D6.3b - Performance of the Studied Systemic Renovation Packages - Single Family Houses

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

iNSPiRe

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D6.3b - Performance of Studied Systemic Renovation Packages – Single Family Houses

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1 Executive Summary

One of the primary objectives of the iNSPiRe project was to develop a tool that predicts the energy and cost saving impacts of various systemic retrofit interventions. This tool is now available for all those involved in the renovation of older buildings (from consulting offices, moving through construction companies and to decision makers) to use as a means of selecting which retrofit package will deliver the greatest costs savings and most improved energy performance.

The whole set of Renovation Packages in the published database includes results for a range of SFH typologies, from detached to row houses, with different external surface over building volume ratio.

In order to compare the same Envelope Renovation when applied to different SFH typologies and climates, we adopted the detached constructions as the basis to define insulation, windows and mechanical ventilation measures that match the heating demand standards sought (15, 25, 40, 70 kWh/m^{2}y). Since the solutions found are the most conservative, lower heating demands are obtained for semi-detached and row houses.

The solutions elaborated in terms of window features, and walls/roof cross sections and materials, are reported in Deliverable 6.3a for the whole range of buildings and the 7 climates analysed.

In this document we comment the results relative to the reference buildings built 1945-1970, renovated with four generation systems (AWHP, GWHP, gas boiler and biomass boiler) and three distribution systems (radiant ceilings, radiators and fan coils). In order to limit the number of solutions discussed, here we report results only for the detached SFHs. The full range of solutions is published on the iNSPiRe website.

The generation plants are hybrid solutions designed to combine heat pumps or boilers with solar thermal and/or PV technologies. These combinations integrate multiple renewable energy sources, thus allowing to reach in the best cases the 50 kWh/m^{2}y primary energy consumption limit that is the objective of the retrofit packages devised.

1.1 Main Results

The combinations are described in terms of thermal comfort produced in the building, energy use and economics. Detailed results and comparisons among solutions are reported in the single sections of chapter 2. Here we report only the main highlights of the analysis.

1.1.1 Thermal comfort

The envelope renovation packages result in space heating demand close to the ideal objectives of 15, 25, 40, 70 kWh/m^{2}y. 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 as well as their sizing.

Whereas the heating demand can be significantly decreased after renovation the cooling demand, despite the attempts to limit solar gains with shading devices remains in the same order of magnitude after renovation for all climates. For most climates there is a small increase in cooling demand with better insulation standard for the envelope renovation. The insulation and better windows limit the transmission losses also during the cooling seasons, however this effect is of second order in particular if compared to the effect of sun shading.

In northern countries however, the increase of cooling load does not necessarily mean that a cooling system has to be setup, since night ventilation can be effectively used to provide the needed comfort. Night ventilation is not accounted for in this study, allowing a reliable comparison of the results.

Fan-coils and radiators with split units can provide good thermal comfort in both summer and winter in all climates apart for a very few operating hours in the extreme climates. Radiant panels also provide good thermal comfort in most climates, but are less suited to humid climates with a significant cooling demand as there are hours when humidity is outside the comfort zone during the summer, although indoor temperature is properly established. If full comfort is sought dehumidification units must be necessarily adopted.

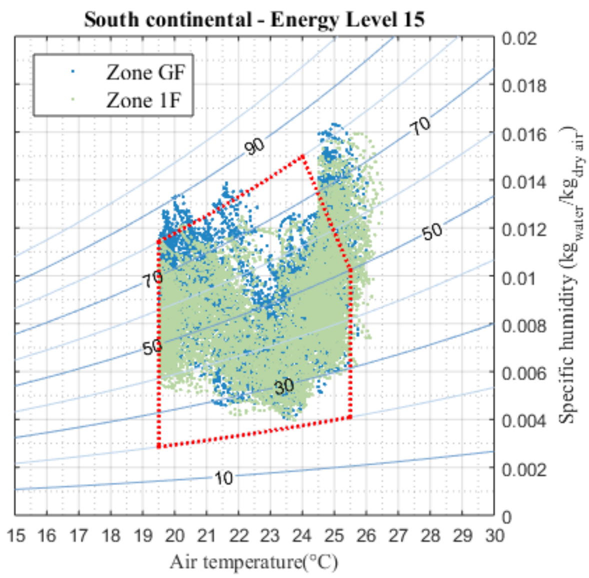

Figure 1 - Psychometric charts of the case southern continental, Energy Level 15, radiant ceilings, space heating water temperature 35°C

1.1.2 Energy use

The energy demand is influenced by the choice of the energy level, independently of the climate and the distribution and generation technology.

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

With respect to fan coils and radiators, the convective to radiative contribution ratio is around 70% / 30%. On the contrary, the radiative contribution of the radiant ceilings (around 70%) impacts mainly on the external walls' temperature.

Where renovations with limited amounts of insulation are performed in mild climates, the higher wall temperatures obtained with radiant ceilings result in increased transmission losses and final energy uses higher than expected.

Radiant ceilings (or floors) have therefore to be handled carefully in case buildings with "average" space heating standards (i.e. 70 kWh/m2y) are tackled. If transmission losses are limited by means of effective envelope insulation and windows (standards 45 kWh/m^2y and below), the quantity of energy needed to cover space heating loads is fairly independent of the way heat is delivered to indoor air.

Again, 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.

Operative temperatures with radiant ceilings are equal to convective temperatures, thus the perceived temperature is actually higher compared to that with fan coils and radiators, for a specific convective temperature set point. In the latter cases, operative temperatures can be as much as 1 – 1.5°C lower than the convective temperature set.

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.

During summer, fan coils and split units cover both sensible and latent loads, 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.

The largest reduction of the energy used is due to the envelope renovation.

In terms of energy effectiveness, gas boilers can hardly reach the 50 kWh/m^2y primary energy consumption for nearly all climates and energy levels, even with solar (thermal and PV) included in the renovation package.

Better results are obtained by using heat pumps. The primary energy reduction compared to the gas boiler case is around 25 kWh/m^2y if we take the best Energy Levels (15 kWh/m2y space heating demand) into consideration. The reduction is even more significant (around 55 kWh/m^2y) when the 70 kWh/m2y space heating demand cases are considered.

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 40 - 50 kWh/m^2y can be obtained also without exploiting solar energy.

The analysis shows that, apart from the system with pellet boiler, solar technologies must be used in most cases if the 50 kWh/m2y primary energy is targeted.

Due to the very low heating energy used in all cases simulated, a non-negligible solar contribution to space heating is also obtained with the smallest collectors' field (2 solar collectors, 100 l/m^2). In this case, the solar fraction for space heating and DHW preparation can vary from 15 - 25% in the Mediterranean countries (for heating demand standards from 70 to 15 kWh/m^2y respectively) to 12 - 40% in the Northern ones. Interestingly, better results can be obtained in the northern countries thanks to the longer winter season. The effect of the collectors' inclination on the SF for space heating is insignificant.

With respect to the same collector area, a larger influence of both inclination and storage tank volume is found for the SF for DHW. By inclining solar collectors from 30° to 90°, the solar fraction for DHW decreases about 10% in the Nordic climates and 15% in the southern.

For large collectors' areas, the overall duration of the stagnation condition is strongly influenced by the inclination. While more than 2000 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.

This indicates that façades are the recommended surfaces from the technical point of view when large solar thermal collector fields are envisaged.

For PV technology, the study shows that installing 1 kWp (7.8 m2 PV field area) allows to self-consume almost all the PV electricity when heat pump systems are exploited, based on net hourly energy balance. Around 90% of the renewable electricity is consumed by HVAC system and domestic appliances.

In all the other cases, a significant portion of the production needs to be fed into the grid. This is because we do not consider batteries in the proposed solutions, thus the PV electricity can only be stored as warm water in the thermal storage tank, and used to cover appliances' electric consumption.

Either batteries or small PV surfaces should be considered in case national regulations discourage feeding renewable electricity into the grid.

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.

The study shows that the two solar technologies can be operated together and produce a synergic effect, by addressing all thermal loads.

1.1.1 Investment and running costs

The investment costs for the renovation of the envelope are larger than those for the energy generation and distribution systems in all cases, due to the high S/V ratio encountered in detached SFHs.

With respect to generation systems, 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: the additional costs of the heat pump are covered by the additional need of split units in the gas boiler case (when required as in the warmer climates).

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 between

750 and 1700 €/y versus 500 to 1000 €/y in case an air-to-water heat pump with radiant ceiling plant is used.

The overall annualised costs of the air-to-water heat pump systems are significantly lower than those for gas boilers: 33-43 €/m2y versus 40-50€/m2y (over an investment horizon of 30 years).

The incidence of solar technologies results in less than a 3 €/m2y increase of the total annualised investment costs, and even combinations of the two add around 5 €/m2y.

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 it is not in this study).

The annualized costs for the pellet boiler systems without solar of 40 to 50 €/m2y are significantly higher than for the heat pump and in line with the gas boiler solution, but solar technologies are not necessary to reach low primary energy targets.

The difference in annualized costs for different energy renovation levels is small, as it is when different climates are accounted for. The trends encountered are affected by the uncertainties in the specific costs assumed, showing that all the solutions reported are equally recommendable looking at this performance figure.

2 Results: Single Family Houses (SFH) from 1945-1970

The whole set of Renovation Packages in the published database includes results for a range of SFH typologies, from detached to row houses, with different external surface over building volume ratio (see Table 1). In order to reduce the number of cases tackled, in this document we report on the results relative to the reference buildings built 1945-1970, renovated with four generation systems (AWHP, GWHP, gas boiler and biomass boiler) and three distribution systems (radiant ceilings, radiators and fan coils).

Table 1 Surface over Volume ratios for the range of SFH considered

S/V RATIO	
SFH Detached	*0.87*
SFH Semi-detached	*0.73*
SFH Row houses	*0.58*

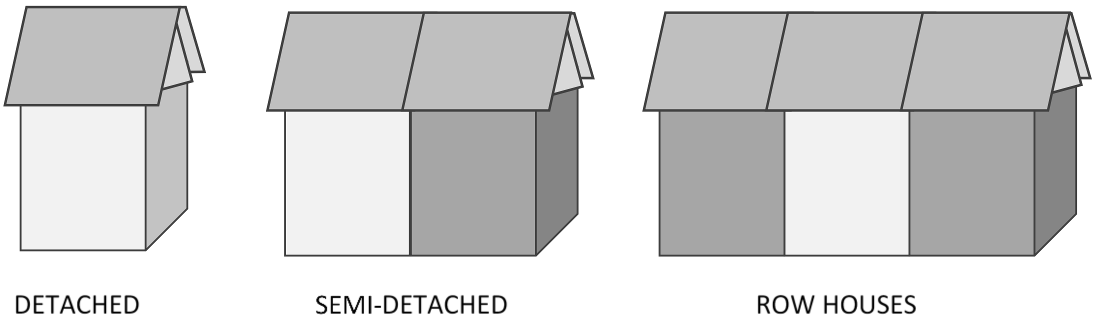

Figure 2 – representation of the range of SFH types

In order to compare the same Envelope Renovation when applied to different SFH typologies and climates, we adopted the detached constructions as the basis to define insulation, windows and mechanical ventilation measures that match the heating demand standards sought (15, 25, 40, 70 kWh/m^{2}y). The energy used vary from these nominal demands due to renovation packages constraints (4 cm minimum insulation, two windows typologies, mechanical ventilation present or not). In the cold climates the level of 15 kWh/m^{2}y cannot be reached due to the limitations imposed on the maximum wall and roof insulation installed. This has to be taken into account when analysing the diagrams.

The solutions elaborated in terms of window features, and walls/roof cross sections and materials, are reported in Deliverable 6.3a for the whole range of buildings and the 7 climates analysed. As a general set of rules for the definition of the renovation measures, we followed this strategy:

1. The external walls are setup with maximum 40 cm of EPS insulation
2. The roof is setup with external wall insulation thickness + 10 cm
3. Perimeter and cellar are setup with maximum 10 cm of EPS insulation

4. Infiltration rates are limited to the maximum allowed for the certification of Passiv Haus Standard (15 kWh/m^{2}y) or EnerPhit Standard 25 kWh/m^{2}y according to the Passiv Haus Institut (www.passiv.de).
5. Window quality is commensurate to the maximum thermal losses suggested by the Passiv Haus Institut (www.passiv.de) for the specific heating demand standards of 15 and 25 kWh/m^{2}y. The features of the windows for 45 and 70 kWh/m^{2}y energy levels are extrapolated from the latter.

The generation plants are hybrid solutions designed to combine heat pumps or boilers with solar thermal and/or PV technologies. These combinations integrate multiple renewable energy sources, thus allowing to reach in the best cases the 50 kWh/m^{2}y primary energy consumption limit that is the objective of the retrofit packages devised. PV electricity is calculated with hourly-timestep weather data, which overestimates self-consumption up to 5 - 10% compared to calculating on a minute basis.

Good shading practices by the inhabitants are assumed in all cases after renovation, which leads to lower cooling demands while the heating demand is not significantly affected.

The assumption of no night ventilation increases energy use and costs for cooling compared to the case with night cooling. 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 mainly with respect to boiler based systems. In addition the self-consumption of PV would be lower, due to the lower summer load. However, it is not clear to which extent night cooling can be performed in the different climates and what the impact on the comfort is.

Indoor air control is made with convective temperature. Thermostats most likely sense not more than about 20% radiant heat transfer and thus the temperature sensor will be sensitive to the temperature of room air (i.e. the convective temperature), which is why this temperature was used. However, in real operation the user sets the temperature of the thermostat more based on operative temperature (the perceived one), resulting in lower convective set temperatures for radiant panels than fan-coils and radiators, therefore in lower energy bills. In this study, this assumption leads to overestimate energy use for radiative ceiling compared to the other heat/cold distribution systems. The difference reduces with better envelope quality.

The split units have ideal dehumidification that limits the absolute humidity in the building. This provides better thermal comfort than the fan coils, which provide limited dehumidification, and radiant panels (that provide no dehumidification).

2.1 Air Source Heat Pump with Radiant Ceilings

For the results presented here, 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. The supply temperature for cooling has been fixed to 15°C and increases to 18 °C in case of high relative humidity to avoid condensing water on the ceilings surface.

2.1.1 Used Energy

The Envelope Renovation measures adopted produce an effect on the heating demand as well on the cooling demand of the building. Moreover, as already stated, the Used Energy is significantly influenced by the H&C distribution system.

Figure 3 shows Used Energy for both heating and cooling for the range of climates, detached SFHs and air to water heat pump systems delivering thermal energy through radiant ceilings.

Noticeable is that the solutions aiming to reach the 15 kWh/m^{2}y level vary in a large range in relative terms; this is due to the fact that for such low energy uses, small changes in the insulation thicknesses produce a large relative variation of heating demand.

Looking at the cooling demand, after renovation it is observed a certain demand reduction. In particular, in the warmer climates the cooling demand reduction amounts to 25-40% thanks to a more conscious user's behaviour of the shading devices. The effect of a higher insulation and higher quality windows is more evident in those cases with low cooling demand. In these cases, in fact, the cooling demand after renovation is slightly higher that, in absolute terms, amounts to 1 to 6 kWh/m^{2}y. In any case, this result shows how this load has to be considered carefully also in the northern climates, since its size can increase to DHW and heating demands' levels.

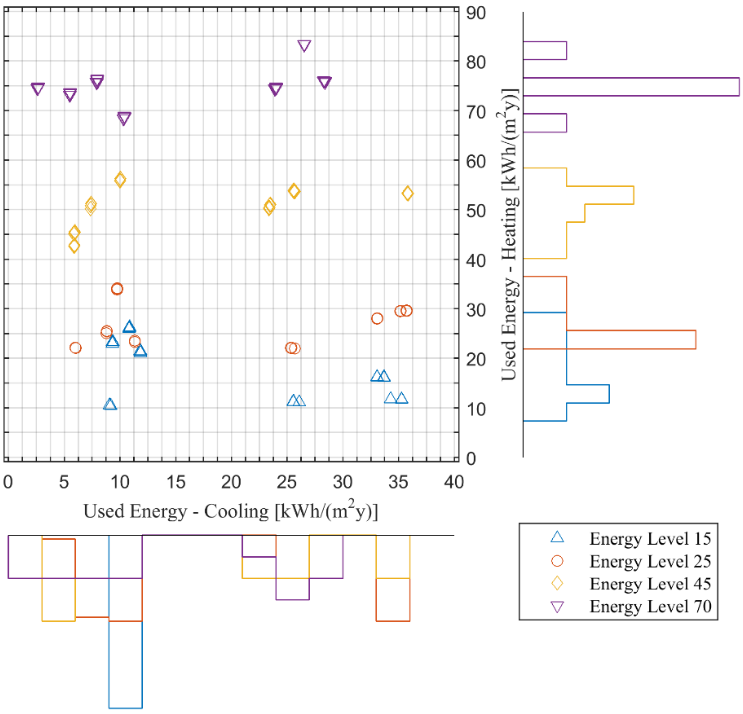

Figure 3 – Used Energy for heating and cooling of the different energy standards

For the sake of clarity, in Table 2 the energy use for space heating, space cooling, DHW production and ventilation is reported. It can be noticed that we considered the DHW load as a constant in all the climates (i.e. in cold climates with colder fresh water temperatures, energy use for DHW preparation is underestimated). This simplification does not largely affect the final results, while it allows comparing primary energy consumptions for different Energy Levels in different climates.

Table 2 Used energy for H&C, DHW and ventilation

CLIMATE	ENERGY LEVEL	SPACE HEATING	SPACE COOLING	DHW PRODUCTION	VENTILATION
	[kWh/m²y]	*[kWh/m²y]*	*[kWh/m²y]*	*[kWh/m²y]*	*[kWh/m²y]*
Northern Continental	15	**23.3**	**9.4**	21.7	5.0
	25	**25.5**	**8.8**	21.7	5.0
	45	**45.5**	**6.0**	21.7	5.0
	70	**73.7**	**5.5**	21.7	0.0
Oceanic	15	**10.5**	**9.1**	21.7	4.2
	25	**22.2**	**6.0**	21.8	4.2
	45	**42.9**	**5.9**	21.8	0.0
	70	**74.8**	**2.7**	21.8	0.0
Southern Continental	15	**11.2**	**25.6**	21.8	4.2
	25	**22.1**	**25.4**	21.8	4.2
	45	**51.1**	**23.5**	21.8	0.0
	70	**74.8**	**24.0**	21.8	0.0
Southern dry	15	**11.8**	**34.3**	21.8	4.2
	25	**29.6**	**35.2**	21.8	4.2
	45	**53.3**	**35.9**	21.8	0.0
	70	**85.6**	**26.6**	21.8	0.0
Mediterranean	15	**16.2**	**33.1**	21.8	4.2
	25	**28.1**	**33.1**	21.8	4.2
	45	**53.7**	**25.7**	21.8	0.0
	70	**75.9**	**28.4**	21.8	0.0
Nordic	15	**21.5**	**11.8**	21.7	5.2
	25	**23.6**	**11.3**	21.7	5.2
	45	**51.3**	**7.4**	21.7	5.2
	70	**76.4**	**8.0**	21.7	0.0
Continental	15	**26.3**	**10.9**	21.7	4.5
	25	**34.1**	**9.8**	21.8	4.5
	45	**56.3**	**10.1**	21.7	0.0
	70	**68.9**	**10.4**	21.7	0.0

2.1.2 Thermal comfort

Radiant ceiling panels maintain thermal comfort in winter as in summer, mostly through radiant exchanges with the room occupants (directly or indirectly via the surrounding walls).

As stated in Deliverable 6.3a, in this study, they have been sized based on the heating loads, as done in praxis in European residential buildings.

Looking at the heating energy use, simulations are carried out accounting for both 30°C and 35°C as supply temperature to the radiative panels. The penalty function represented in Figure 4 shows that 30°C are sufficient in almost all cases, and even for the 70 kWh/m^{2}y standard (again in the Southern dry climate) it is less than 2%. Even in this case, the temperature never drops below 18.5°C and the winter average is 19.5°C as in all the other cases (indoor set temperature 19.5 - 20.0 °C).

Higher discomfort can be noticed with respect to the summertime: the penalty function with respect to cooling exceed 10 - 20% in some cases (heating supply temperature equal to 35 °C). In the renovations with the highest energy savings in winter, significant cooling load peaks can be encountered that cannot be effectively covered through the radiative system installed.

This indicates that the radiative panels installed for a supply heating temperature of 35 °C are indeed too few for covering the cooling load.

Looking to the instantaneous time distribution of temperatures, during some hours in summer the temperature can top 26.5 °C, however the average indoor air temperature varies between 24.5 and 25.3°C in all cases, showing that this is a suitable distribution for both heating and cooling.

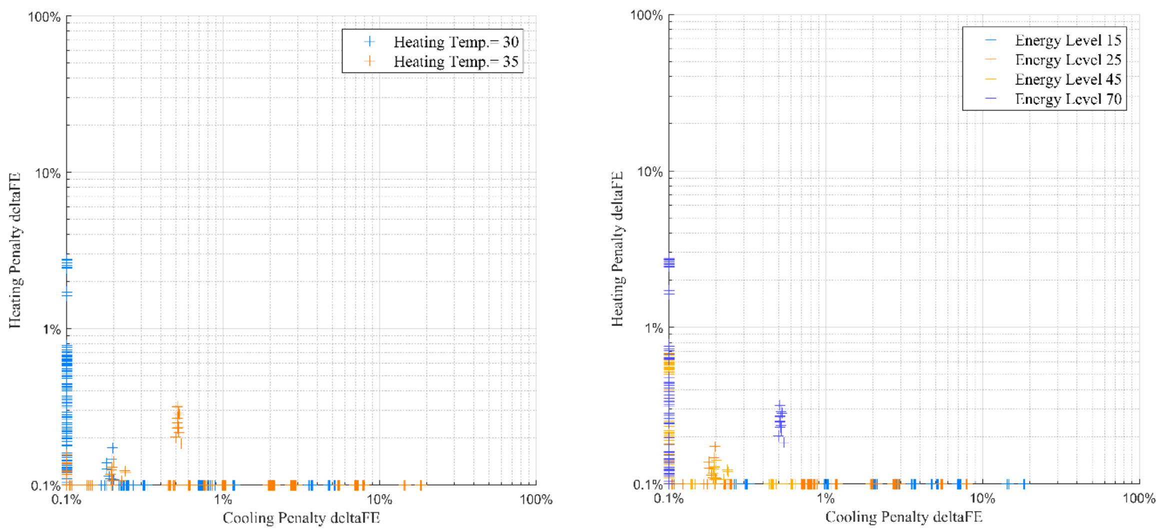

Figure 4 – Cooling and Heating penalty functions for different distribution water supply temperatures (a, left) and energy levels (b, right). The penalty is a measure of how much the room temperature is too high/cold over the year.

Figure 5 shows the psychometric charts of the cases with the highest heating and cooling penalty function: Southern dry, Energy Level 70, heating water temperature 30°C and Southern continental, Energy Level 15 respectively with 35 °C supply temperature.

The red dotted lines delimit a recommended thermal comfort zone[1]. Each point represents an average value over a period of 1 hour; the thermal comfort in ground floor (Zone GF) and the first floor (Zone 1F) of the SFH are distinguished.

In both extreme cases, temperature and humidity generally remain within the comfort zone or in the close vicinity. In the most unfavourable case for winter comfort, the room air temperature may decrease down to 19°C for few hours, providing however an acceptable comfort. In the case most unfavourable in summer, a certain amount of time is spent at both high temperature (above 26°C) and humidity (above 60%). In this case, dehumidification is needed in case a full comfort control is sought.

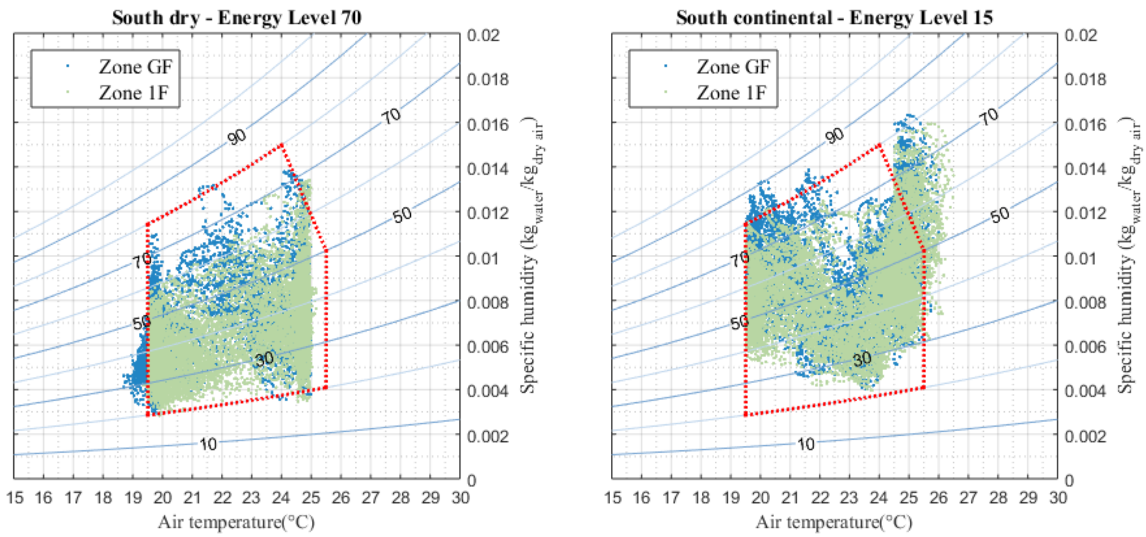

Figure 5 – Psychometric charts of {Southern dry, Energy Level 70, heating water temperature 30°C} and {Southern continental, Energy Level 15, heating water temperature 35°C}

2.1.3 Final Energy and SPF

Figure 6 shows the Final Energy consumption of the H&C system simulated following the energy uses reported (distribution water temperature 30°C). The base cases without solar energy utilisation are reported first.

