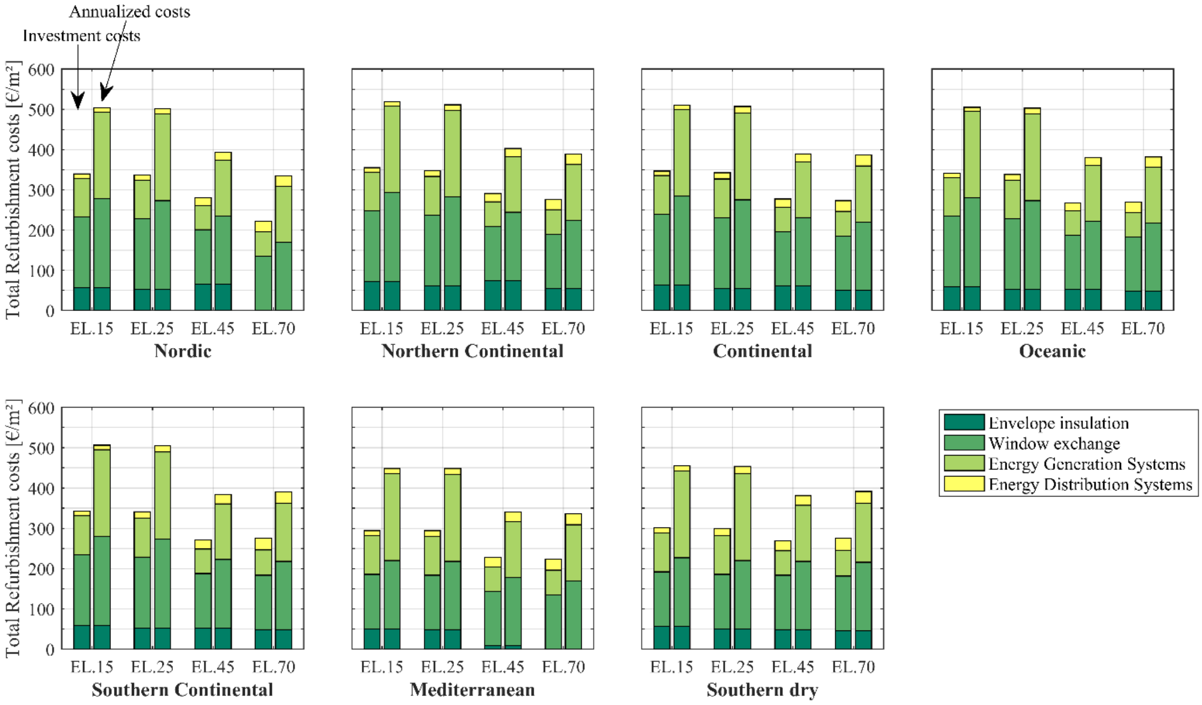

Figure 131 - Investment costs distribution (first year investment and annualized costs) without solar systems (35 °C water distribution temperature)

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