The final energy use is mainly influenced by the choice of the energy level, independent of the climate and the technology.

In all cases (apart for southern dry climate, 70 kWh/m^{2}y), the FE consumption is lower than 40 kWh/m^{2}y. The consumption related to the DHW becomes significantly high after renovation (in relative terms, in the order of 10 – 12 kWh/m^{2}y), while FE use for cooling is significant only in the southern cases. In this climates, in fact, for the most energy efficient Envelope

[1] Norbert Lechner (2008). Heating, Cooling, Lighting: Sustainable Design Methods for Architects. Chapter. 4: Thermal Comfort.

Renovation solutions (15-25 kWh/m^{2}y) the FE used for cooling has higher impact than the one employed for heating.

When moving from a heating temperature supply of 30°C to 35°C, the FE consumption augments by around 10%, with same Used Energy.

The electricity consumption for the mechanical ventilation is comparable with the consumption for heating the building in most cases. Particularly large consumption is noted in the northernmost countries, due to the use of energy for de-icing the heat exchangers (below -3°C, in this study).

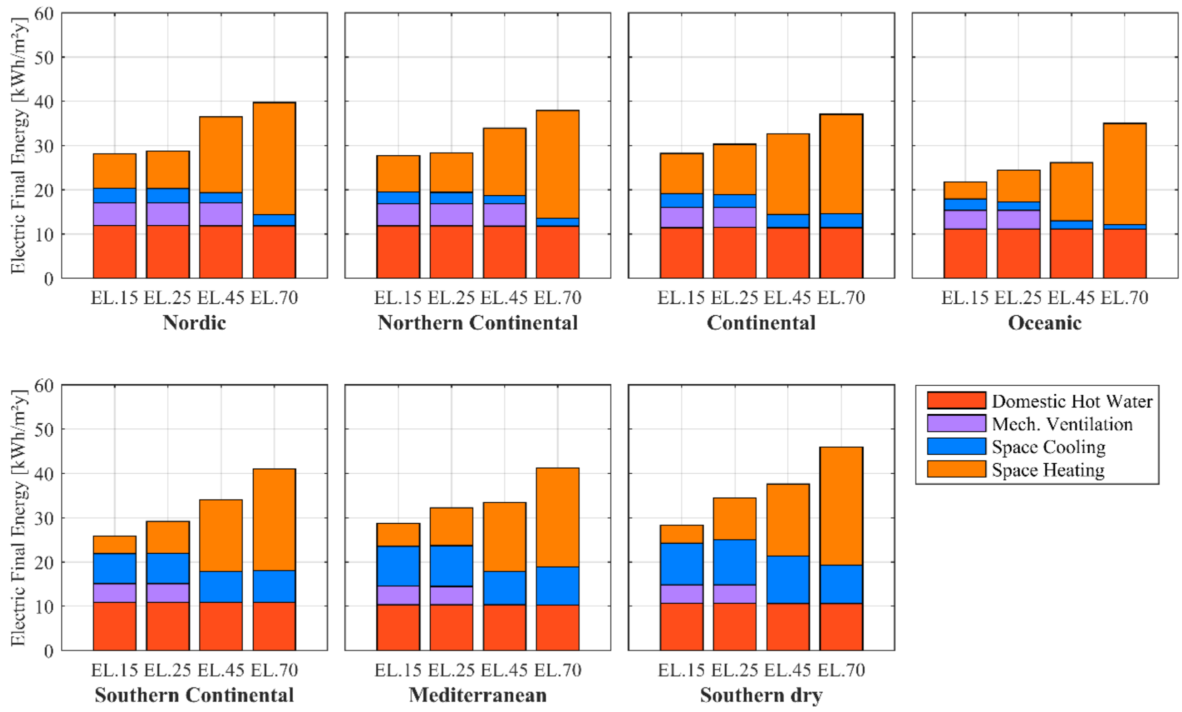

Figure 6 – Final energy distribution without solar systems and a heating water temperature level of 30°C.

The SPF figures (see Figure 56 to Figure 58) vary between 2.8 and 3.8 with respect to the heating loads and between 3 and 3.8 looking at the cooling loads.

Relatively low, in all cases, are the SPFs related to the DHW preparation that ranges between 1.8 and 2. The low SPF for DHW has a relatively large impact on the overall SPF for the cases where heating and DHW demands are comparable.

Relating to this, the overall SPF values accounting for heating, cooling, DHW loads and ventilation vary in a range of 2 to 3.2, the lower values being related to the highest envelope efficiency standards. The FE consumption for mechanical ventilation is accounted for in this calculation.

Having in mind a CED_{NRE} of around 2.9 (see chapter 2, electricity), none of these solutions is sufficient to achieve a Primary Energy consumption of the whole building below 50 kWh/m^{2}y. In case this goal is pursued, the use of additional renewable energy is necessary.

2.1.4 Solar thermal energy utilisation

Solar thermal collectors are used both for space heating or/and for DHW preparation in the Energy Generation Packages we recommend.

The analysis of the data (see Figure 53 to Figure 54) shows that due to the very low heating energy used in all cases simulated, a non-negligible solar contribution to space heating is also obtained with the smallest collectors' field (2 solar collectors, 100 l/m^2). In this case, the SF for space heating can vary from 15-25% in the Mediterranean countries (for heating demand standards from 70 to 15 kWh/m^{2}y respectively) to 12-40% in the Northern ones. Interestingly, better results can be obtained in the northern countries thanks to the longer winter season. The effect of the collectors' inclination on the SF for space heating is insignificant.

With respect to the same collector area, a larger influence of both inclination and storage tank volume is found for the SF for DHW. By inclining solar collectors from 30° to 90°, the SF for DHW decreases about 10 percentage points in the Nordic climates and 15% in the southern. A decrease in SF for DHW from 1 up to 20 percentage points is obtained by increasing the storage volume from 50 to 100 l/m^2, due to the storage losses. Higher difference in the SF for DHW is verified for the buildings with lower energy levels up to be almost zero in the ones with high energy level standards.

When larger collectors' areas are used these effects are reversed: let's consider the 6 collectors' case (13.8 m^2). The SF for DHW preparation increases to 70-90% in the Mediterranean climate and to 40-60% also in the Nordic. These very high values render the effect of the storage size completely negligible and the influence of the inclination reduces to less than 5%.

The effect of the storage tank size is on the other hand relevant with respect to the SF for heating, at least for the southern countries: +5-15% when storage tank volume is doubled. Again, the effect of the inclination reduces to less than 5%. In general, SFs for space heating range between 10 and 30% in the northern climates and peak up to 70% in the southern, for the best construction standards and largest storage volume.

For large collectors' areas, however, the overall duration of the stagnation condition is strongly influenced by the inclination. While more than 2000 hours of stagnation are found for the 30° inclination, no such condition is revealed with the installation of the collectors onto the façade of the building.

Thus, from a purely technical point of view, the utilisation of façade mounted solar collectors, is to be preferred when large solar fields are planned.

Figure 53 in Annex I reports on the trends of the SFs of all the considered climates and heating demands standards. Average increases in the order of 5 % are obtained when reducing distribution temperature by 5°C.

Figure 7 shows the effect of the solar energy utilisation on the FE used. The integration of solar thermal systems in the HVAC installations allows to decrease the total final energy consumption with an amplitude depending mainly on the climate and size of the collector field, while size of the storage tank and inclination of the surface do not have any evident effect.

In northern climates, the best solar thermal system variants (13.8 m^2) enable to reduce the electricity consumption by around 6 to 8 kWh/m^{2}y, whereas in southern climates, the electricity savings rise up to 12 kWh/m^{2}y.

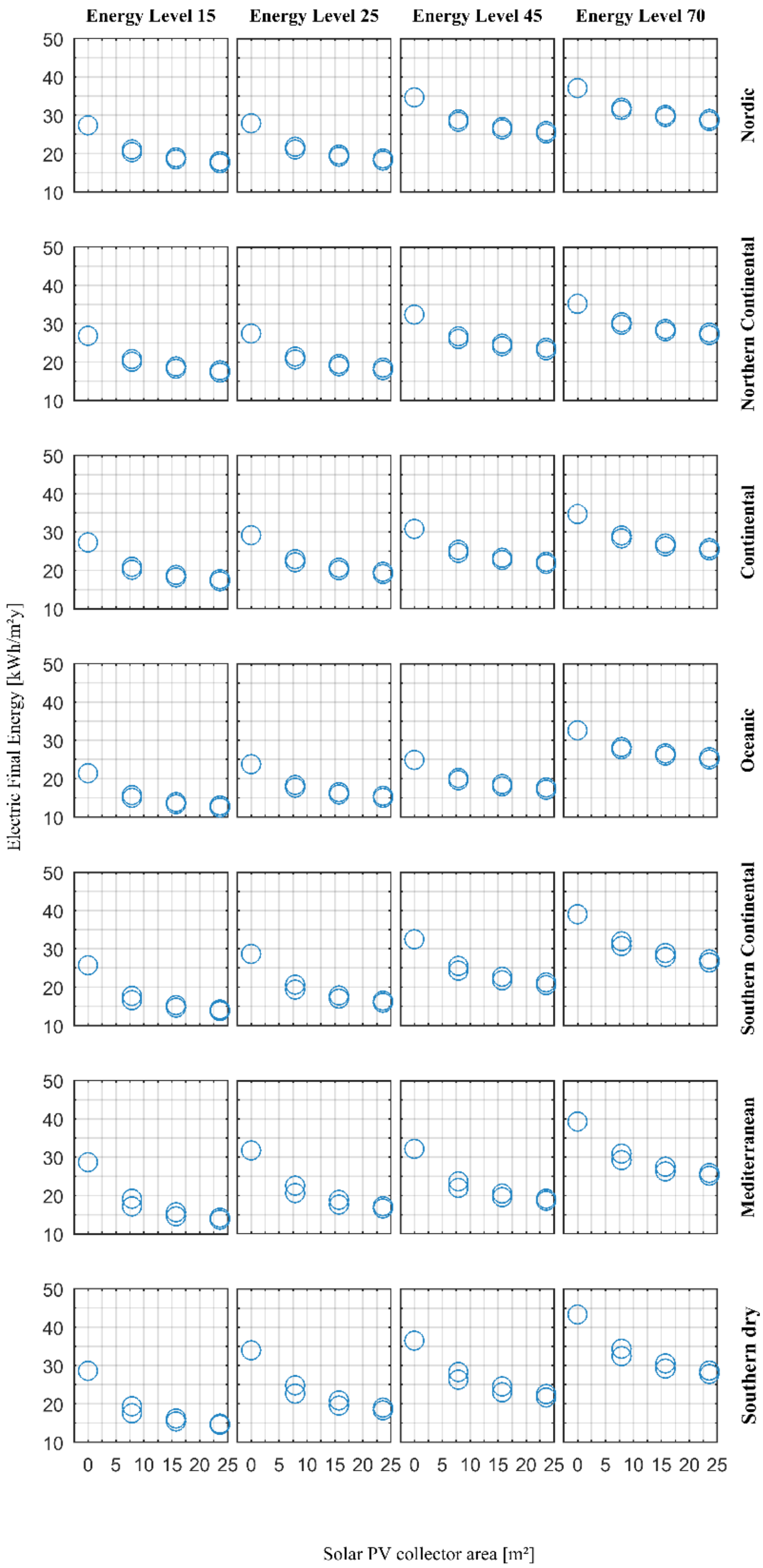

Figure 7 - Total final energy for several variants air-source heat pump and PV system

Again, despite the relevant reductions of FE utilisation, only a limited number of solutions drop below the 50 kWh/m^{2}y PE consumption without solar technologies, although most are between 50 and the 70 kWh/m^{2}y PE.

2.1.5 Solar PV energy utilisation

Figure 55 in Annex I shows the utilisation of the PV electricity to drive the HVAC system, to drive lighting and appliances, and finally fed into the grid (when production exceeds all energy uses).

Installing 1 kWp (7.8 m^2 PV field area) allows to self-consume almost all the PV electricity (around 90%), while in the other cases, a relevant portion of the production needs to be fed into the grid.

The utilisation of PV electricity with regard to the HVAC system varies from 750-950 kWh/y in the southern countries to 450-650 kWh/y for the Nordic climate, if 1 kWp is installed. In case of a 3 kWp installation, the figures increase by 25% to 35% (depending on climate and heating standard), to around 1200 - 1500 kWh/y and 700 - 900 kWh/y respectively.

This is because we do not consider batteries in the proposed Packages, thus the PV electricity can only be stored as warm water in the thermal storage tank or thermal mass of the building, but no special control algorithms were implemented to promote this.

The inclination of the panels on the façade has a minor effect on the energy self-consumption for the HVAC system.

A larger increase is related to the domestic uses (lighting and appliances): the PV electricity utilisation doubles when tripling the PV panels' area.

The effect of PV fields utilisation on the buildings' specific FE is reported in Figure 7 that accounts only for the electricity self-consumed for running the HVAC system (in order to allow for a comparison with the solar thermal cases). The results are similar to the ones discussed for the solar thermal collectors:

In northern climates, the FE reduction is in the range of 8 to 10 kWh/m^{2}y, whereas in southern climates, the electricity savings rise up to 14 kWh/m^{2}y (23.6 m^2 - 3 kWp cases), which is comparable to that found for solar thermal (per m^2).

2.1.6 Final Energy and Primary Energy considerations

In all cases discussed and under the boundary conditions already reported, the renewable energy harvested and self-used is mostly not sufficient to reduce primary energy consumption to below 50 kWh/m^{2}y. Thus, for detached SFHs, combinations of PV and solar thermal systems are necessary.

Figure 56 to Figure 58 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. Solar thermal and PV energy utilisation have nearly the same effect on increasing the SPF for DHW preparation in northern countries, while solar thermal is shown to be much more effective in the southern cases. Again, this effect is stronger in the renovations with the highest envelope standards.

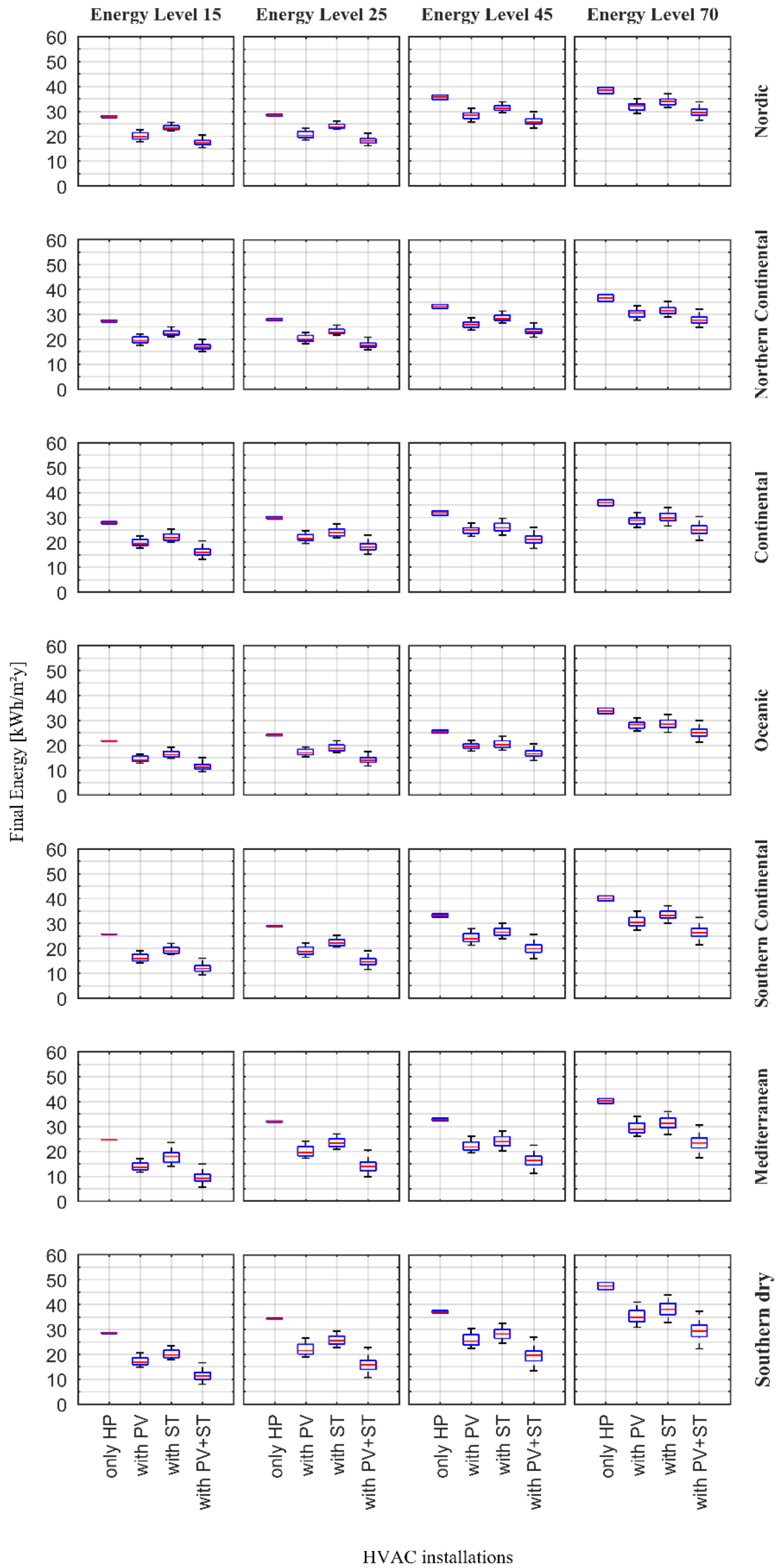

Figure 8 – Total final energy range for different HVAC installation types

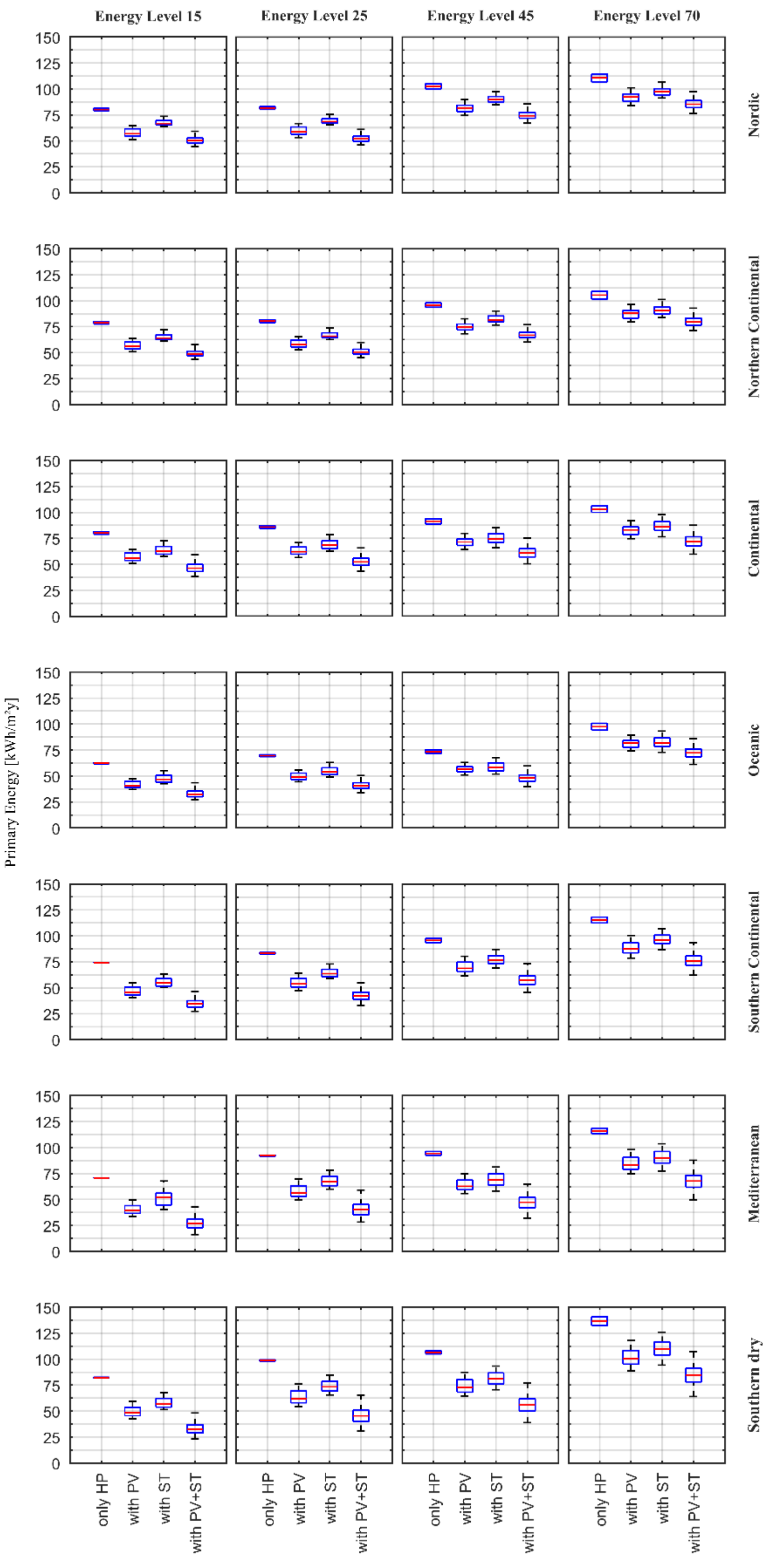

Figure 9 – Total primary energy range for different HVAC installation types

We can draw similar conclusions with respect to the SPF for space heating. Here, however, the utilisation of solar thermal energy gives always better results due to the low temperatures of the distribution (30-35°C).

The SPF for space cooling is only affected by the PV electricity harvested. Values between 4 and 25 are encountered in most cases, with a clear increasing trend moving from south to north. Again, the latter applies to cases where irrelevant cooling demand is assessed.

Figure 8 shows the same results in terms of FE used for the HVAC systems. For Nordic and Northern continental climates, average values lower than 20 kWh/m^{2}y can be reached in some cases only combining both PV and solar thermal solutions. A cost-effective solution for new constructions in northern countries is therefore to install exhaust air heat pumps, recovering heat wasted through the ventilation system at the heat pump evaporator.

With respect to the milder climates and the more efficient envelope solutions (15 to 45 kWh/m^{2}y), we reach FE consumptions in the range of 10 to 20 kWh/m^{2}y in all cases.

Despite the utilisation of modest envelope solutions and no mechanical ventilation systems for the renovation of the “70 kWh/m^{2}y” buildings, FE uses in-between 20 to 30 kWh/m^{2}y are found.

Figure 9 reports on the distribution of PE use. The trends are clearly the same as only electricity is used in the HVAC system discussed. Due to the severe CED factor used, the 50 kWh/m^{2}y is reached only for the cases which FE utilisation is lower than around 20 kWh/m^{2}y. Even in the worst cases, however, we obtain PE values of 85-90 kWh/m2y.

If we considered that in the cases prior renovation, space heating and DHW are provided by gas boilers and no cooling devices are installed, these results have to be compared with initial PE uses of around 350 kWh/m2y, corresponding to PE reductions of 75-85% in all cases.

2.1.7 Economic evaluations

For each of the components renovated or newly setup in the buildings, purchasing, installation and maintenance costs are reported. For the sake of simplicity, installation costs are calculated as a percentage of the purchasing ones, while maintenance costs, are computed as a percentage of the total purchasing + installation. Purchasing + installation costs represent the investment costs in this chapter.

The costs reported correspond to average products available on the market while the present report is being elaborated, and to average EU installation/maintenance charges. Those values strongly vary among EU countries. Therefore, the considerations following hereafter are reported to show trends and to compare technologies. Detailed analyses can be carried out by means of the database tool available on the iNSPiRe website.

More in detail, the following assumptions affect the results:

- We assumed 30% additional costs for triple-pane windows compared to double accounting for a slightly higher purchasing cost and more complex installation procedure (old frame removed and new one installed improving thermal bridges and air-tightness).
- The heat pump units used are average devices available on the market, without compressor speed control.

- The life-time of each component is based on the experience of the authors. However, not many reliable data are available on the topic in the open literature. The users of the database, should carefully decide this value based on their experience, or even better a parametric analysis should be carried out varying components lifetime within reasonable ranges.
- Fuel prices reported represent EU averages from the EUROSTAT databases (2013-2015).
- Inflation rate (1%) and energy cost increase rate (2%) are merely indicative of what could happen in the next 30 years (duration of the investment period considered): the trends of the period 2000-2013 are completely different from the last years’, therefore impeding any consistent long-term extrapolation. In any case, when these values are limited to less than 5% percent, their effects on the conclusions drawn with this study are also reduced.
- Loans and incentives are not considered, since these vary significantly with countries and time.

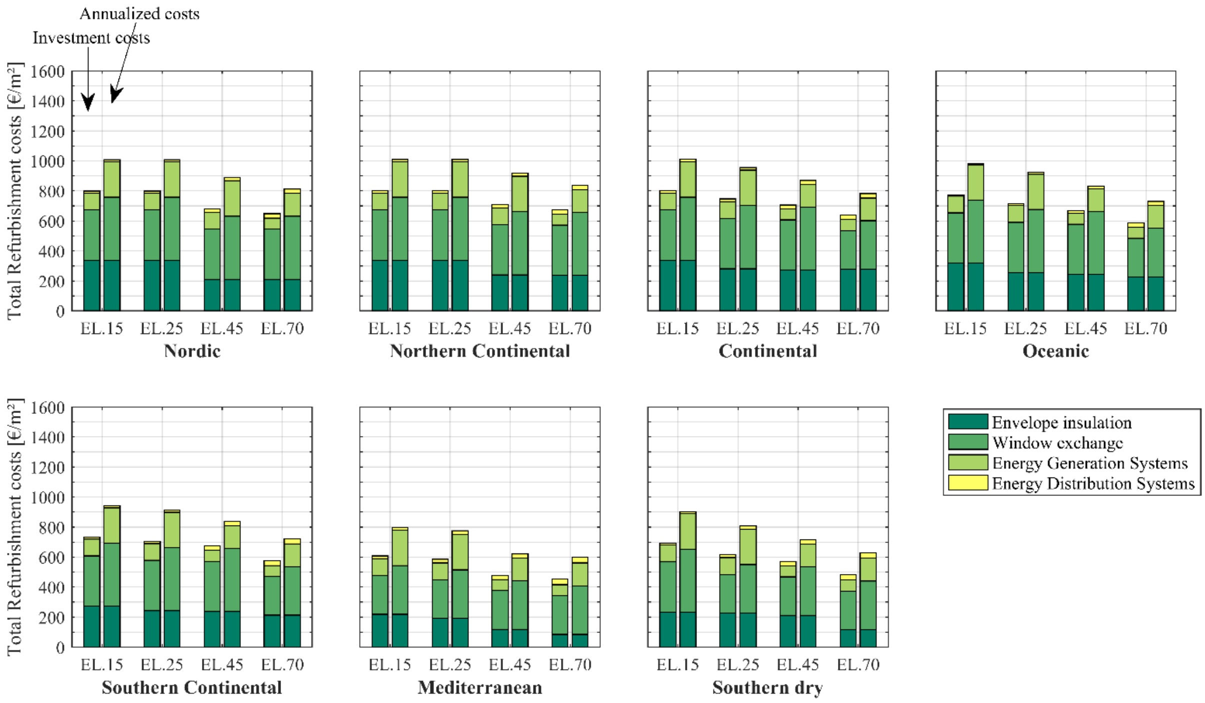

Figure 10 – Investment costs distribution (first year investment and annualized costs over 30 years) without solar systems (30 °C water distribution temperature)

Figure 10 shows investment costs per unit living surface area, both initial and annualised. As can be noticed, envelope initial expenditures (insulation and windows) are larger than for generation and distribution systems. This is due to the large S/V ratio and to the large glazed area (33 m^2) considered. If semi-detached and row houses are considered, the costs decrease consequently to the reduction of external walls and windows. For the latter typology, the envelope renovation spending can approximately halve. Investment costs for generation and distribution systems range in the simulated cases between 100 and 130 €/m^2. The cost for the generation system is usually lower for Energy Level 70 than for 15 and 25, because in the latter cases a mechanical ventilation system is most often used. For the same reason, in some cases (e.g. Mediterranean climate) the envelope insulation costs more when average Energy Levels are considered, because thicker insulation is needed if mechanical ventilation is not used.

If we look to the annualised costs, the investments for the envelope renovation almost remain unchanged (life duration of insulation is considered 30 years and windows 25 years), while generation system costs double, since the lifespan of most components is considered to be 15 years (therefore one full replacement is accounted for).

Annualised costs in the range of 350-700 €/m² and 170 - 260 €/m² are assessed for envelope and generation + distribution solutions respectively.

The utilisation of solar technologies increases investment costs (annualised costs considered) less than 100 €/m², and even combinations of the two (necessary to cut PE consumption to lower than 50 kWh/m²y) add around 150 €/m² on top of the generation system costs.

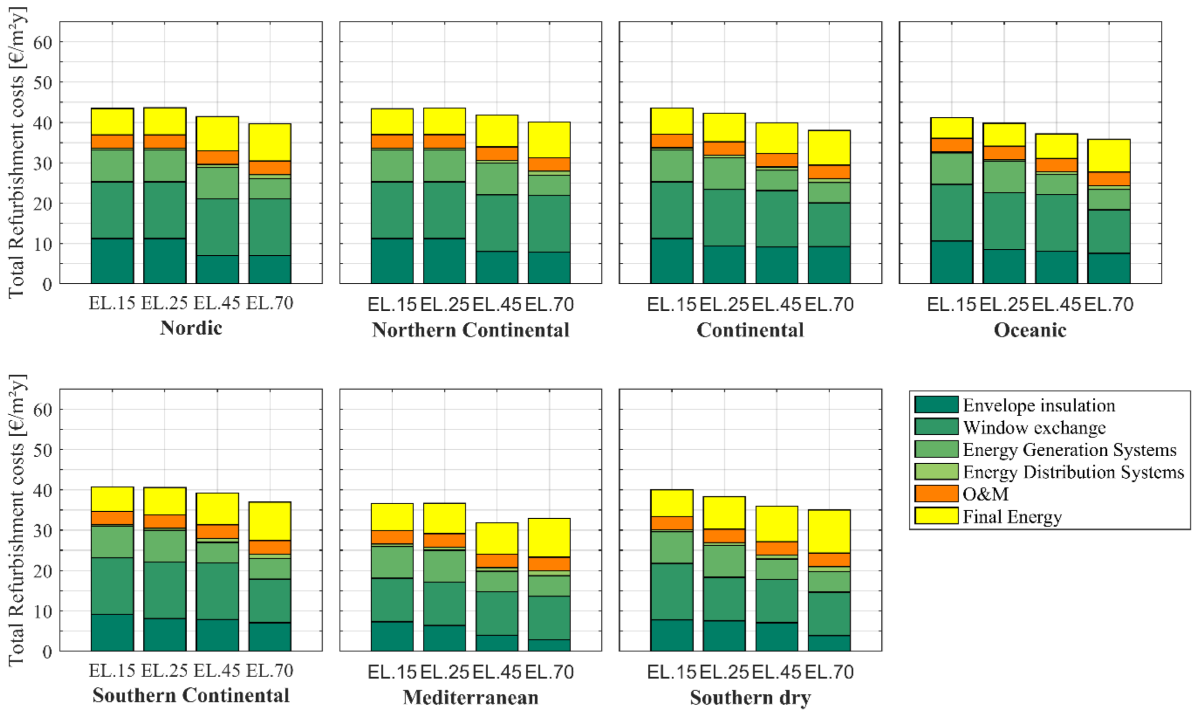

Figure 11 – Yearly annualised costs distribution for variants without solar systems

To compare investments with maintenance and energy costs, the first have been divided by the duration of the investment itself (30 years).

Figure 11 shows how the investment costs have the largest influence (60-75%) on the yearly costs, while energy costs impact with 20-30%. In any case considered, we found a low variability of total yearly costs in the range of climates and renovation packages proposed, all values being between about 30 and 45 €/m²y. The operation and maintenance expenses are also significant in comparison to the other operational costs for energy, being around 10% of total costs. Figure 59 in Annex I shows the variability of the results with the adopted solar technologies. Even combinations of the two add on average less than 2 €/m²y on top of the yearly costs (5-10% of the total).

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 12 shows the Final Energy consumption of the H&C system simulated following the energy uses reported (distribution water temperature 30 °C). The base cases without solar energy utilisation are reported.

The same trends as in the previous case are seen. Clearly, the absolute values are slightly lower due to the improved effectiveness of the HP when working in a more beneficial range of working conditions at the evaporator. The effect of using the ground source instead of the air results in a few kWh/m^{2}y in the northern countries, while it is insignificant in the southern. Only in the southern dry climate, a significant effect (again few kWh/m^{2}y) is obtained on the FE consumption for cooling and with respect of the best envelope renovation solutions.

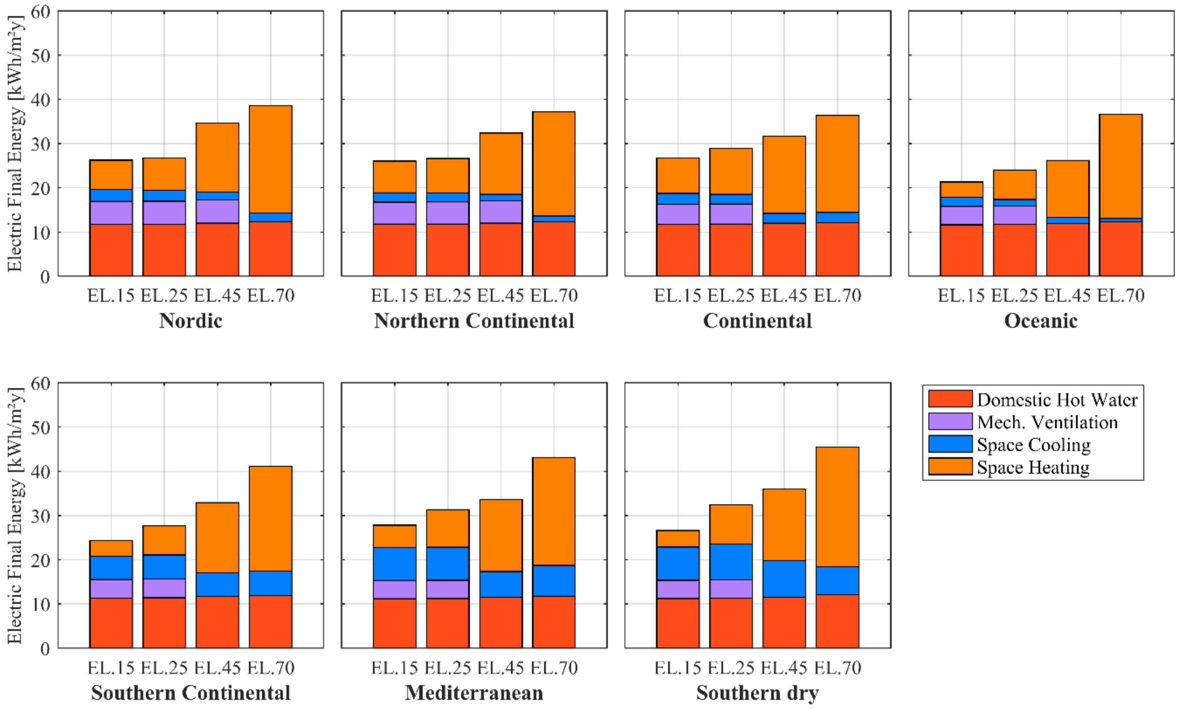

Figure 12 - Final energy distribution without solar systems and a heating water temperature level of 30°C.

The SPF figures vary between 3.0 and 3.8 with respect to the heating loads and between 3.0 and 4.4 looking at the cooling loads. Relatively low in all cases are the SPFs related to the DHW preparation that ranges between 1.8 and 1.9.

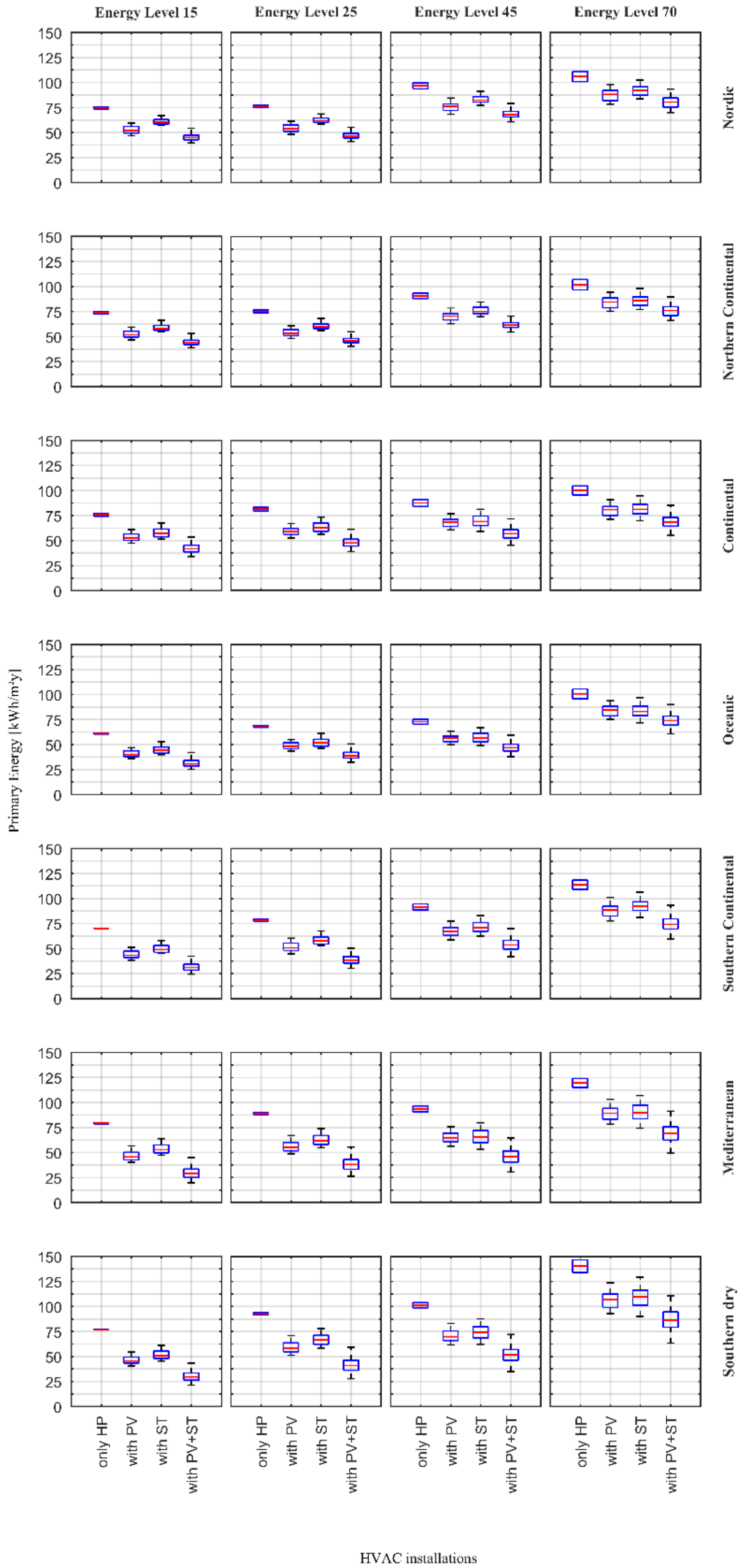

Figure 13 – Total primary energy range for different HVAC installation types

Relating to this, the overall SPF accounting for heating, cooling DHW loads and ventilation varies in a range of 1.9 and 3, again the lower values being related to the highest envelope efficiency standards.

The reduction of PE consumption with respect to the air to water HP is in the range of 2 to 6 kWh/m^{2}y (see Figure 13).

2.2.2 Economic evaluations

Figure 14 shows investment costs per unit living surface area, both initial and annualised. Envelope initial expenditures (insulation and windows) are still largely prevailing on generation and distribution systems. In this case however, the costs of the generation system are much larger due to 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 290 and 345 €/m², while the annualised costs vary between 370 and 470 €/m².

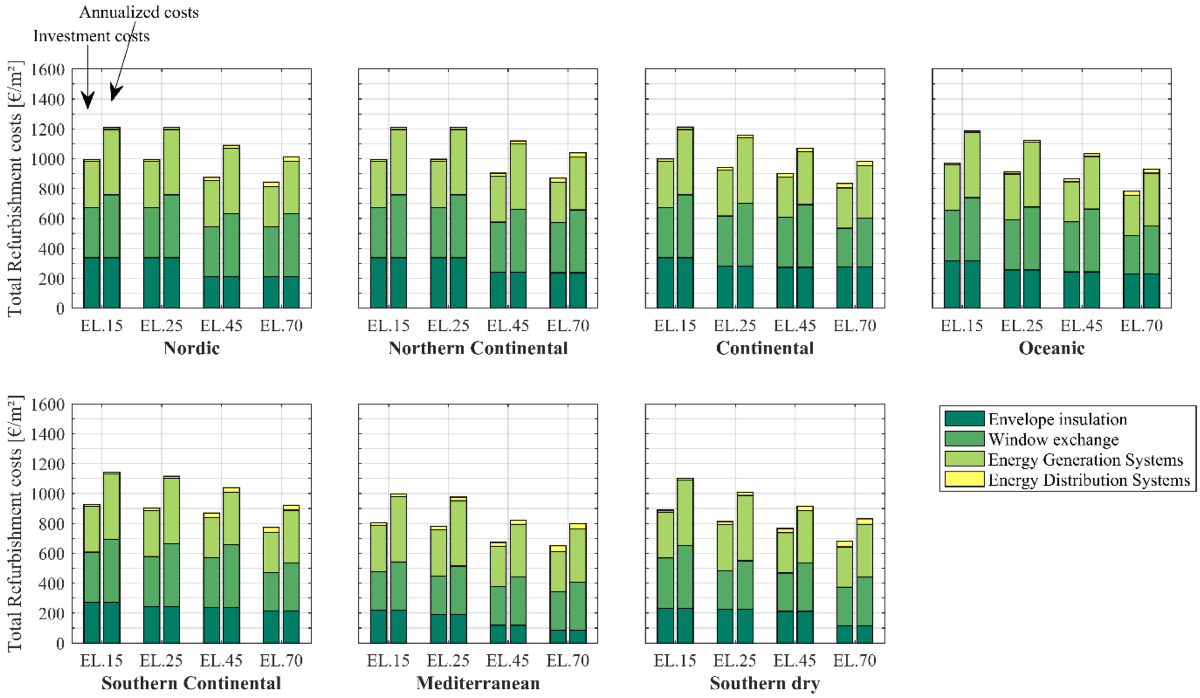

Figure 14 – Investment costs distribution without solar systems (30 °C water distribution temperature)

The incidence of the utilisation of solar technologies on the investment costs (annualised costs considered) results once more in around 150 €/m^2 on average, corresponding to about 10-15% of the total annualised costs.

Figure 15 shows that the entry costs here impact for around 80% both on the yearly costs (25 - 40 €/m^{2}y). Total annualised costs vary between 40 and 50 €/m^{2}y if solar technologies are not accounted for. The latter influence the annualised costs by about 2 €/m^{2}y.

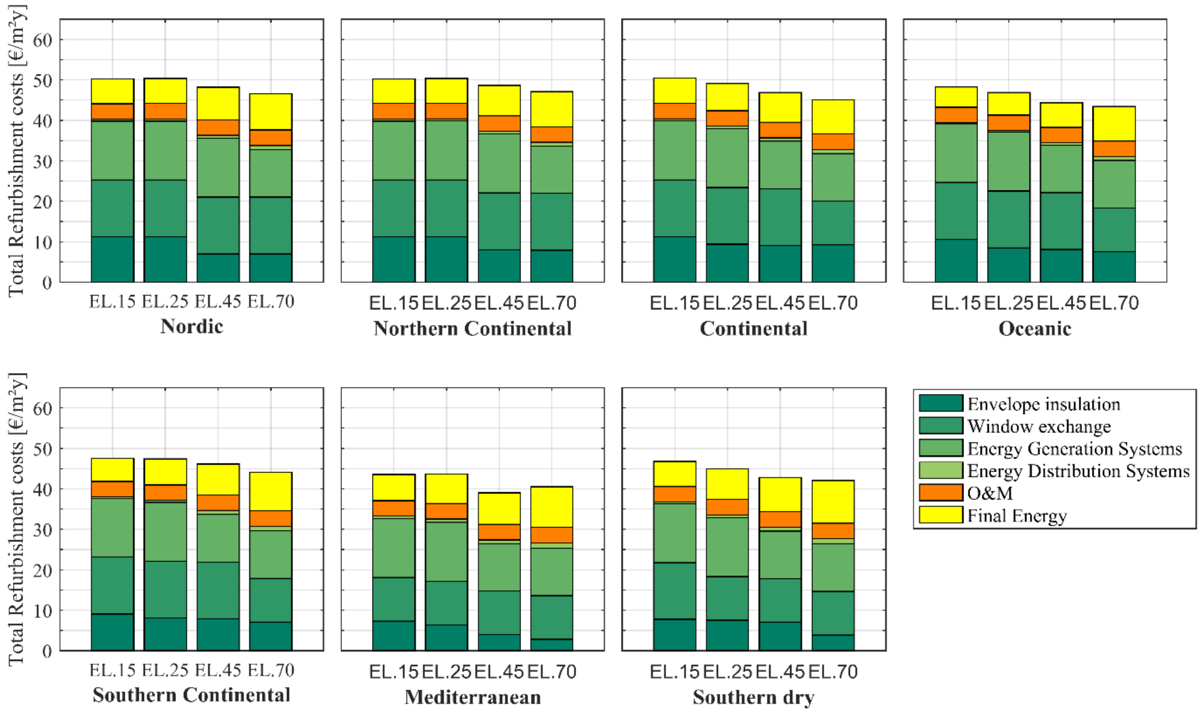

Figure 15 – Yearly annualised costs distribution for variants without solar systems

2.3 Gas and Pellet Boilers with Radiant Ceilings

Gas and pellet boilers solutions are reported together for two reasons: at first we wanted to directly compare the two systems in terms of primary energy consumption and costs. Secondly, the boilers are simulated with the same model, while final and primary energy use are computed via post processing by means of different thermal efficiencies and primary energy coefficients.

As for the previous cases with radiant ceilings, distribution temperature of 30 and 35°C are accounted for here. In this configuration, the space cooling is covered by split units that aim to maintain the internal set temperature. Ideal dehumidification is assumed here allowing to maintain an absolute humidity value of 12 g/kg.

2.3.1 Used Energy and Thermal Comfort

The thermal behaviour of the two systems in wintertime is the same as already described in the previous sections, since the same distribution system is used.

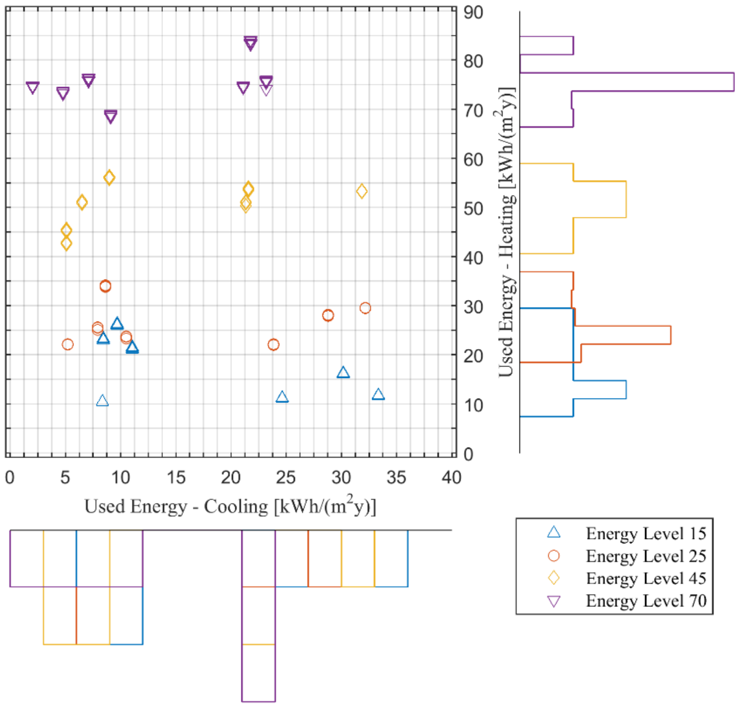

Figure 16 - Used Energy for heating and cooling of the different energy standards

During summer split units are used to deliver the needed cooling. Despite the fact that these devices cover both sensible and latent loads Used Energy for cooling is in the same range as the cases with radiant ceilings, which do not cover latent loads. Split units mainly remove energy from air, while radiant ceilings act both on air and walls to produce the same convective temperatures, resulting in lower operative temperatures compared to those achieved by spit units.

Looking into the comfort conditions in summer time (Figure 17), the model used for the split units allows to cover the sensible loads only by limiting the temperature to the needed level. The removed latent heat has been ideally calculated up to maintain 12 g/kg of absolute humidity. This quantity has been therefore used for the considerations on the removed heat and additional electricity consumption.

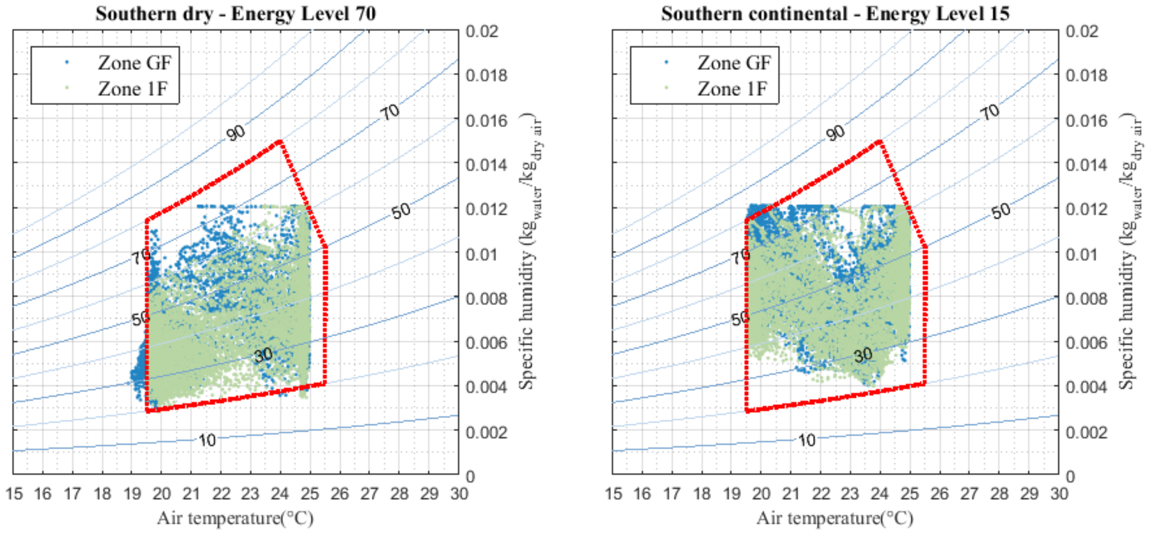

Figure 17 - Psychometric charts of {Southern dry, Energy Level 70, heating water temperature 30°C} and {Southern continental, Energy Level 15, heating water temperature 35°C}

2.3.2 Final Energy and Primary Energy

With respect to the systems reported in this chapter, DHW and space heating relate to gas or pellet consumption, while mechanical ventilation and cooling to electricity use.

Electric energy use (Figure 18) ranges in the same intervals as the previous cases. Final energy use linked to DHW preparation is about 40 kWh/m^{2}y, while thermal energy consumed for space heating varies between around 15 and 100 kWh/m^{2}y (Figure 19).

The trends are the same for gas and pellet boilers, with slightly higher values for pellets boilers which have a lower thermal efficiency.

When considering the primary energy used (see Figure 20), gas boilers solutions (without solar technologies) span between 85 and 220 kWh/m^{2}y, while pellet systems (Figure 21) never exceed 50 kWh/m^{2}y due to the very low Cumulative Energy Demand coefficient equal to 0.19 kWh$_{PE}$/kWh$_{FE}$ (only non-renewable energy considered).

Figure 20 shows also the effect on the primary energy of using solar energy with gas boiler: PV panels contribute only marginally to reducing the primary energy used, since the electricity consumption of these systems is small in percentage, and only related to cooling and ventilation. The reduction varies between around 10 and 20 kWh/m^{2}y, being larger where the cooling loads are noteworthy.

Much more relevant is the contribution related to the thermal utilisation of the solar energy, mainly with respect to covering DHW preparation loads. In this case, the primary energy reduction ranges between about 30 and 60 kWh/m^{2}y, depending on energy demand of the building and obviously climate.

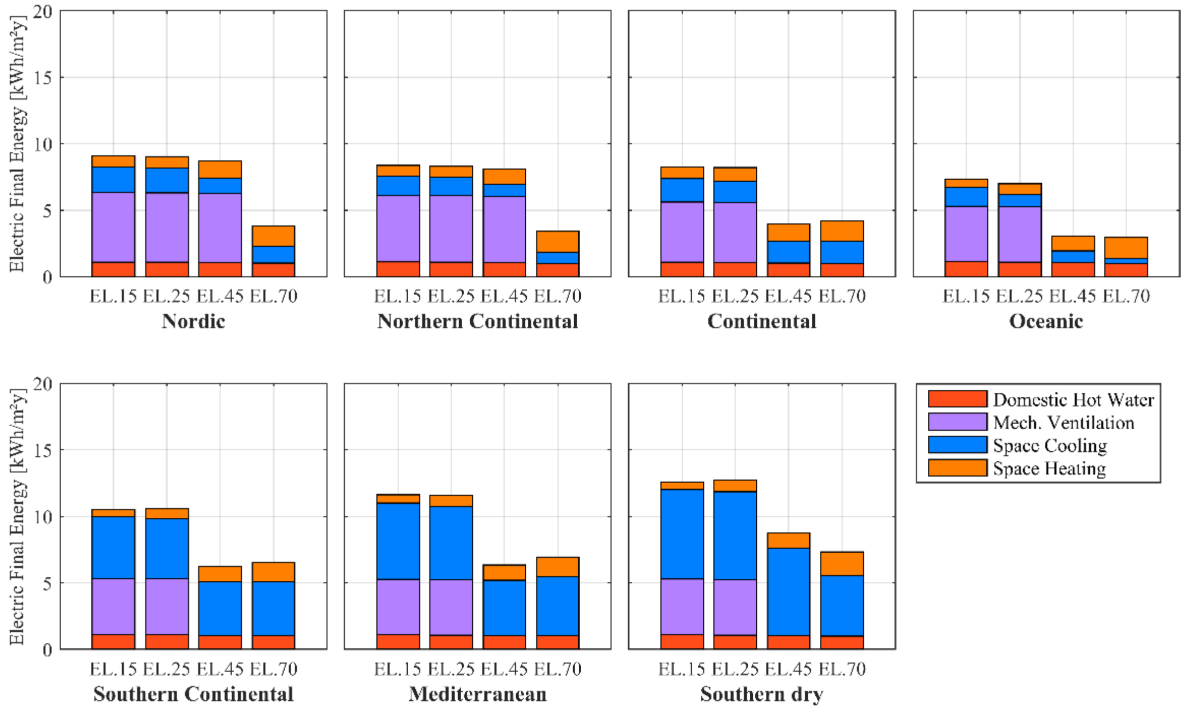

Figure 18 - Final energy for different building typologies and climates – Gas Boiler. Electric consumption only

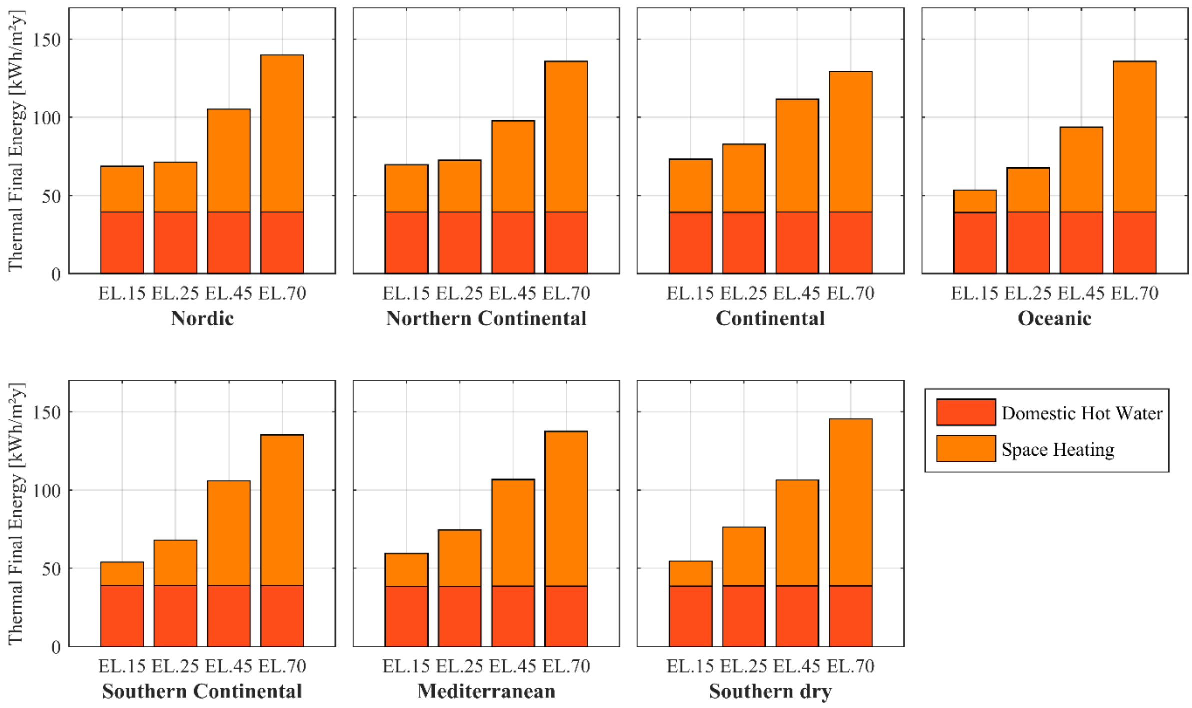

Figure 19 - Final energy for different building typologies and climates – Gas Boiler. Fuel consumption for DHW and space heating.

Even with regards to combinations with extensive use of solar energy, the 50 kWh/m^{2}y primary energy limit can be reached only for the buildings that have the lowest space heating uses (15 kWh/m^{2}y) and in the three southernmost climates.

The opposite behaviour is noticed with respect to the pellet boiler solutions (see Figure 21). In this case, PV panels contribute again with 10 to 20 kWh/m^{2}y to reducing the primary energy consumption. On the other hand, solar thermal energy contributes only slightly here, since the primary energy consumed for DHW preparation and space heating is already minimal.

Figure 21 shows that the utilisation of solar technologies in addition to pellet boilers solutions adds to the investment costs and contributes to a minimum extent to the reduction of (non-renewable) primary energy.

Extremely limited is the energy use for cooling. Modern split units can reach EER values as high as air-to-water chillers. In the latter case however, thermal losses at distribution and distribution pumps' electricity consumption must be accounted for. In the end therefore, while EERs of reversible heat pumps working with radiant ceilings range in between 3 and 3.5, EERs of split units vary between 5 and 5.5.

Moving from here, the impact of using PV electricity on the summer SPFs is reported in Figure 69, which shows that values up to 10 – 20 can be reached in southern countries. As already highlighted previously, this has a minor effect on the absolute electricity consumption (3 - 5 kWh/m^{2}y) due to the low overall cooling demands encountered in our climates.

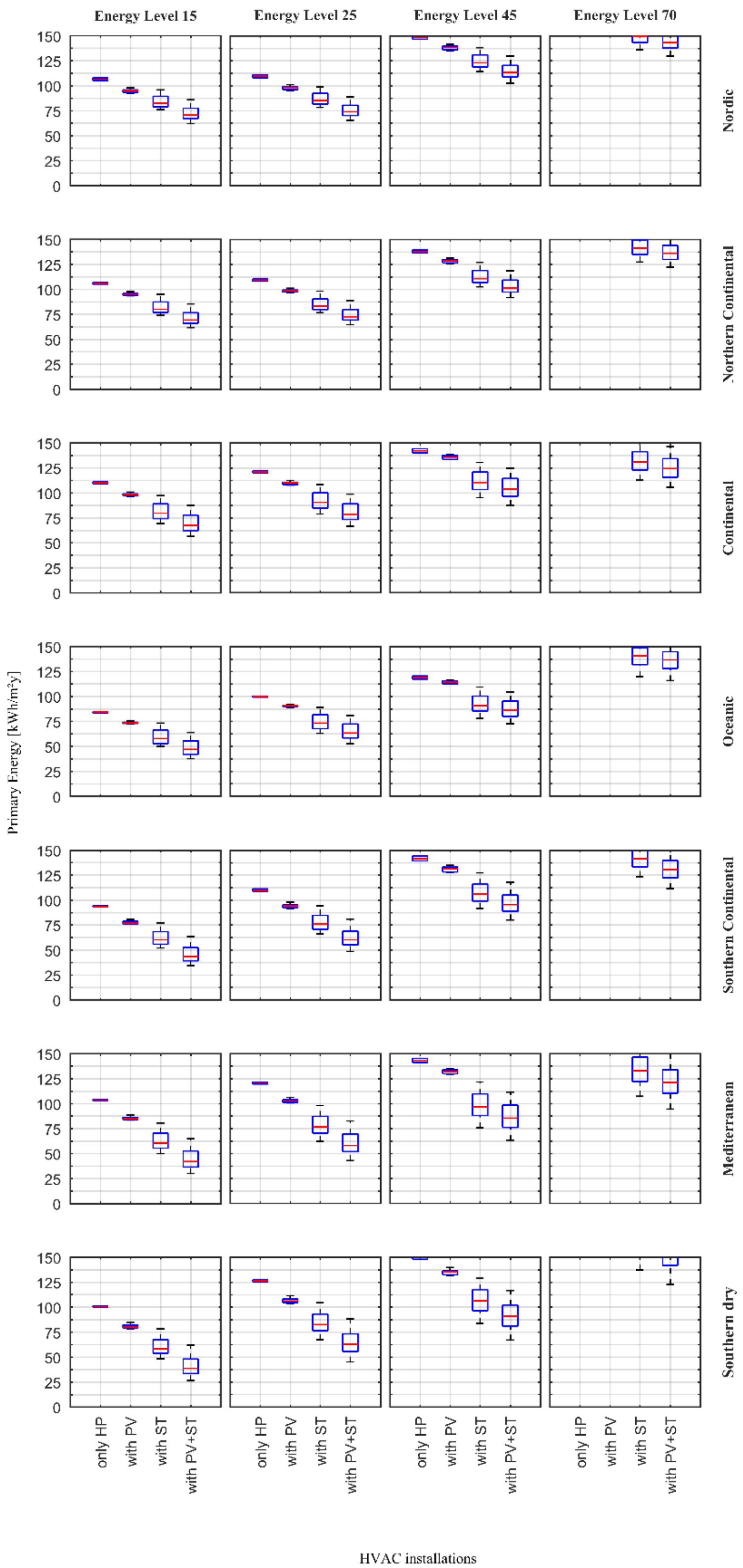

Figure 20 - Total primary energy for different HVAC installation types – Gas Boiler

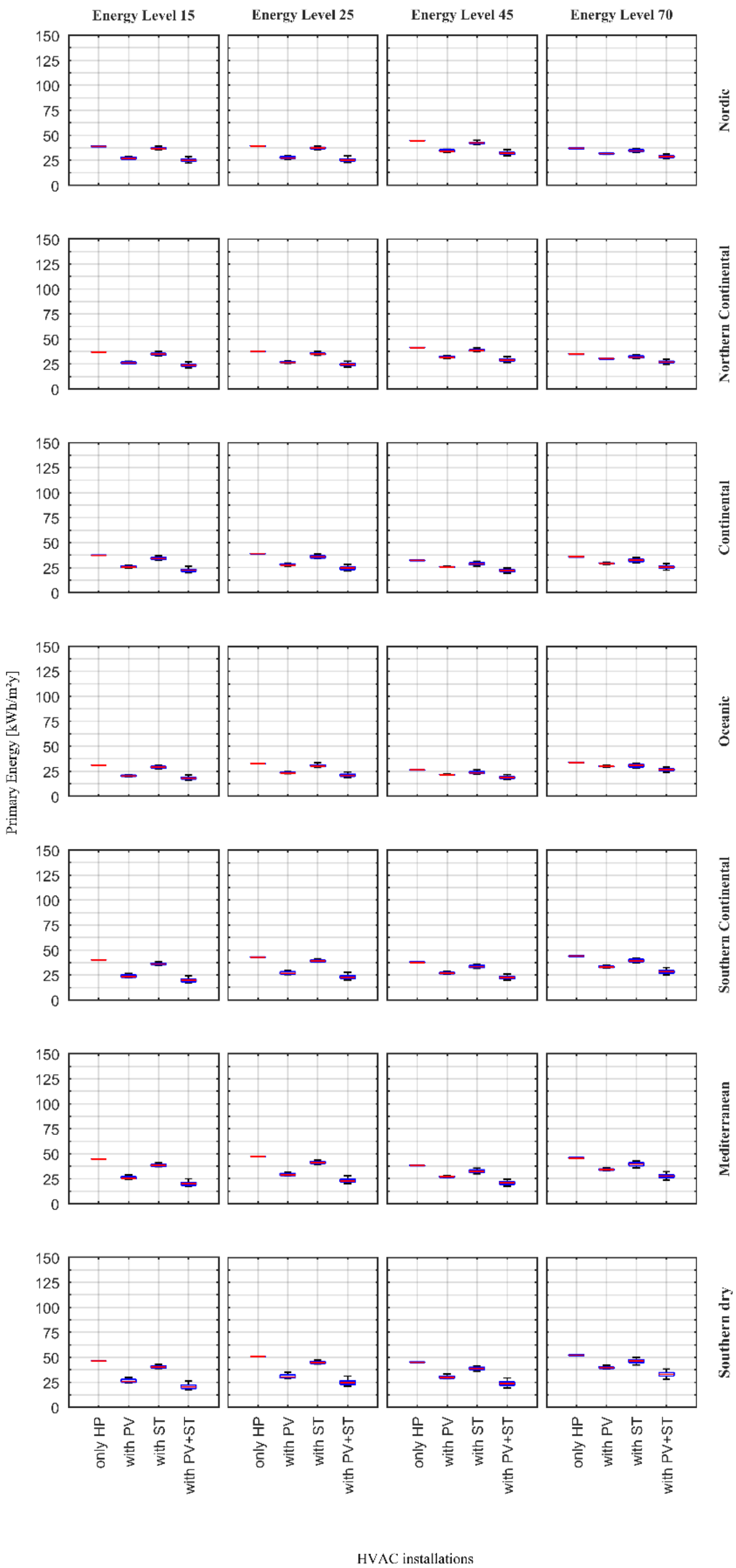

Figure 21 - Total primary energy for different HVAC installation types – Pellet Boiler

2.3.3 Economic evaluations

Figure 22 and Figure 24 show investment costs per unit living surface area, for gas and pellet boilers respectively. In both cases, envelope initial expenditures (insulation and windows) are still larger than for generation and distribution systems, in a ratio of around 3:1 – 5:1.

Systems with gas boilers are clearly cheaper, the boiler having a cost of around 4500 € (25 kW thermal power, installed). Pellet boilers investment cost (installation included) varies between 12000 and 15000 € in the cases simulated. The unit itself is only a portion of the entire heating and cooling system that includes also pipelines, split units and eventually an air handling unit. Therefore the difference between the generation systems' investment costs is much smaller. In case of gas boilers it varies around 100 €/m², while in case of pellet boilers it varies around 200 €/m².

We remark once again that these are indicative cost values and that more precise evaluations can be made by using the database files uploaded on the iNSPiRe website.

If we look to the annualised costs, the investments for the envelope renovation almost remain unchanged (life duration of insulation is considered 30 years and windows 25 years). The difference between gas and pellet generation systems decreases with respect to the initial costs, since we considered a shorter lifetime for the gas boilers (12 years instead of 15). Therefore annualised costs for gas boilers increase almost three times with respect to initial ones.

Annualised costs for the generation system are in the range of 230 - 330 €/m^2 and 440 - 530 €/m^2 for gas and pellet solutions respectively.

The impact of the utilisation of solar technologies on the investment costs (annualised costs considered) results again in less than 100 €/m^2, and even combinations of the two (necessary to cut PE consumption to lower than 50 kWh/m^{2}y) add around 150 €/m^2 on top of the generation system costs.

To compare investments with maintenance and energy costs, the first have been divided by the duration of the investment itself (30 years).

Figure 23 and Figure 25 show how the investment costs have the largest influence on the yearly costs.

Yearly costs for gas consumption are quite relevant: even in case of highly efficient buildings (15 kWh/m²y space heating demand) gas costs can amount to 20% of the total annualised costs, while they are 30 - 40% in cases with lower energy efficiency of the building envelope (70 kWh/m²y space heating demand).

On the contrary, pellets costs are limited in our simulations, therefore the energy costs amount to 15 – 20% of the annualised investment costs.

Despite the obvious reduced initial costs related to using a traditional technology such as the gas boiler one, the total costs the house owner experiences over 30 years are higher for gas boilers than for heat pump systems: 41 - 50 €/m^{2}y.

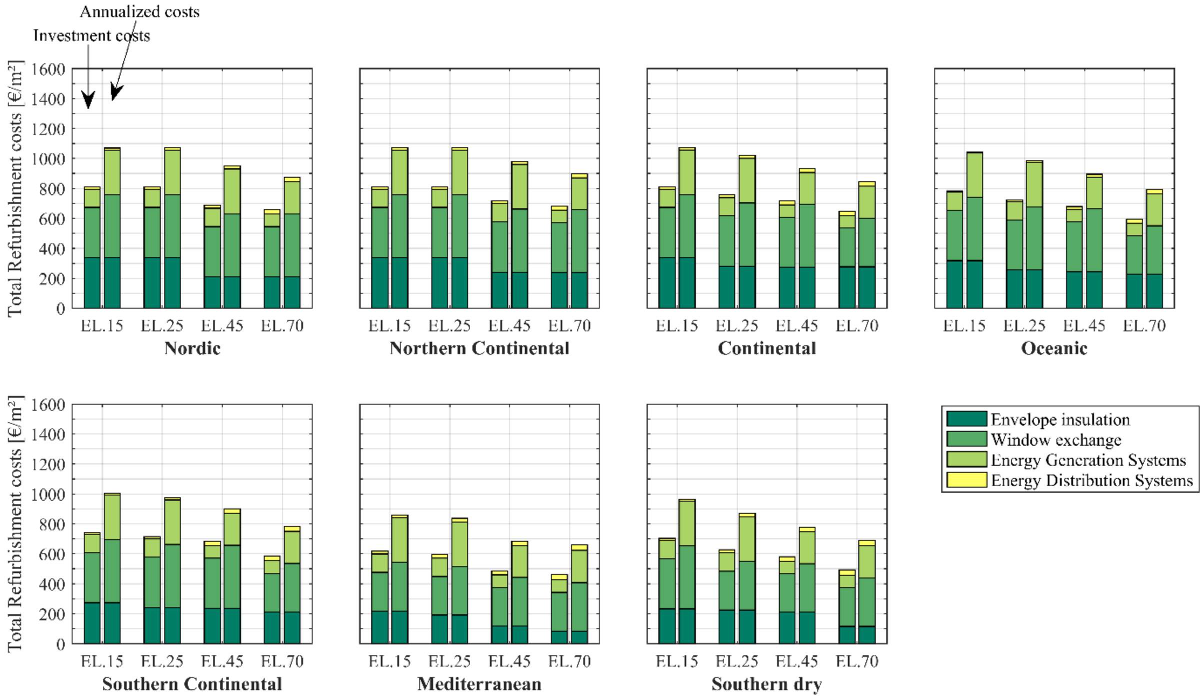

Figure 22 - Investment costs distribution without solar systems (30 °C water distribution temperature) – Gas Boiler

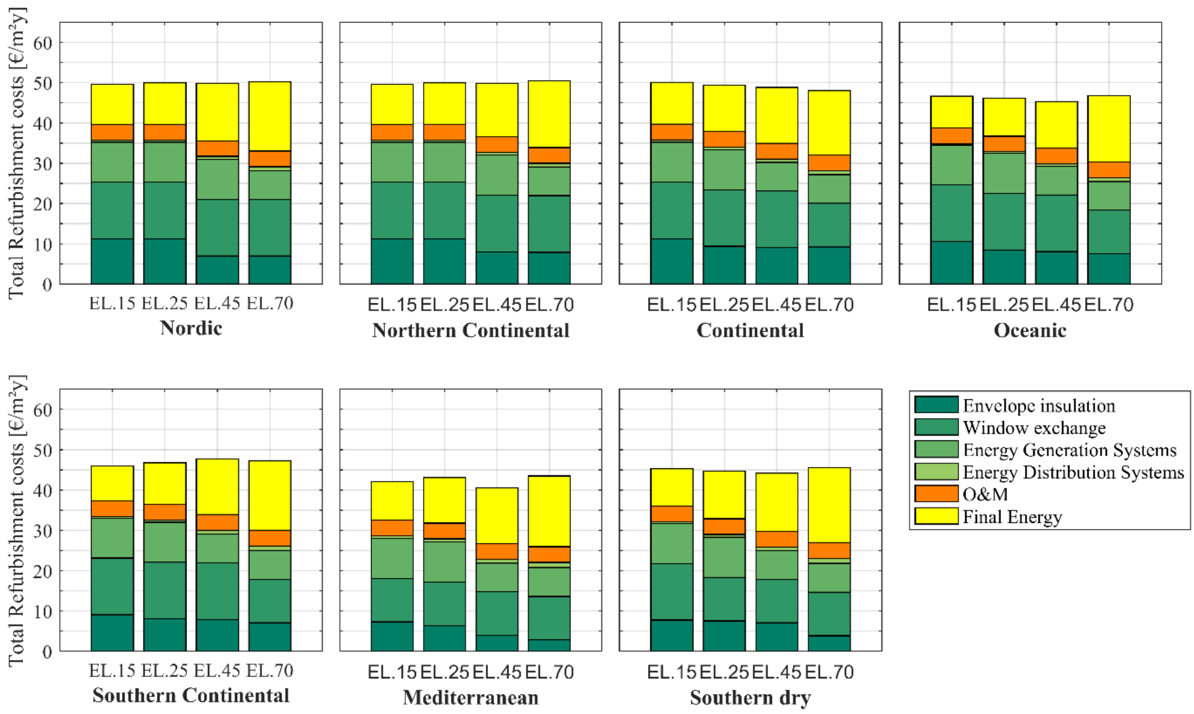

Figure 23 - Yearly annualised costs distribution for variants without solar systems – Gas Boiler

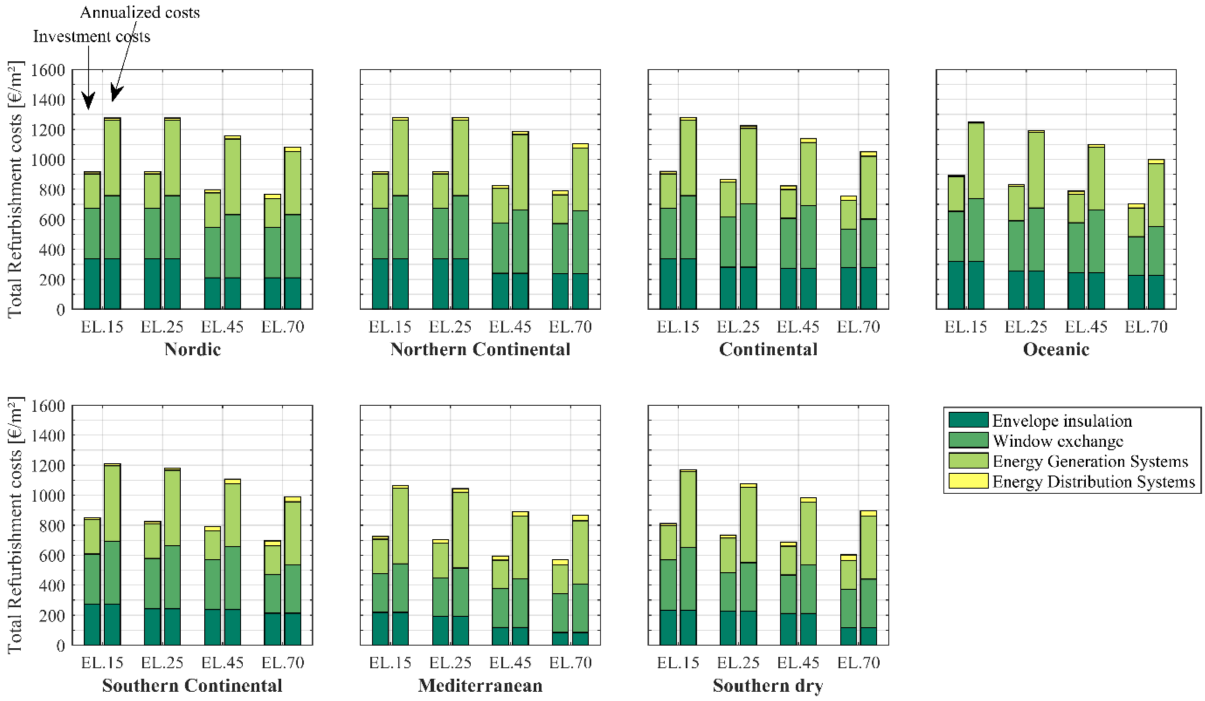

Figure 24 - Investment costs distribution without solar systems - Pellet Boiler

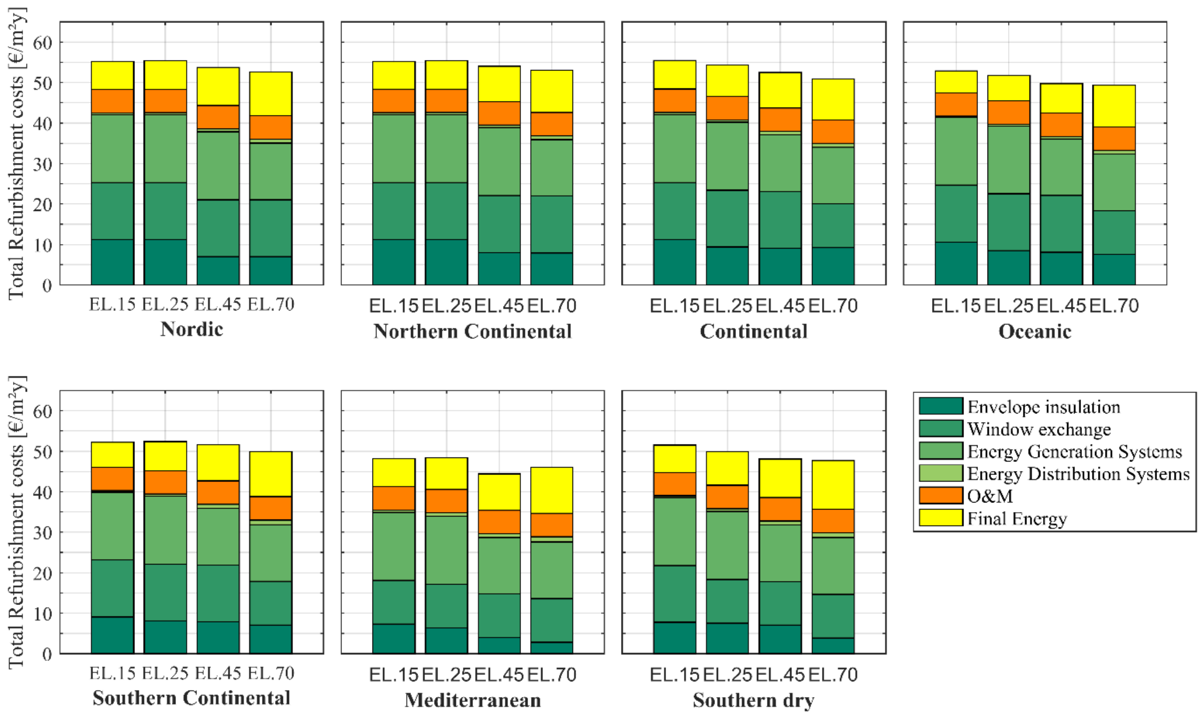

Figure 25 - Yearly annualised costs distribution for variants without solar systems – Pellet Boiler

2.4 Air Source Heat Pump with Fan Coils

For the results presented here, the fan coils have been simulated twice for the same case, once with a design supply temperature of 35 °C and once with 45 °C, with relative sizes. Thus, there are two points for each combination of climate and energy level. Supply temperature for the cooling has been fixed at 7°C.

2.4.1 Used Energy

Figure 26 shows Used Energy for both heating and cooling for the range of climates.

The convective to radiative contribution ratio is set to 70-30% allowing for a precise control of the indoor “convective” air temperature. Operative temperatures are in the same range as the convective ones, thus the perceived temperature is higher and the comfort is lower compared to the cases with radiant ceilings.

Again, this result is consequent to the decision of using the indoor convective temperature to control the H&C systems.

As for split units with respect to cooling, Used Energy for cooling is in the same range as the cases with radiant ceilings despite the fact that both split units and fan coils cover the latent load while radiant ceilings do not. Fan coils mainly remove energy from air, while radiant ceilings act both on air and walls to produce the same convective temperatures by means of lower operative temperatures.

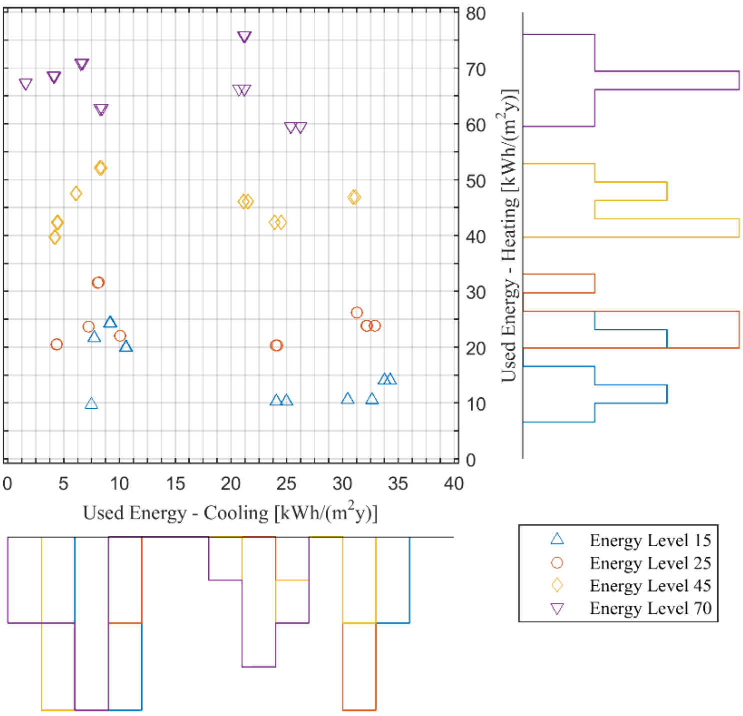

Figure 26 – Energy Used for heating and cooling of the different energy levels

2.4.2 Thermal comfort

In all cases elaborated (Figure 27), the penalty values are very low for heating, in the range of 0.2%, as well as for the cooling.

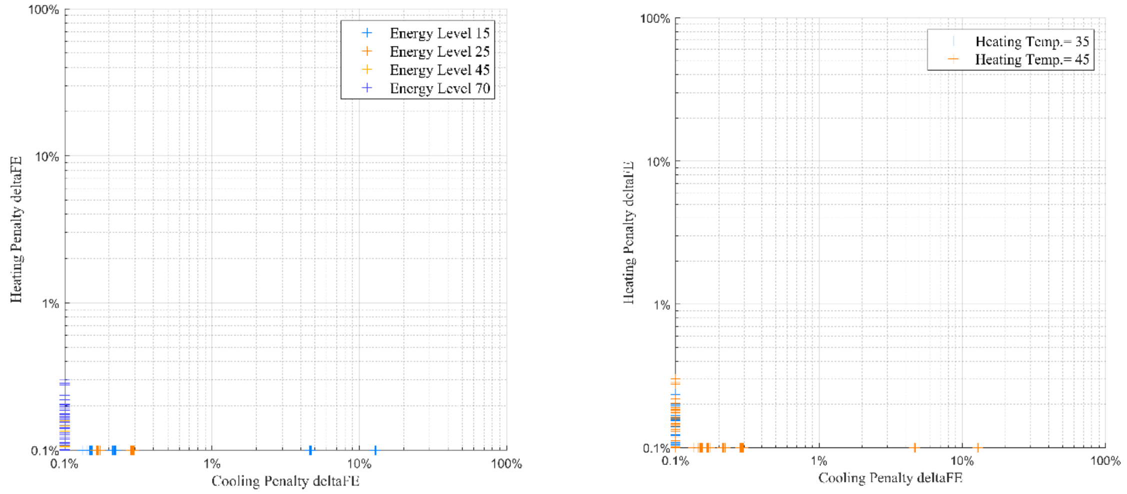

Figure 27 – Cooling and Heating penalty functions for different energy levels and heating water temperature

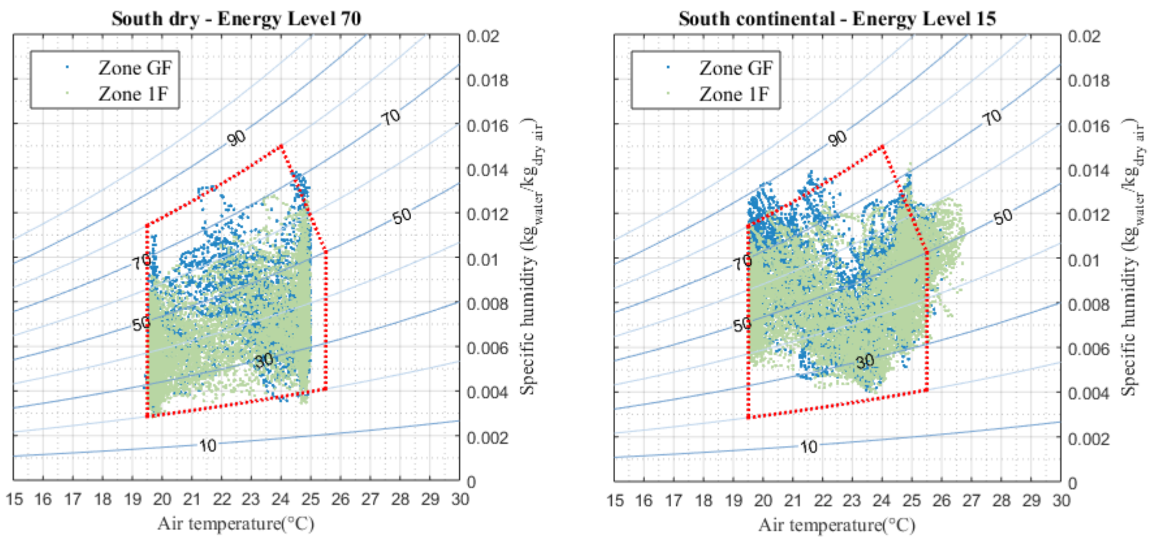

Figure 28 – Psychometric charts of {Southern dry, Energy Level 70} and {Southern continental, Energy Level 15}

Going into details and observing the frequency of the events not respecting comfort conditions (Figure 28), only a very small portion of the hourly averages is located outside the boundaries, the same ranging anyhow between 50 and 60% of relative humidity. The same operation conditions resulted in relative humidities between 60 and 80% for the cases with radiant ceilings.

2.4.3 Final Energy, SPF and Primary Energy

With fan coils, final energy related to space heating and space cooling use is higher than the case with radiant ceilings, for all climates and all energy levels, from 2 up to 6 kWh/m²y. This is due to the electricity needed to run the fans (45 W_{el}/kW_{th}).

Without considering solar contributions, the SPF of the heating system varies around 2 in the northern countries and 2.5 in the southern. The SPF figures for cooling are reversed, ranging around 2.4 in the northern countries and 1.8 in the southernmost.

The overall SPF (H&C and mechanical ventilation) varies between 2 and 2.5 in all the climates.The water distribution temperature only plays a minor role on the final energy utilisation in the cases analysed (35 – 45°C).

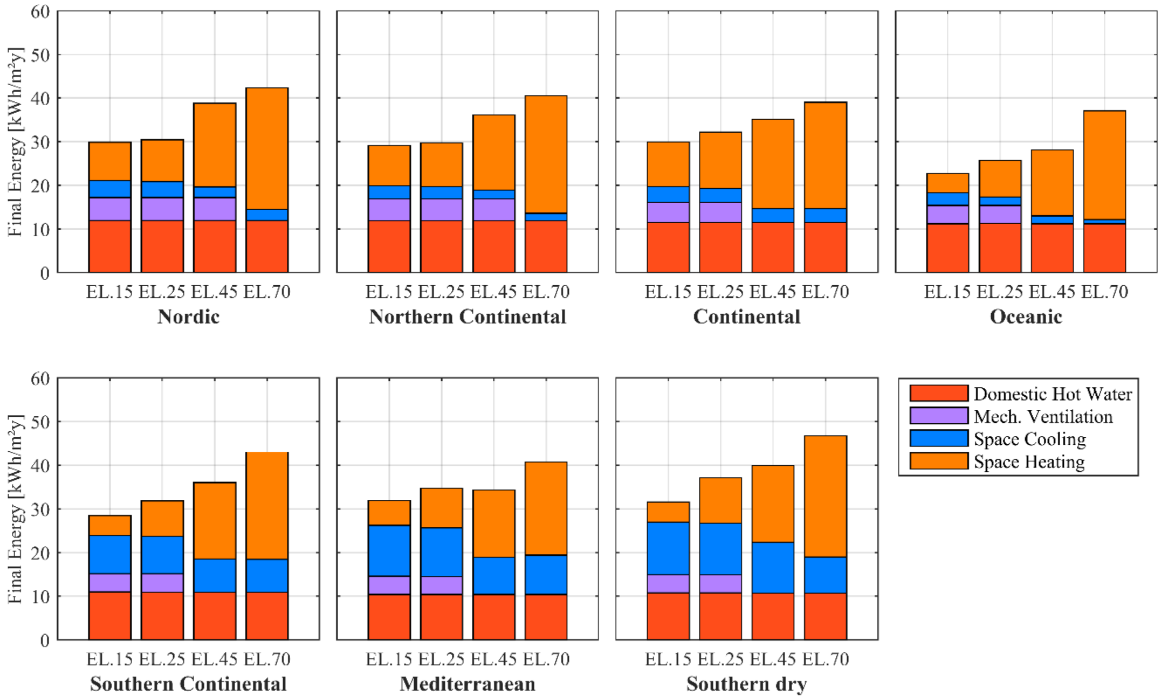

Figure 29 - Final energy distribution without solar systems, and a heating water temperature level of 45°C.

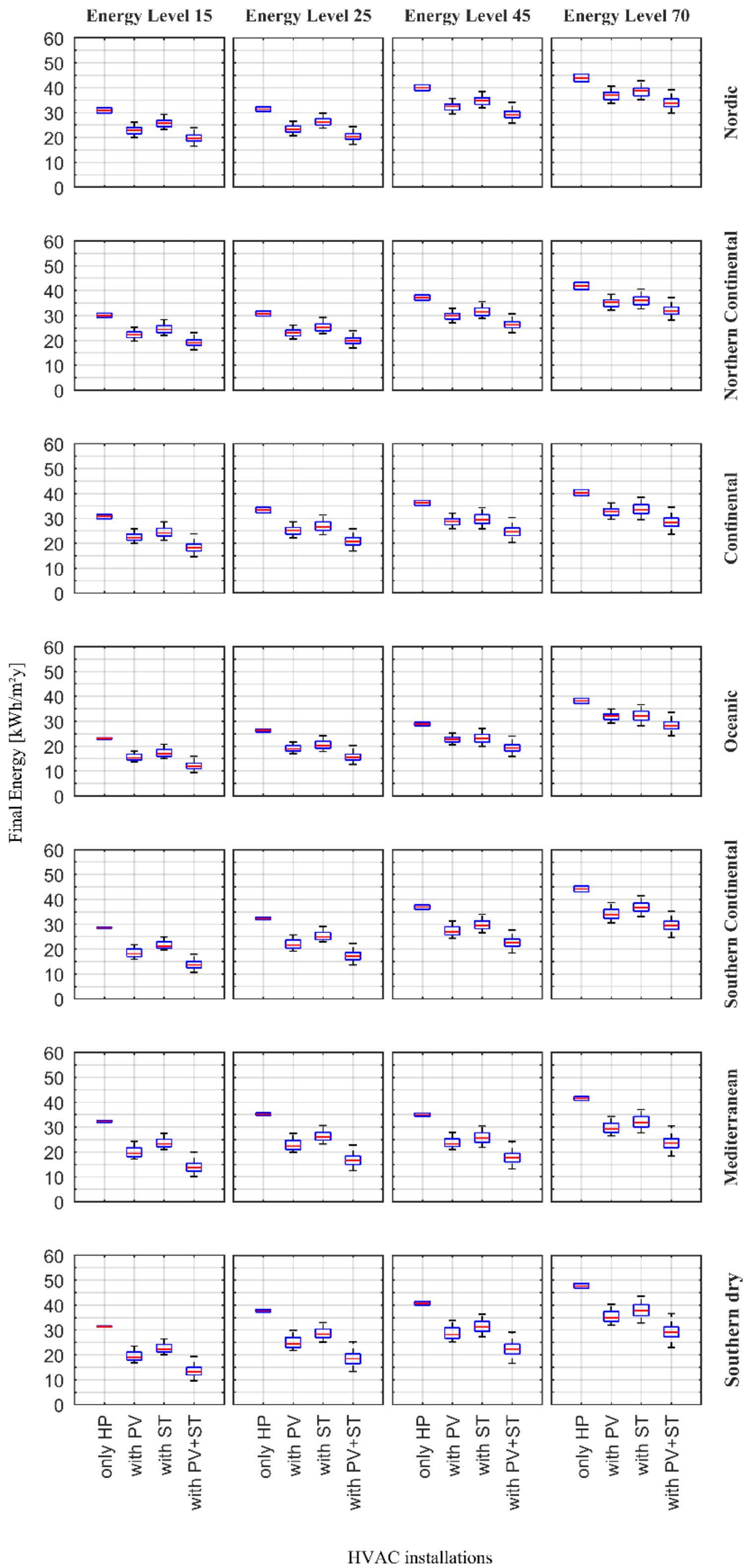

Figure 30 – Total final energy range for different HVAC installation types

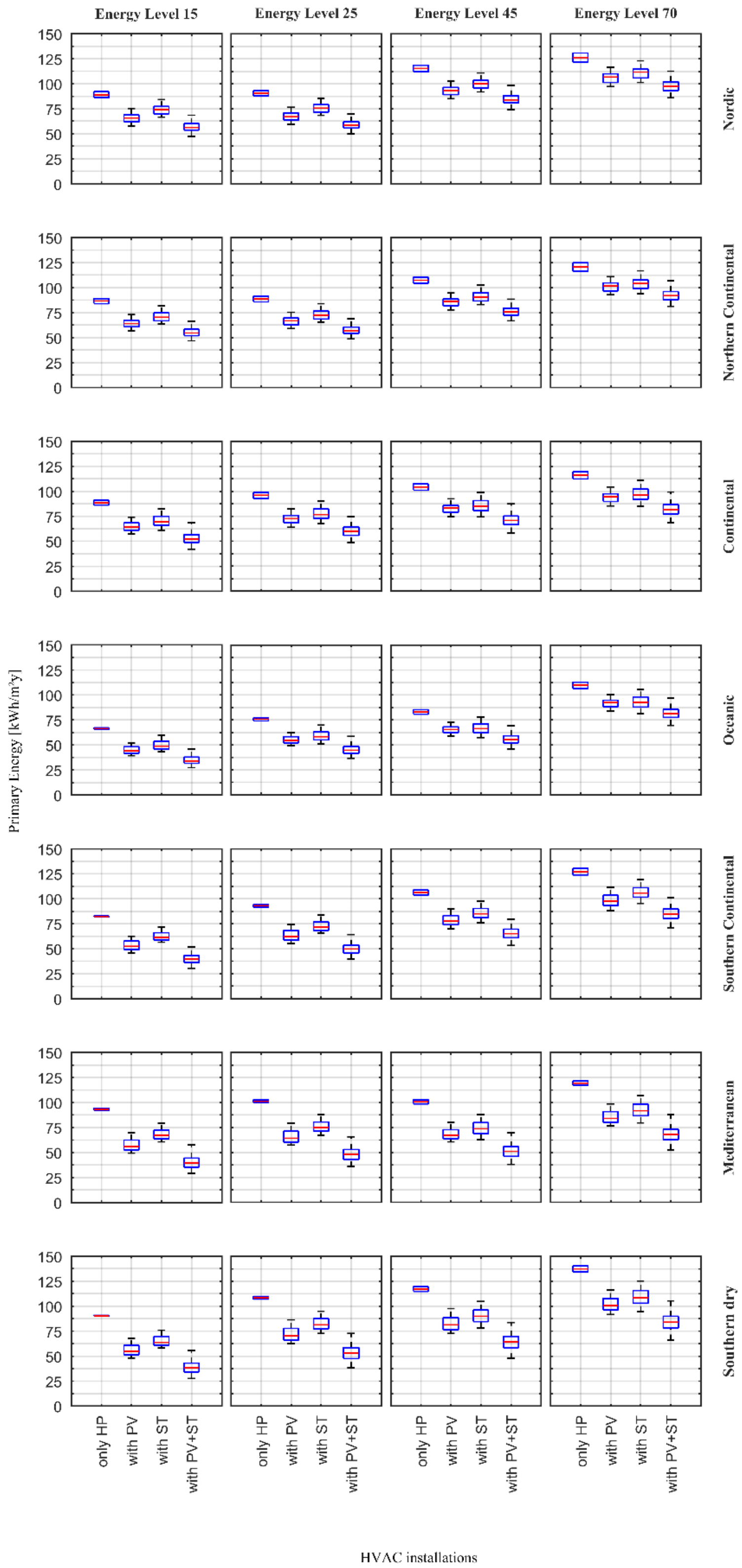

Figure 31 – Total primary energy range for different HVAC installation types

The utilisation of solar energy has comparable effect as for the cases with radiant ceilings (section 2.1), therefore it is not discussed further. However extensive charts are reported in Annex I (section 3.3) and Figure 30 - Figure 31 summarise such effects.

The increase in electricity utilisation poses challenges to reaching the goal of 50 kWh/m²y Primary Energy utilisation. As can be seen, it can only be reached in the three most southern climates and with respect to the two most energy efficient building typologies.

Even though the difference is not very relevant in absolute terms (and the result is somehow biased due to the initial Energy Used which is never exactly equal to the intended demand level, see Figure 26) compared to the cases with radiant ceilings, this shows how details, like an additional electric consumption due to fans, plays a relevant role when such a challenging objective of 50 kWh/m²y of PE is pursued.

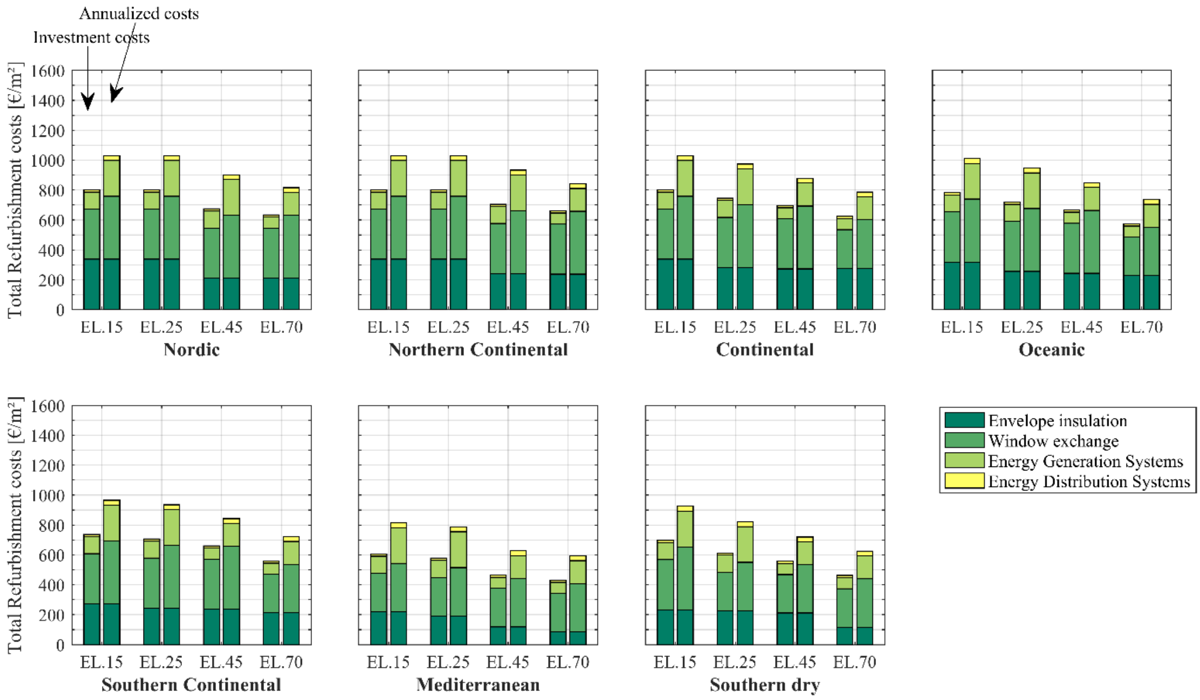

Figure 32 – Investment costs distribution (first year investment and annualized costs over 30 years) without solar systems (35 °C water distribution temperature)

2.4.4 Economic evaluations

Figure 32 shows investment costs per unit living surface area, both initial and annualised. Again, envelope initial expenditures (insulation and windows) are larger than for generation and distribution systems. In these cases, investment costs for distribution systems are slightly higher than for radiant ceilings due to the need of electric connections installed for each fan coils.

Still this contribution is quite limited -in between 20 and 40 €/m²- in terms of investment costs. The annualised costs increase considerably as a consequence of the hypothesis that the terminal must be replaced every 15 years (30 - 45 €/m²).

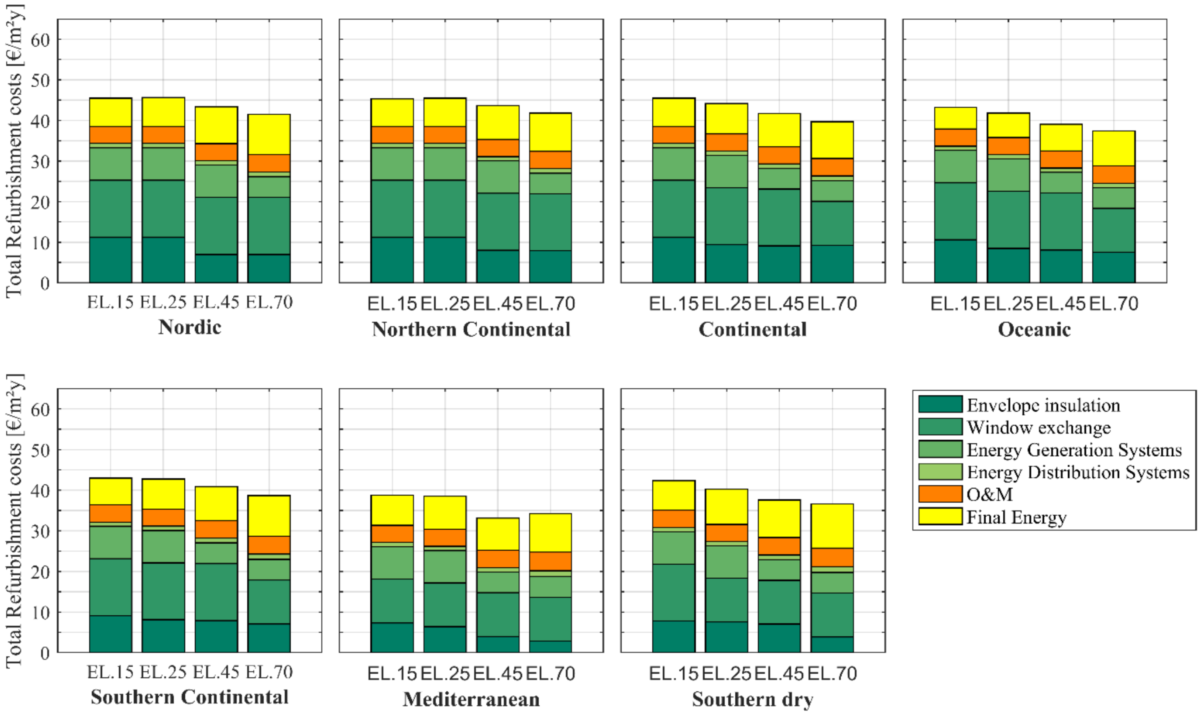

Figure 33 – Yearly annualised costs distribution for variants without solar systems

2.5 Ground Source Heat Pump with Fan Coils

The information highlighted in this section is reported for sake of completeness, since the results differ only by small amounts compared to those described previously.

Figure 34 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.

The values are slightly lower compared to the air source heat pump case 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 gives small advantages in the northern countries with respect to the winter season, and in the southern ones during summers.

Comparing this case to the one with ground source heat pump and radiant ceilings, Figure 34 indicates higher electricity consumed both for space heating and cooling in the range of 2 to 6 kWh/m^{2}y (around 10% more) due mainly to fan coils, while the electricity used at the heat pump is almost unaffected.

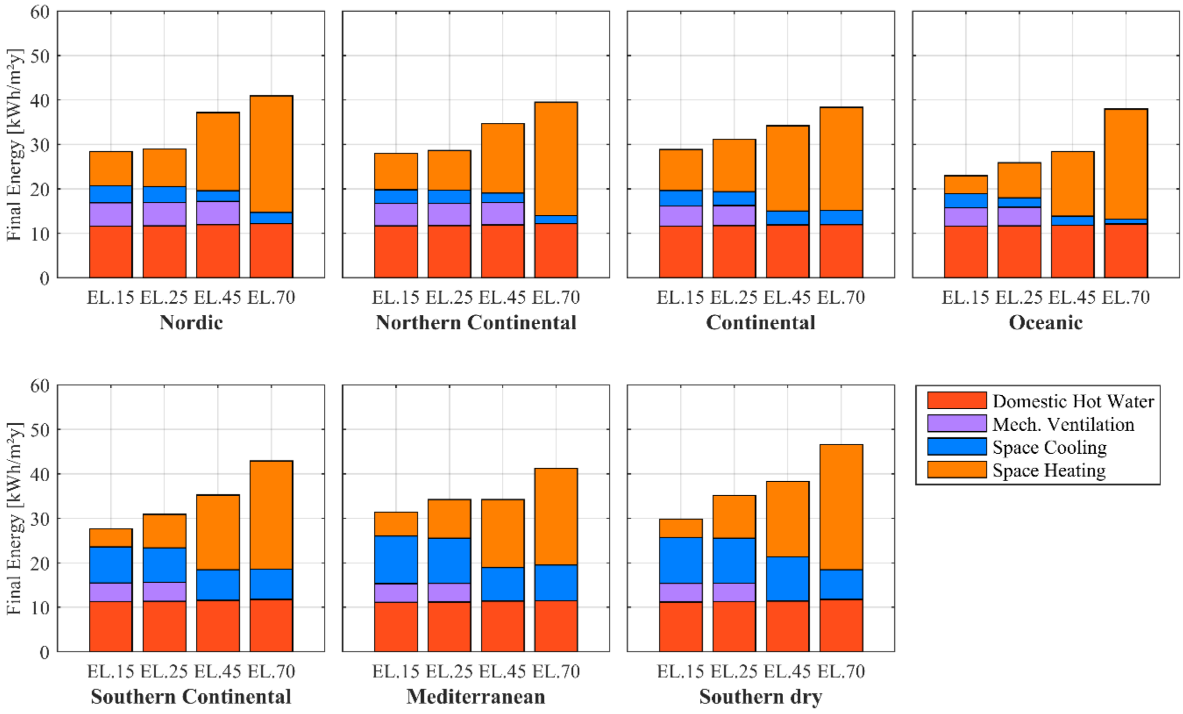

Figure 34 - Final energy distribution without solar systems and a heating water temperature level of 35°C.

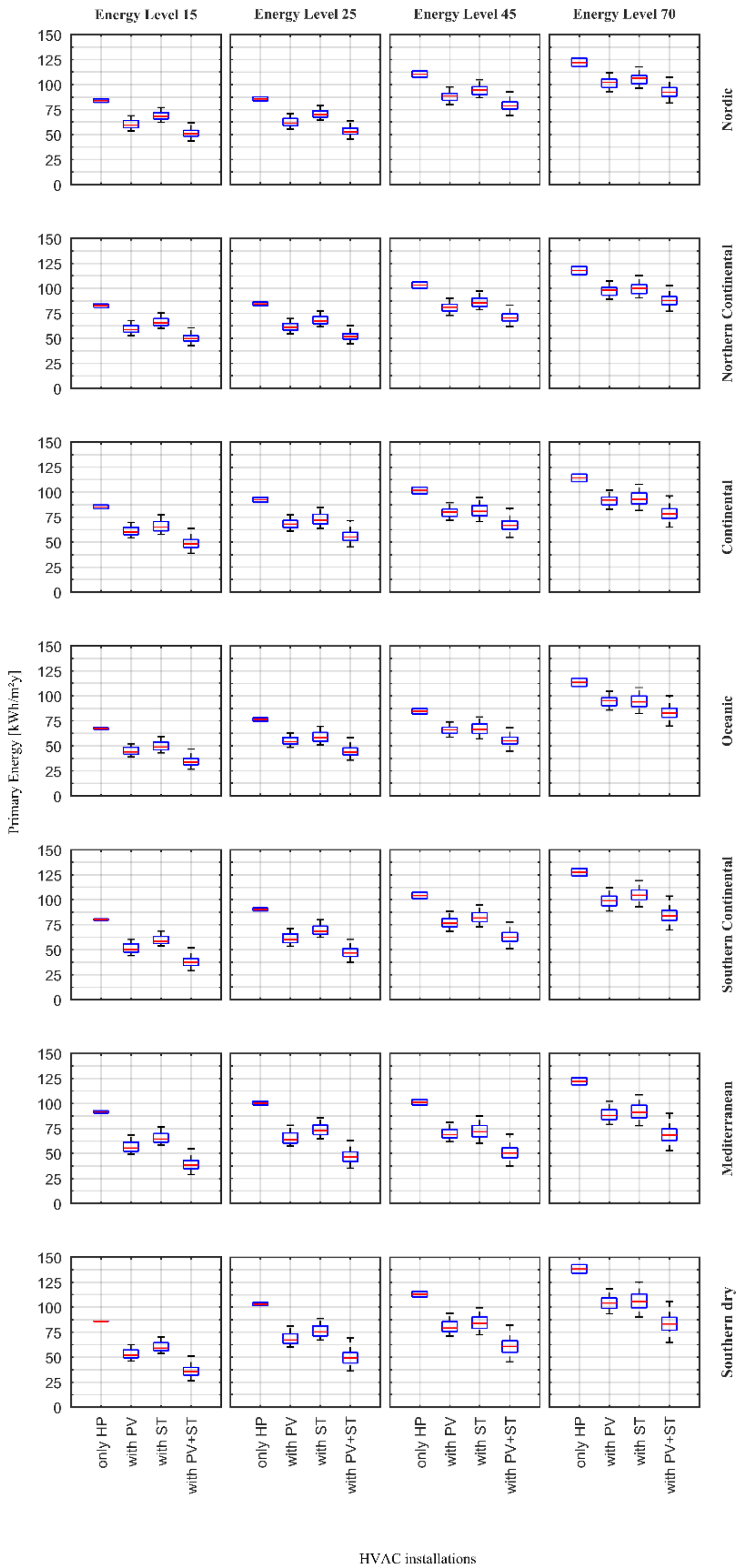

Figure 35 – Total primary energy range for different HVAC installation types

The overall SPF accounting for heating, cooling, DHW loads and ventilation varies in a range of 1.6 and 2.6, again the lower values being related to the highest envelope efficiency standards.

SPF levels higher than 3 can be obtained for space heating and DHW preparation by using solar energy, the effect of solar thermal energy utilisation being larger in all climates, due to the direct reduction of the load - DHW preparation - with lowest SPF associated (Figure 85). The highest effects are encountered with respect to the southern countries and the low space heating demand cases (15 and 25 kWh/m^{2}y), where SPFs higher than 4 can be easily reached. In fact, in these cases, solar thermal systems can contribute strongly to both DHW preparation and space heating (Figure 61).

The reduction of PE consumption with respect to the air to water HP is in the range of 2 to 5 kWh/m^{2}y, while fan coils electricity use produces a small increment with respect to the case with radiant ceilings (section 2.2): 5 to 15 kWh/m^{2}y.

2.6 Gas and Pellet Boilers with Fan Coils

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

2.7 Air Source Heat Pump with Radiators

For the results presented here, the radiators have been simulated twice for the same case, once with a design supply temperature of 35 °C and once with 45 °C, with relevant sizes. Thus, there are two points for each combination of climate and energy level.

Such low temperatures are selected in relation to a high-efficient radiator type and to low heating loads encountered with respect to the heating demand levels analysed. Higher distribution temperatures would hinder an effective operation of the heat pump considered.

2.7.1 Used Energy

Figure 36 shows Used Energy for both heating and cooling for the range of climates.

As with fan coils, with radiators it is possible to reach the 70 kWh/m^{2}y level in all cases. The convective to radiative contribution ratio is again set to 70-30% allowing for a precise control of the indoor "convective" air temperature. Operative temperatures are in the same range as the convective ones, thus the perceived temperature and the comfort is lower compared to the cases with radiant ceilings.

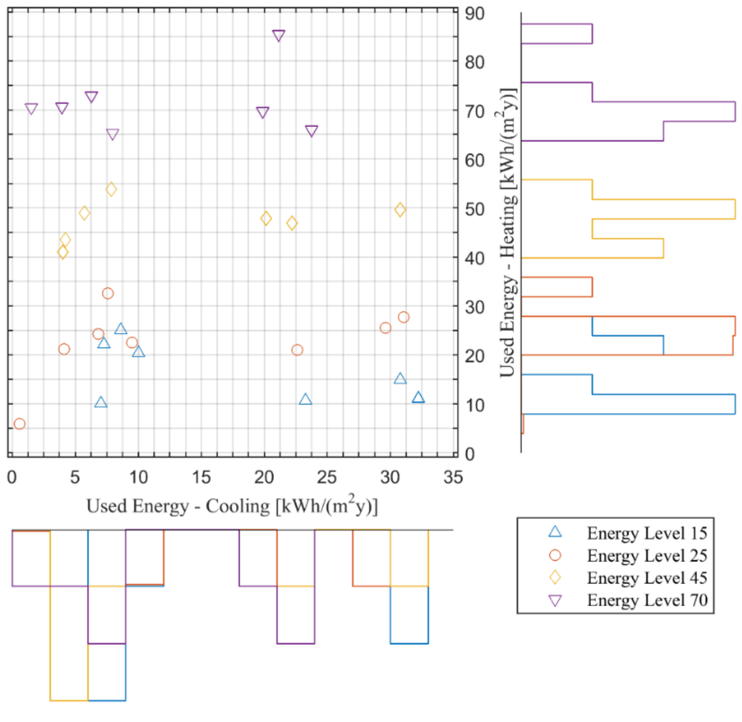

Figure 36 – Used Energy for heating and cooling of the different energy standard

With respect to cooling, split units operate as fan coils in terms of latent and sensible heat treatment, therefore we encountered the same ranges of Used Energy for Cooling.

The two storeys of the SFH have a cooling load between 0.3 and 1.7 kW each, in most cases. However, the smallest split units on the market have a nominal cooling power not going below 2.5 kW (around 8000 Btu/hr). In order to simulate realistic HVAC installation, we consider one unit installed on each floor.

2.7.2 Thermal Comfort

As a consequence of this decision, the cooling distribution system is oversized, leading to an excellent summer thermal comfort.

The heating penalties reach a maximum of 0.4% with respect to the heating demand, while values around 2% are obtained in some sporadic cases, which account for cooling loads at the second floor slightly higher than 2.5 kW.

Therefore, the thermal comfort over the whole year for this HVAC configuration reached very high levels in all climates analysed.

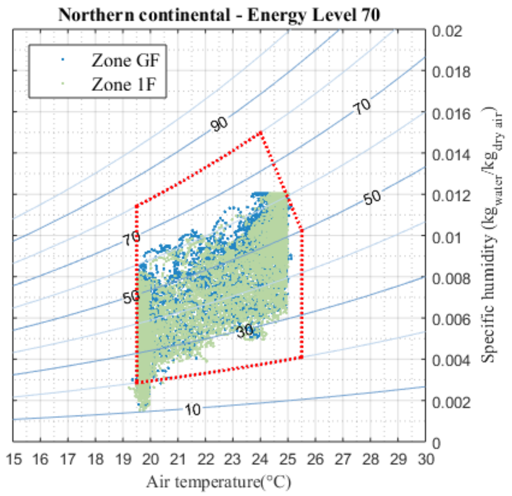

Figure 37 – Psychometric charts of {Northern Continental, Energy Level 70} with heating temperature of 35°C

2.7.3 Final Energy, SPF and Primary Energy

Figure 38 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 once more.

The same trends as in the previous case are demonstrated. The absolute values of final energy for heating are slightly lower than with radiant ceilings due to the reasons reported in 2.7.1.

Looking at a specific distribution temperature (35 °C) for both distribution systems, the radiators allow to save 15-20% of the final energy for heating. However, the radiant ceilings can operate down to 30 °C and the operative temperature is higher than the one produced with radiators.

Without considering solar contributions, the SPF of the heating system varies around 3 in the northern countries and 3.5 in the southern.

As already noticed, final energy uses for cooling purposes has a minor effect on the absolute electricity consumption (1 - 6 kWh/m^{2}y) due to the high effectiveness of the split units considered and to the low overall cooling demands encountered in our climates.

The total final energy demand fluctuates between about 20 and 40 kWh/m^{2}y for most cases and applications studied.

The overall SPF (H&C and mechanical ventilation) varies between 2.5 and 3.4 in the southern countries and between 1.9 and 3.0 in the Nordic climate.

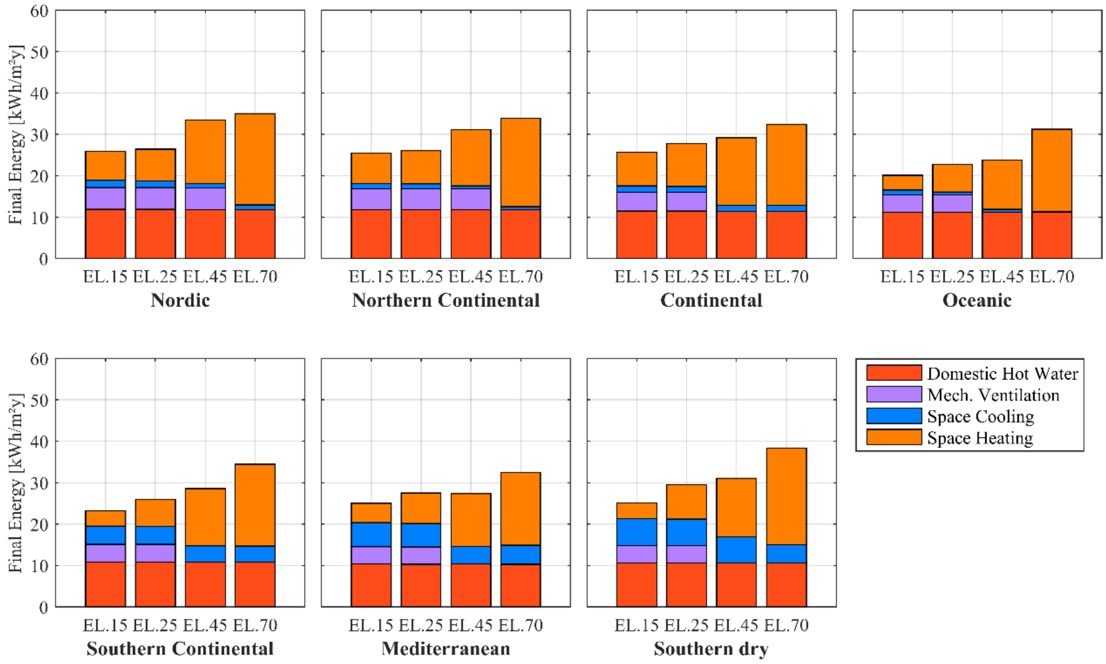

Figure 38 – Final energy distribution without solar systems and a heating water temperature level of 35°C.

The water distribution temperature plays a role on the final energy utilisation in the cases analysed (35 – 45°C), having an impact only on the winter operation. The specific thermal power delivered by the radiator increases by more than a factor 2, from around 350 W/m^2 to 750 W/m^2 (of frontal area of the radiator) when changing the temperature from 35 to 45 °C. At the same time, SPF related to space heating decreases from levels ranging around 2.9 - 3.4 to 2.4–3.0, and final energy (as much as primary energy) increases 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.

Despite the slightly lower final energy consumption, with a CED_{NRE} of around 2.9 (see chapter 2, electricity), none of these solutions is sufficient to achieve a Primary Energy consumption of the whole building below 50 kWh/m^{2}y.

Combinations of solar thermal and/or PV electricity generation make it possible to reach the goal in most cases.

In Northern continental and continental climates, only the combination of solar thermal and photovoltaic panels with large surfaces (14 and 24 m^2 respectively, for instance) for refurbished buildings with a specific heating demand below 25 kWh/m^{2}y can achieve this target.

In the other climates, a building refurbished to Energy Level 45 with well-sized solar thermal or photovoltaic panels is sufficient.

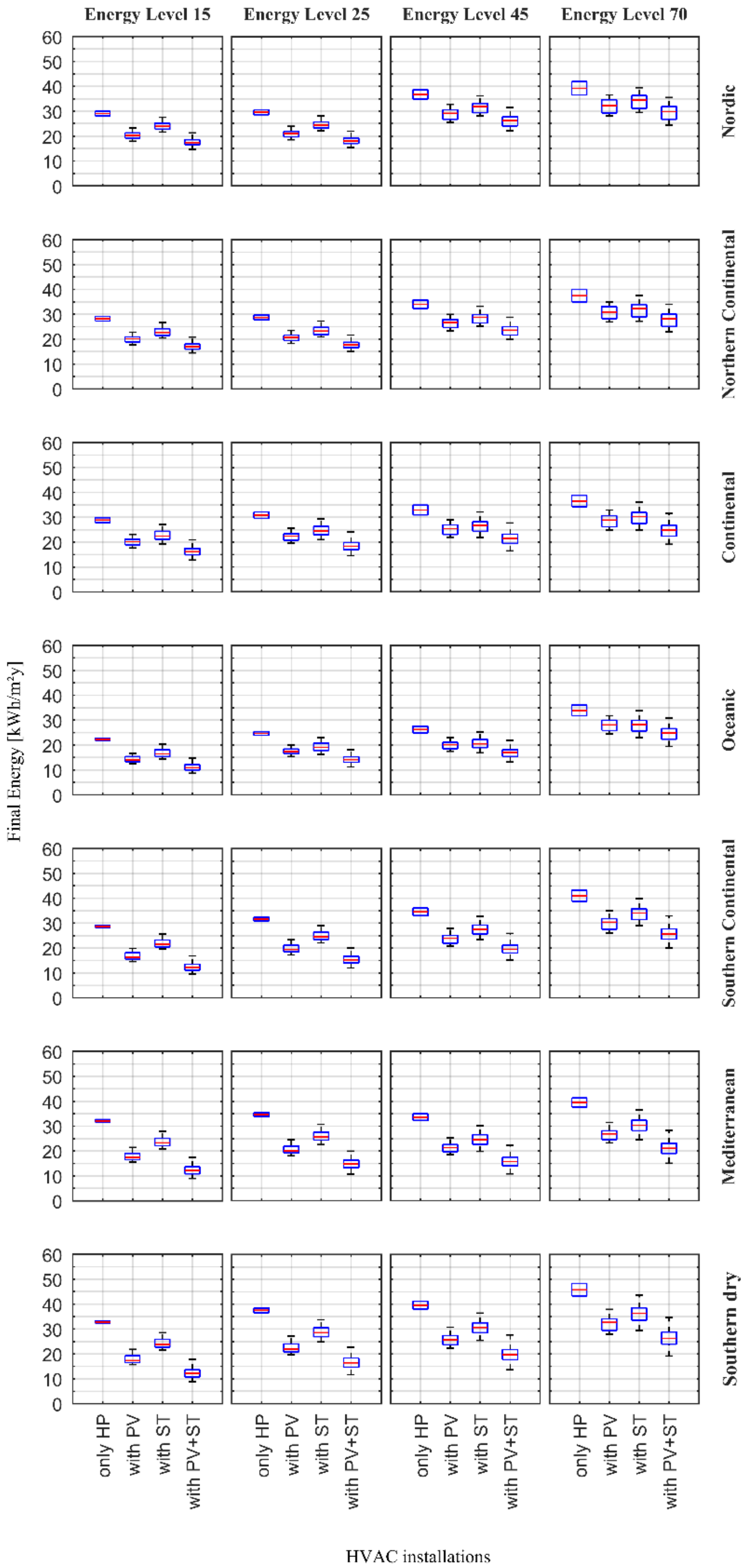

Figure 39 – Total final energy range for different HVAC installation types with solar variants

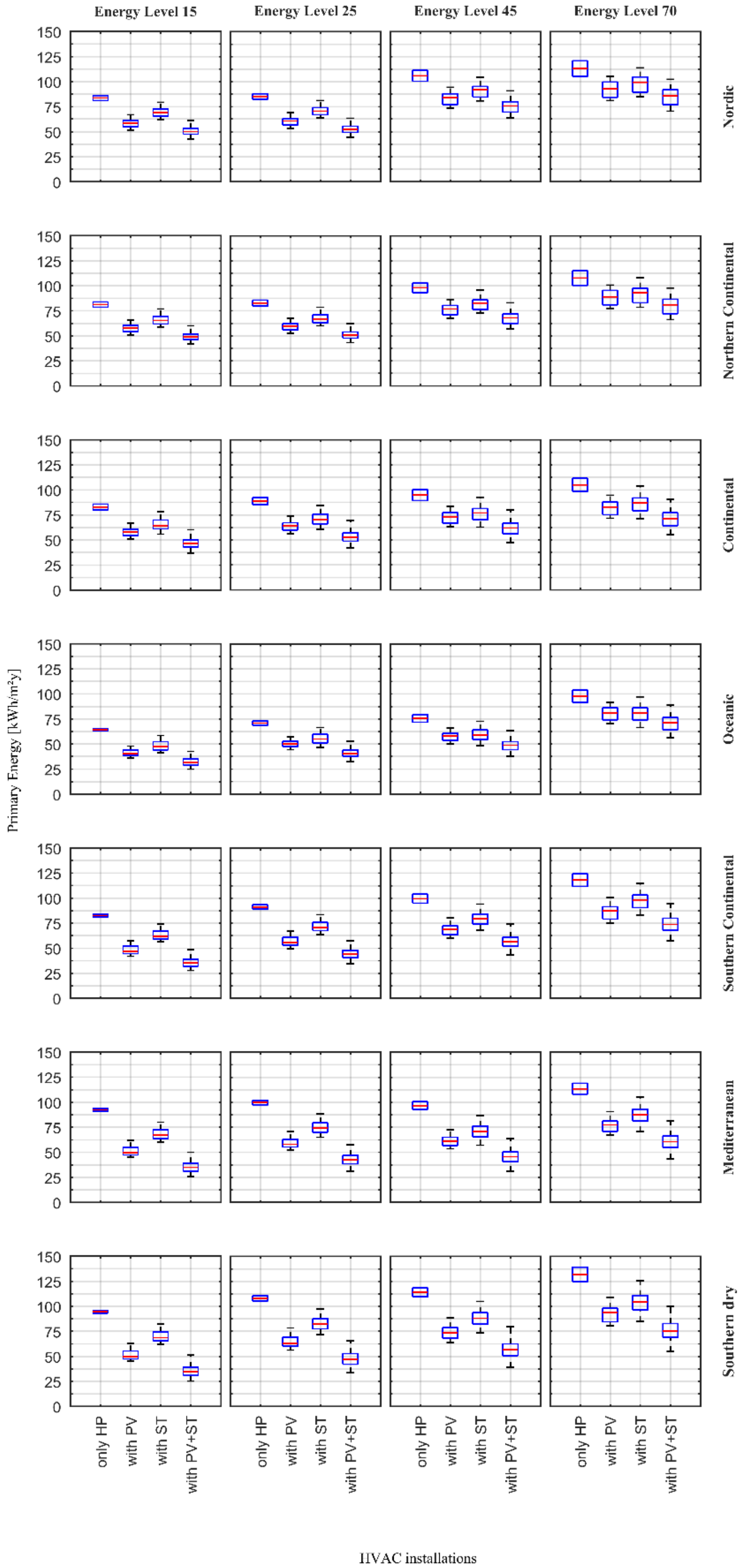

Figure 40 – Total primary energy range for different HVAC installation types with solar variants

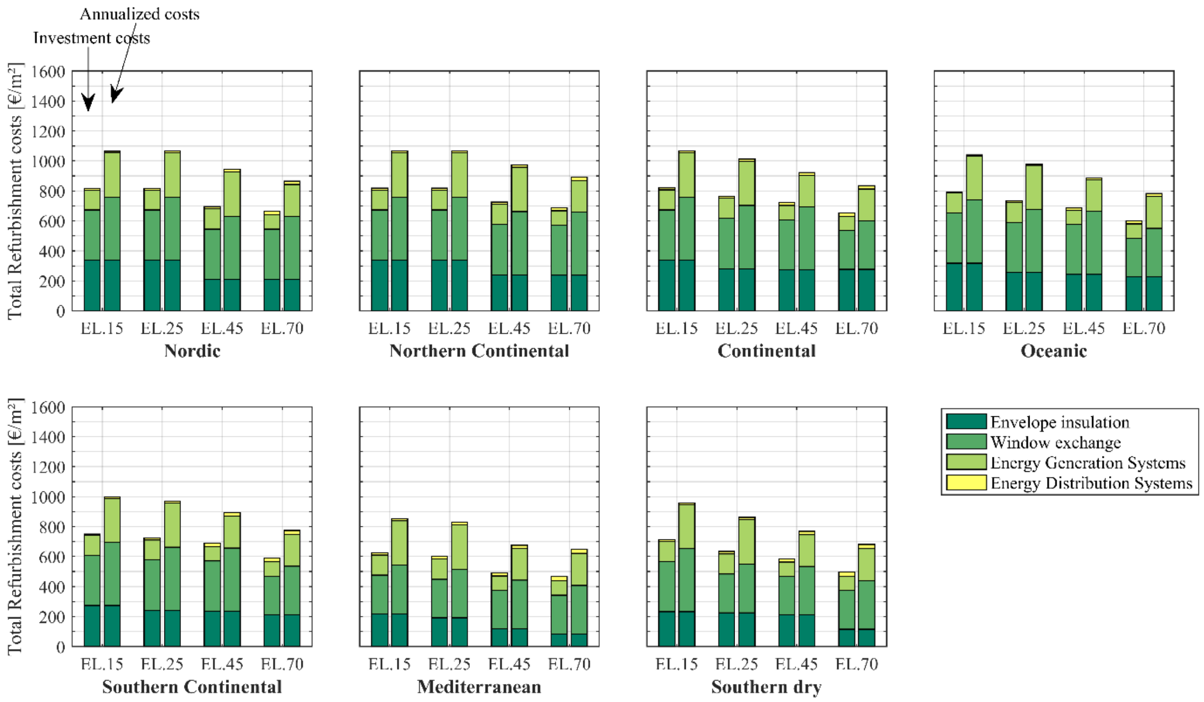

Figure 41 – Investment costs distribution (first year investment and annualized costs) without solar systems (35 °C water distribution temperature)

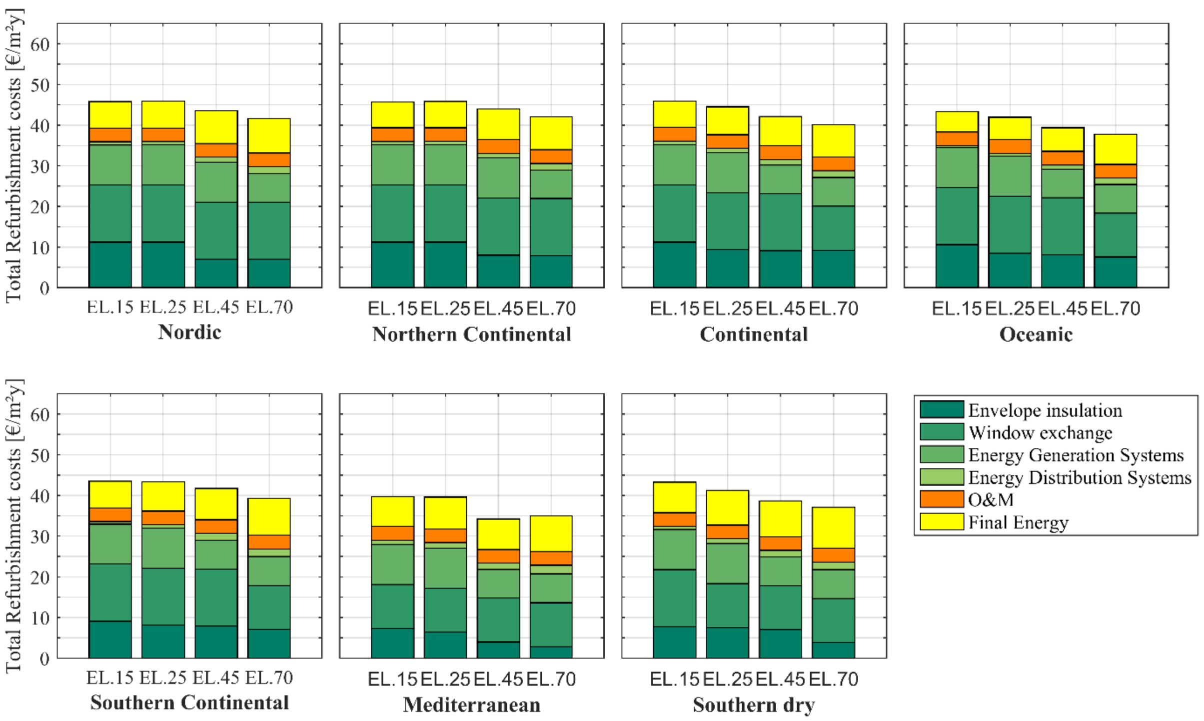

Figure 42 - Yearly annualised costs distribution for variants without solar systems

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 350-700 €/m^2 and 250-320 €/m^2 are assessed for envelope and generation + distribution solutions respectively.

We obtained annualised investment costs for radiators between 10 and 65 €/m^2. Moreover, split units have to be used to deliver cooling during summertime. The costs of the split units are accounted for in the generation system. Consequently, compared to the case of heat pump with radiant panels, this case has an additional cost of 60 €/m². This is again to be included only when cooling is considered an issue and ventilation cannot reduce cooling loads.

Yearly annualised cost including maintenance and energy costs are slightly higher than the air-to-water case with radiant ceiling in a range between 34 and 46 €/m²/y.

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 43 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. Slightly lower final energy consumption is here reported with respect to the case with radiant ceilings as operative temperatures lower in winter, and higher in summer, are obtained with radiators (see Par. 2.1.1).

Again, SPF figures vary between 3.4 and 3.9 with respect to the heating loads and between 4.9 and 5.8 looking at the cooling loads. Relatively low in all cases are the SPFs related to the DHW preparation that ranges between 1.9 and 2.0. The overall SPF accounting for heating, cooling DHW loads and ventilation varies in a range of 2.2 and 3.4.

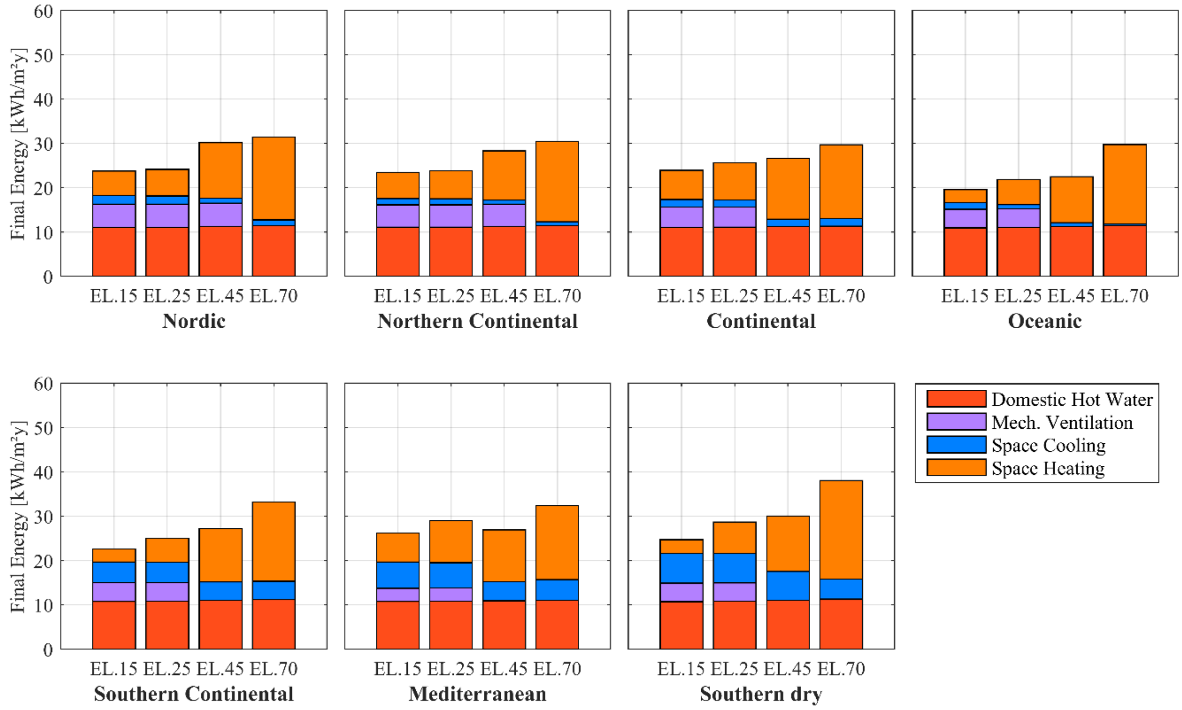

Figure 43 - Final energy distribution without solar systems and a heating water temperature level of 35°C.

The economics are well in line with the results reported in section 2.2, the distribution system costs contributing only marginally.

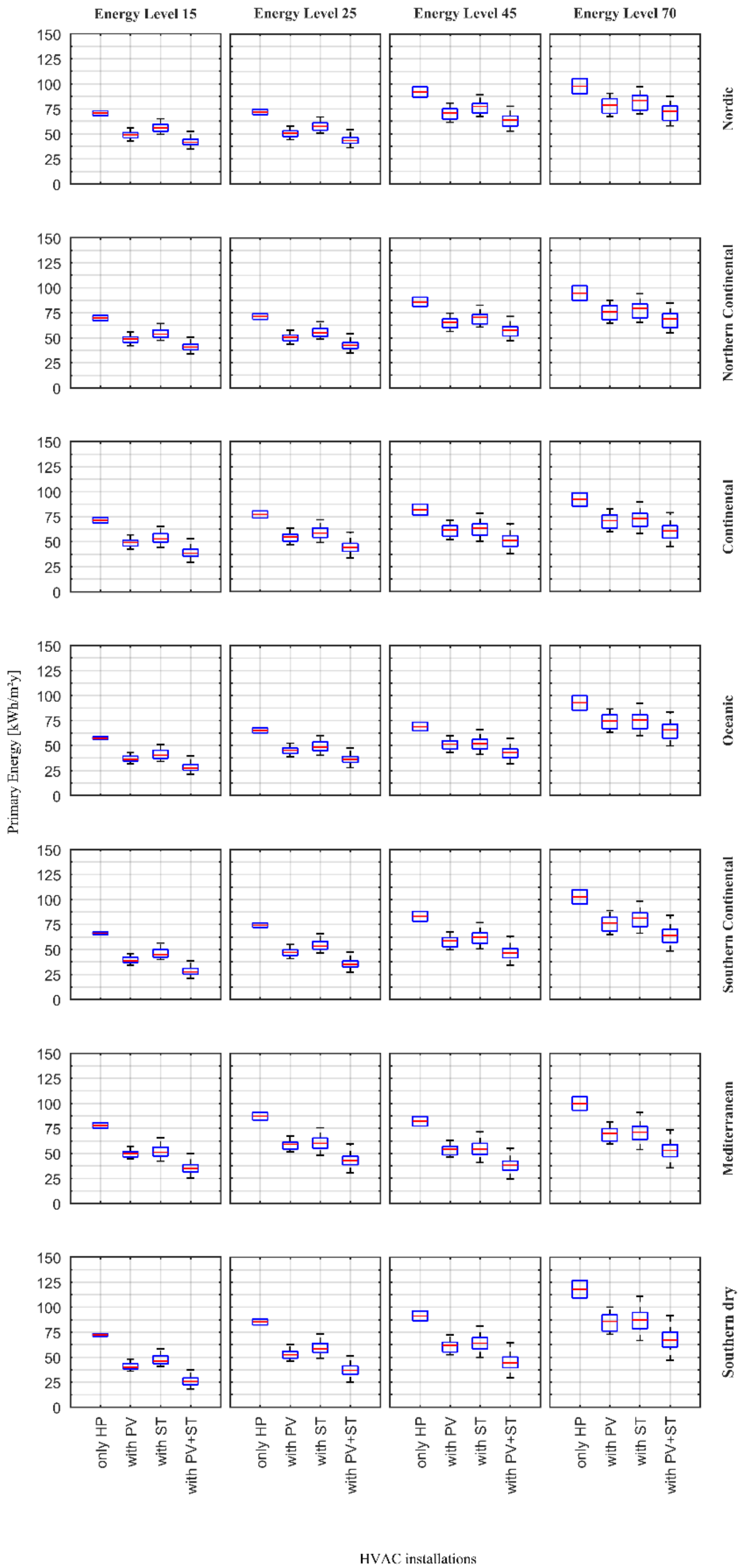

Figure 44 – Total primary energy range for different HVAC installation types

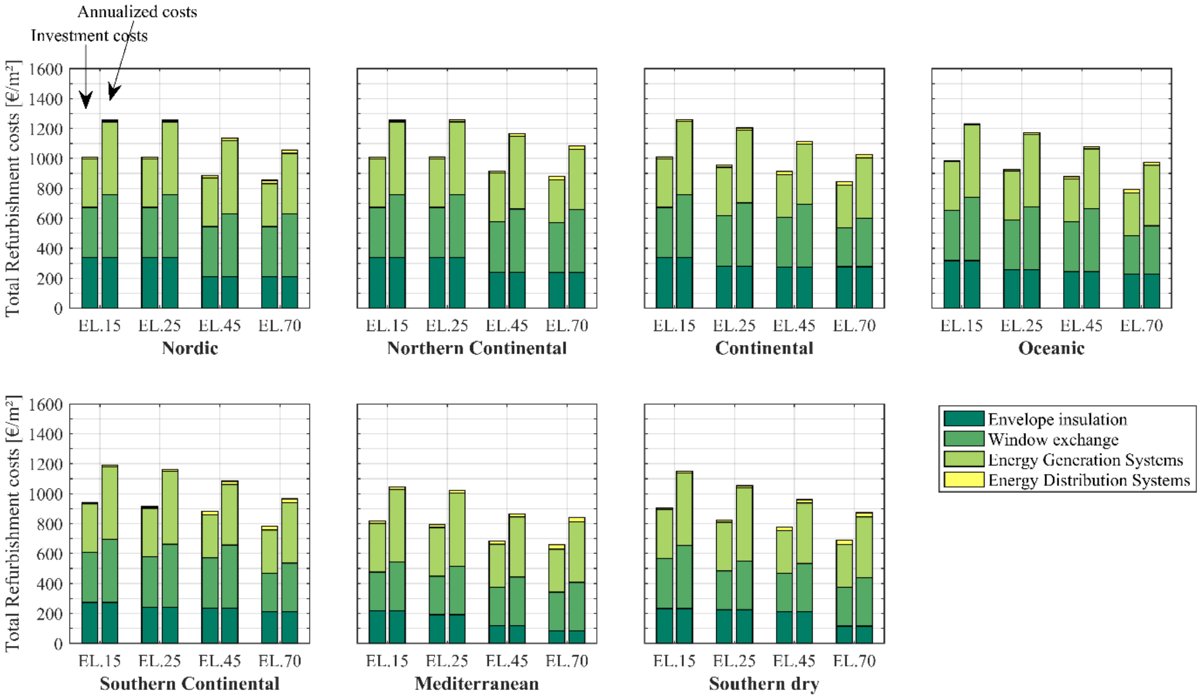

Figure 45 – Investment costs distribution without solar systems (35 °C water distribution temperature)

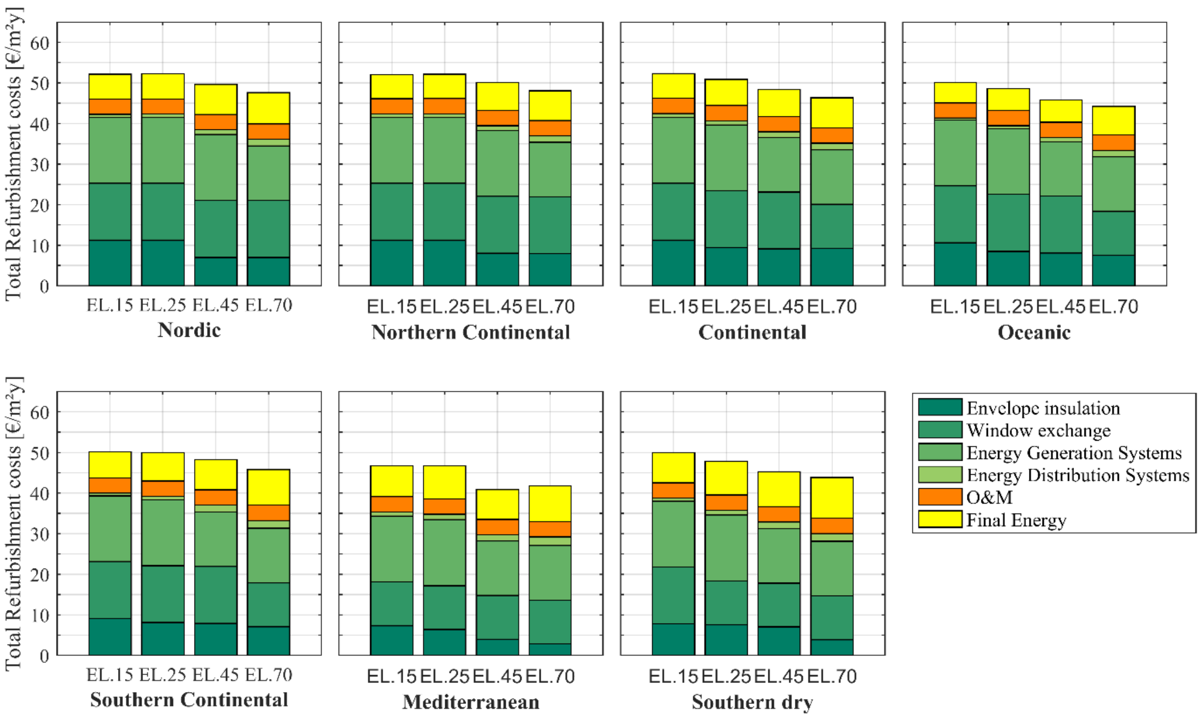

Figure 46 – Yearly annualised costs distribution for variants without solar systems

2.9 Gas and Pellet Boilers with Radiators

The same trends and considerations applies for solutions with radiator as for radiant ceilings (section 2.3), being the boilers' performance independent of the distribution system ones. Therefore, the results are not further discussed in details.

However, we report on some considerations, since this combination of generation and distribution systems are traditionally used in the large majority of the new or refurbished single family houses: solar thermal + condensing boiler is a typical solution in southern countries, while biomass boilers are more common in northern ones.

2.9.1 Gas boiler solutions

Gas boilers hardly allow to reach the 50 kWh/m^{2}y primary energy consumption for any climate or Energy Level, even with solar technologies added. The primary energy reduction with solar thermal solutions is around 25 kWh/m^{2}y if we take into consideration the best Energy Levels (15 kWh/m^{2}y space heating demand).The reduction is even more significant (around 55 kWh/m^{2}y) when the 70 kWh/m^{2}y space heating demand cases are considered.

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 point of view of the energy bill, 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 between 750 and 1700 €/y versus 500 to 1100 €/y in case an air-to-water heat pump with radiant ceiling plant is used.

The overall annualised costs of air-to-water heat pump systems with radiant ceilings are lower than for all other combinations taken into consideration, and especially so compared to the system with gas boilers: 40 – 50 €/m2y versus 33 – 43 €/m2y (solar technologies are not taken into account in this computation).

2.9.1 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 (non-renewable) primary energy use. Primary energy values of about 40 - 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 other hand, solar technologies are not necessary with this combination to reach the primary energy target of 50 kWh/m^{2}y.

The total annualised costs of the pellet boiler solutions are in the range of 10% higher with respect to the other combinations taken into consideration, ranging in between 44 and 56 €/m^{2}y. For specific primary energy level reached, the costs would be comparable.

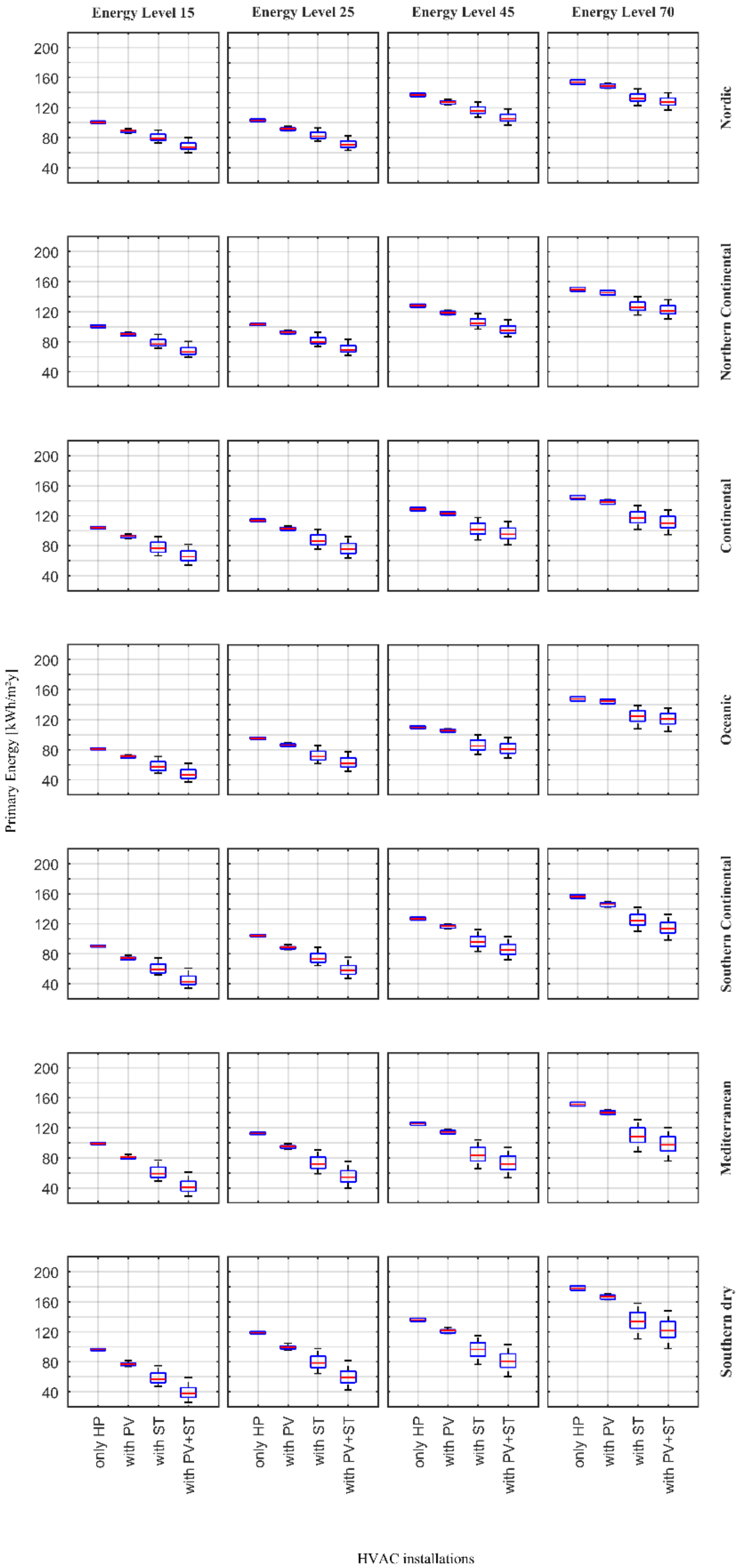

Figure 47 - Total primary energy for different HVAC installation types – gas boiler

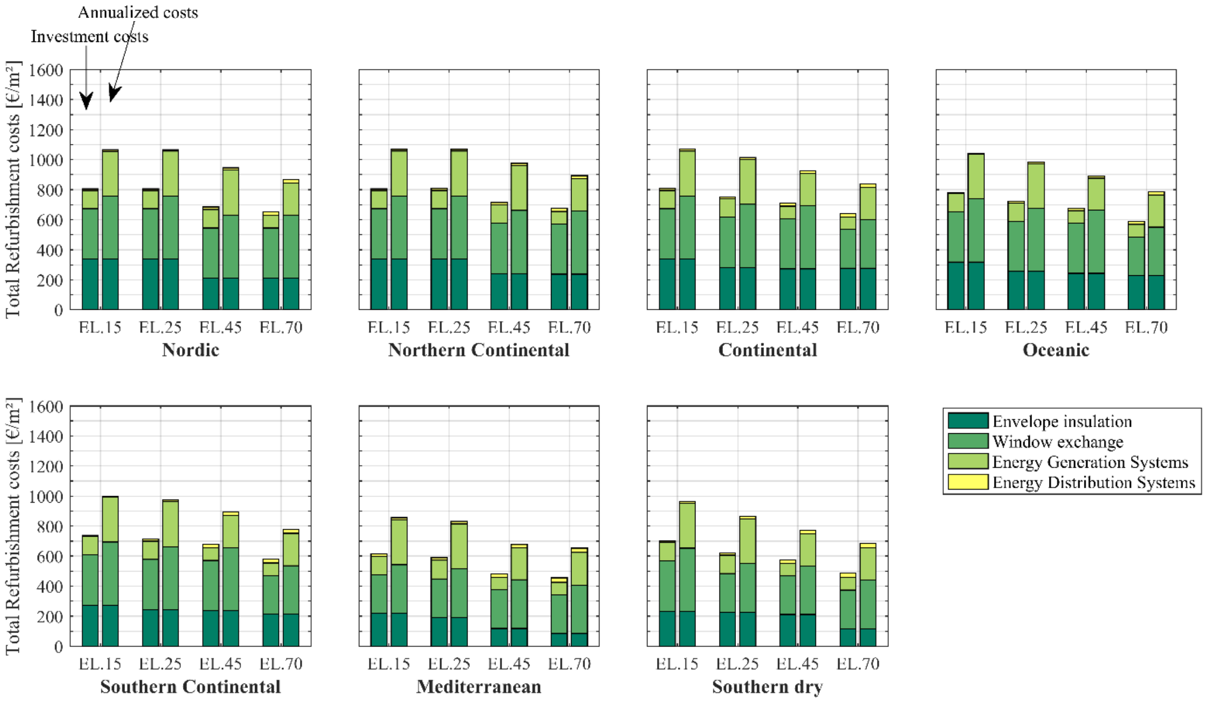

Figure 48 - Investment costs distribution without solar systems (35 °C water distribution temperature) – gas boiler

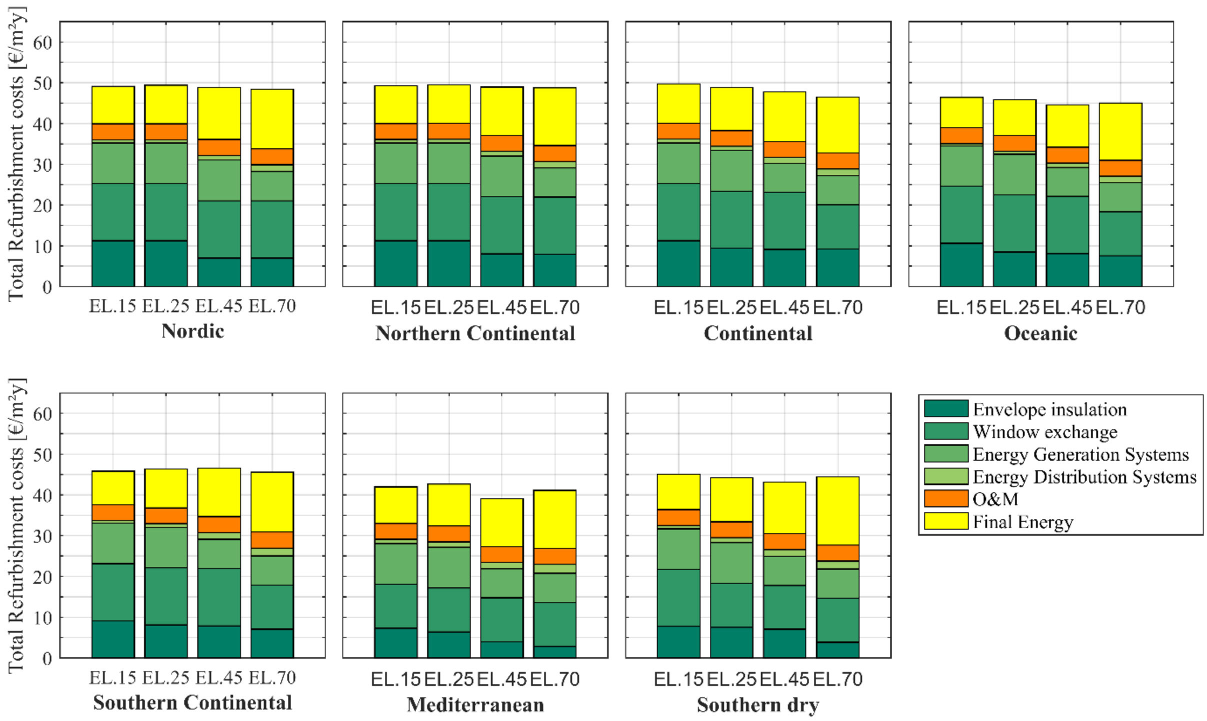

Figure 49 - Yearly annualised costs distribution for variants without solar systems – gas boiler

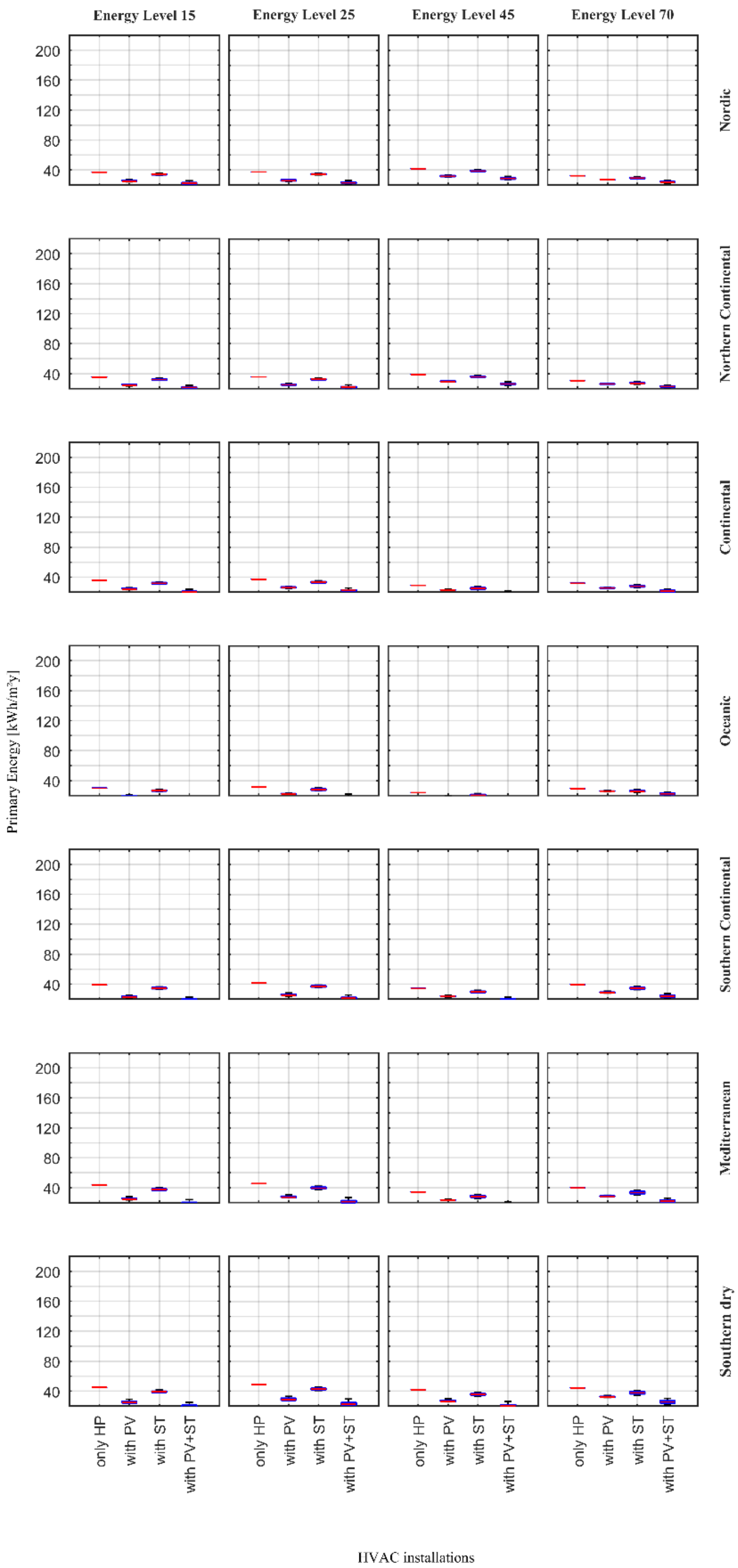

Figure 50 - Total primary energy for different HVAC installation types – pellet boiler

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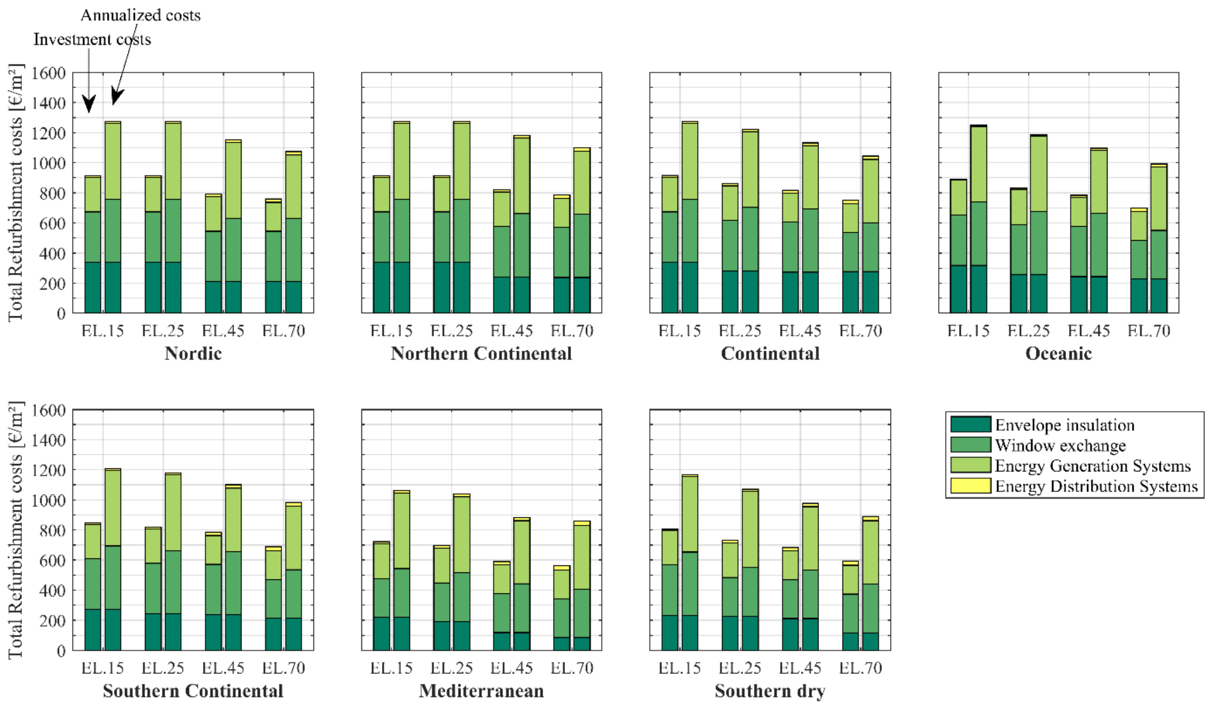

Figure 51 - Investment costs distribution without solar systems (35 °C water distribution temperature) – pellet boiler

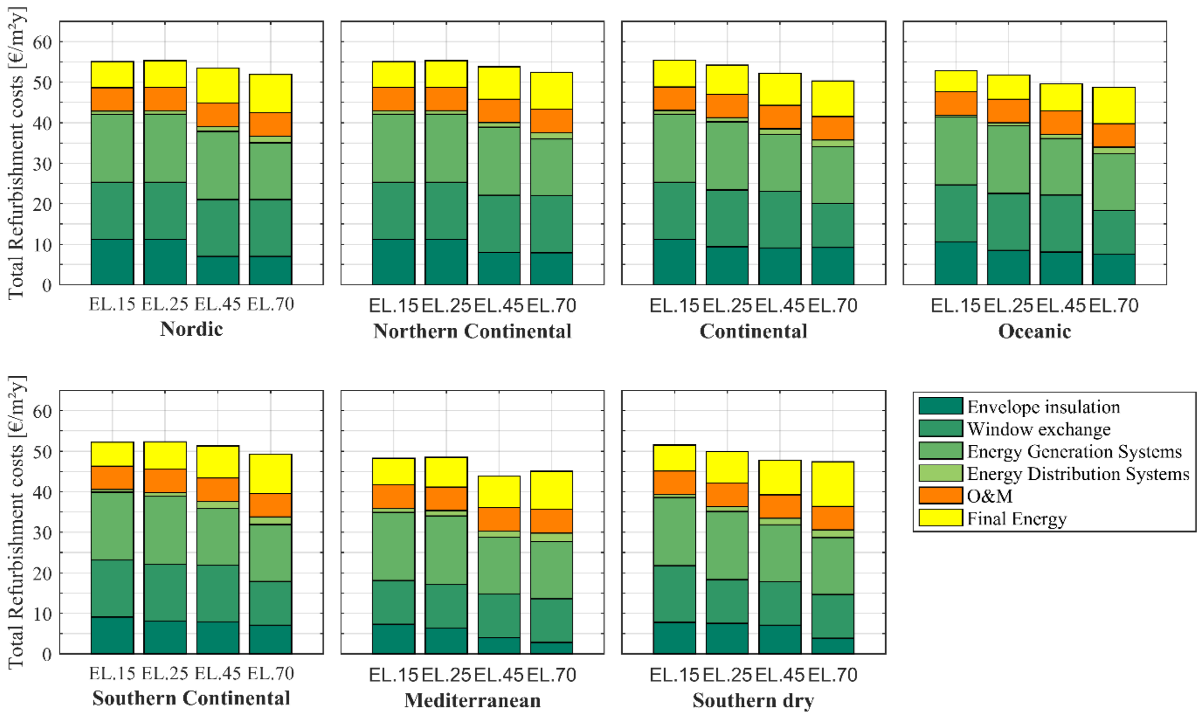

Figure 52 - Yearly annualised costs distribution for variants without solar systems – pellet boiler

3 Annex I - Simulation results

3.1 Single Family Houses - Air to water heat pump + radiant ceilings

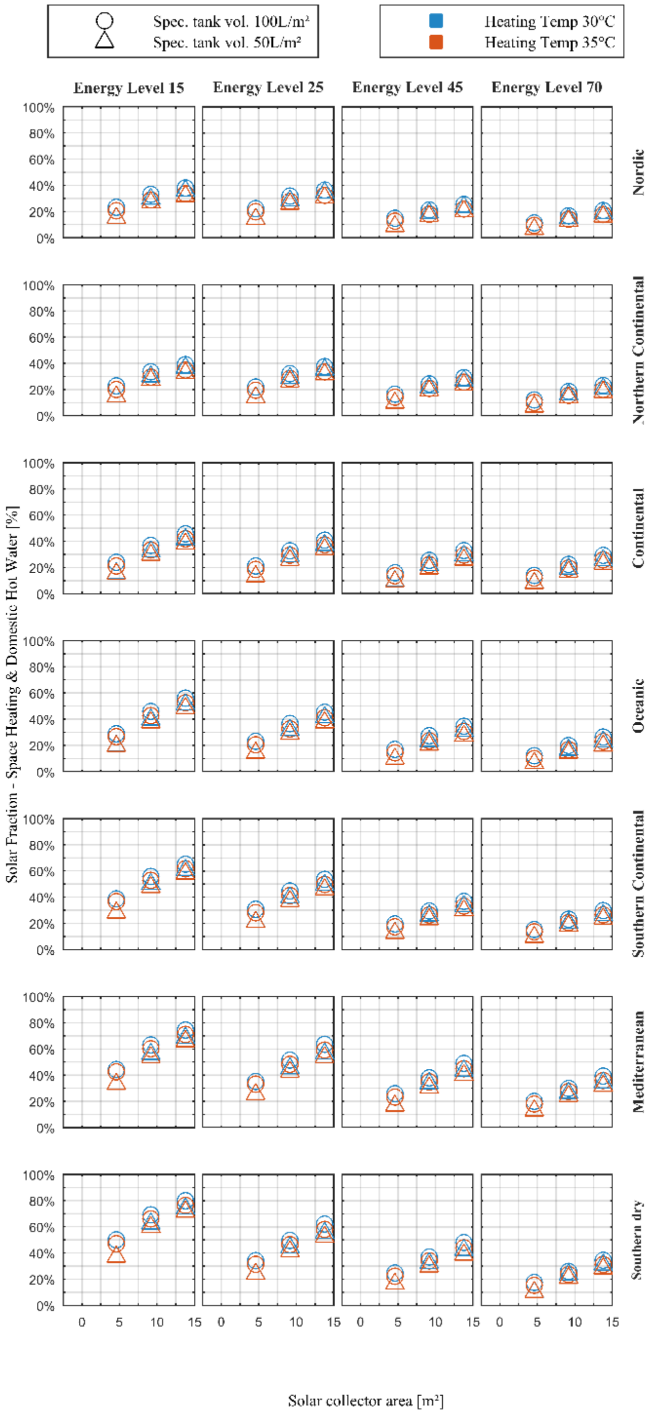

Figure 53 – Solar fraction for heating production – 90° collectors' inclination

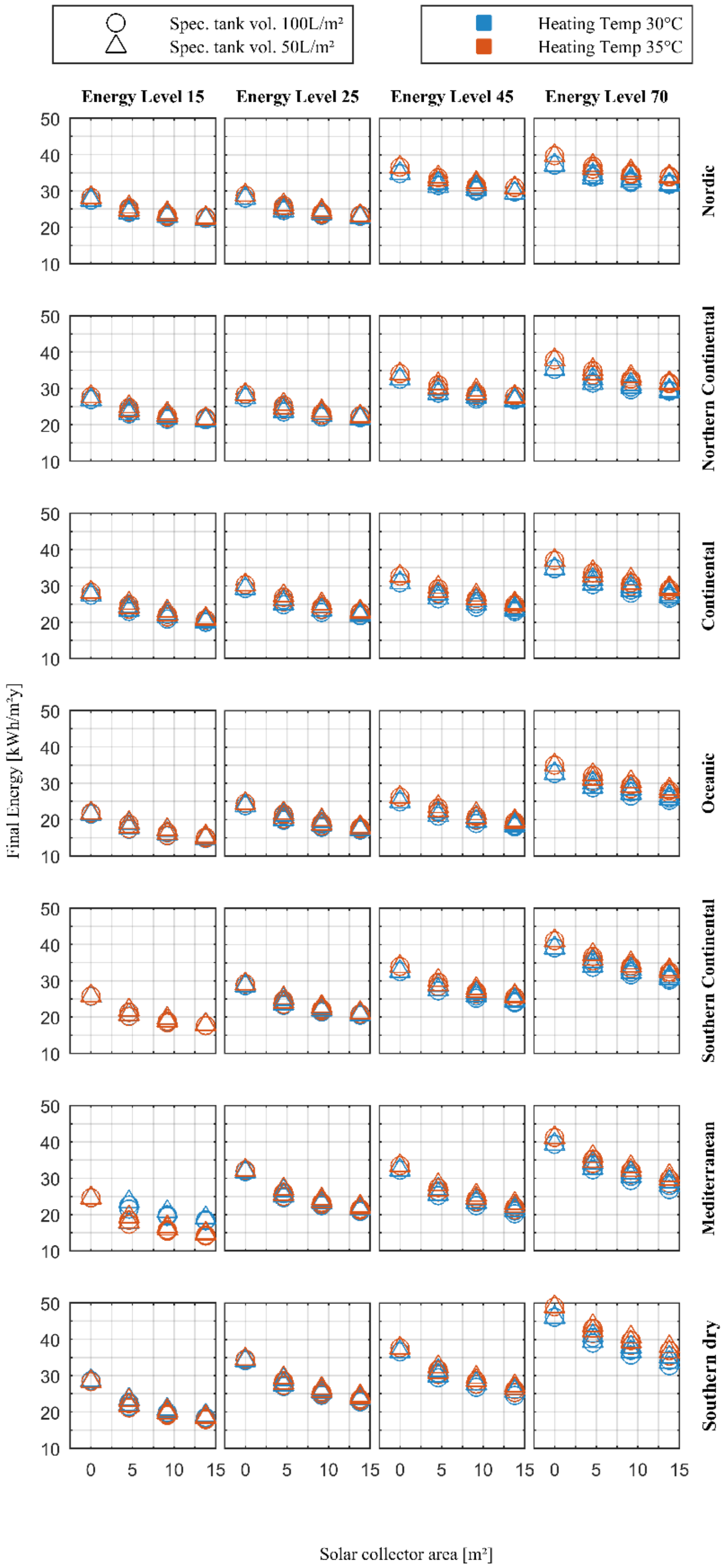

Figure 54 – Total final energy for several variants air-source heat pump and solar thermal system

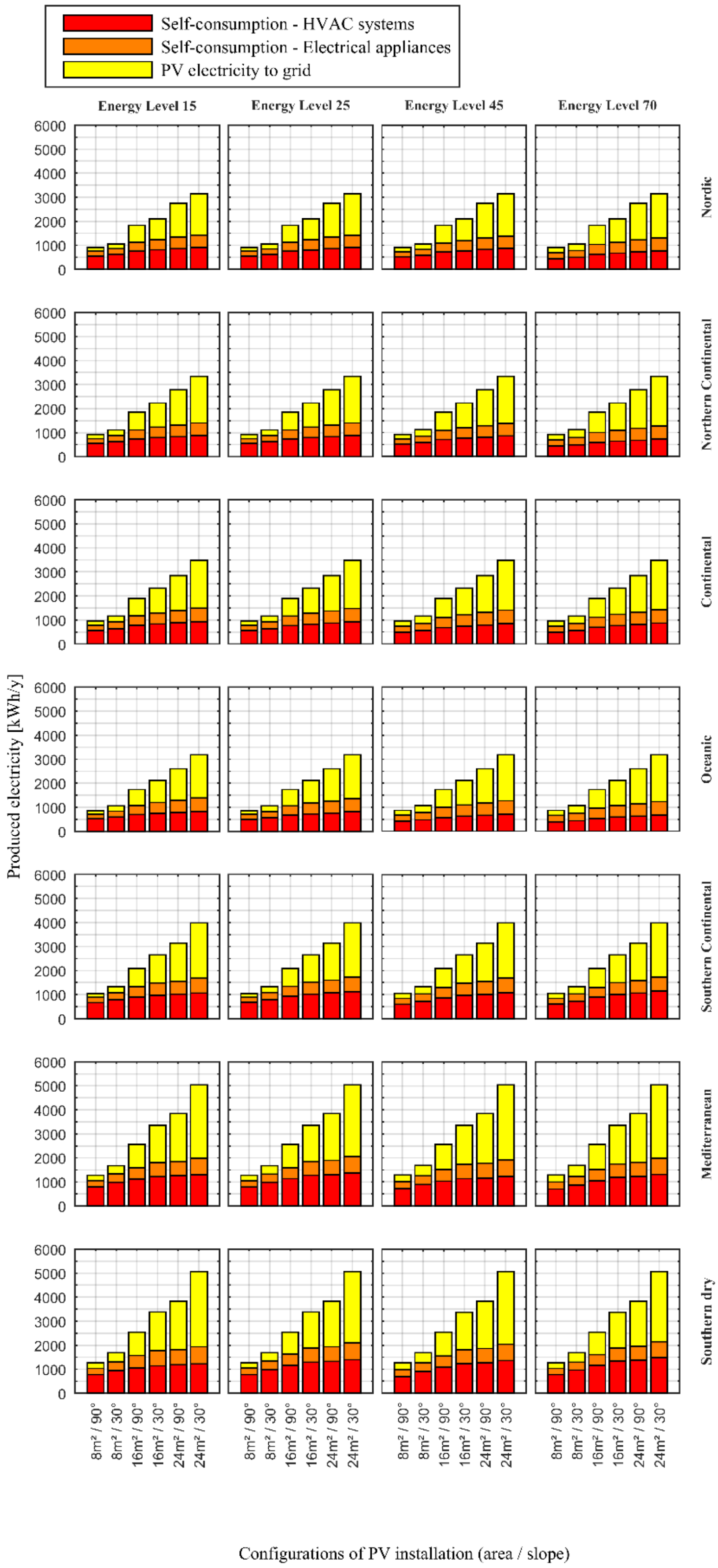

Figure 55 – Photovoltaic electricity

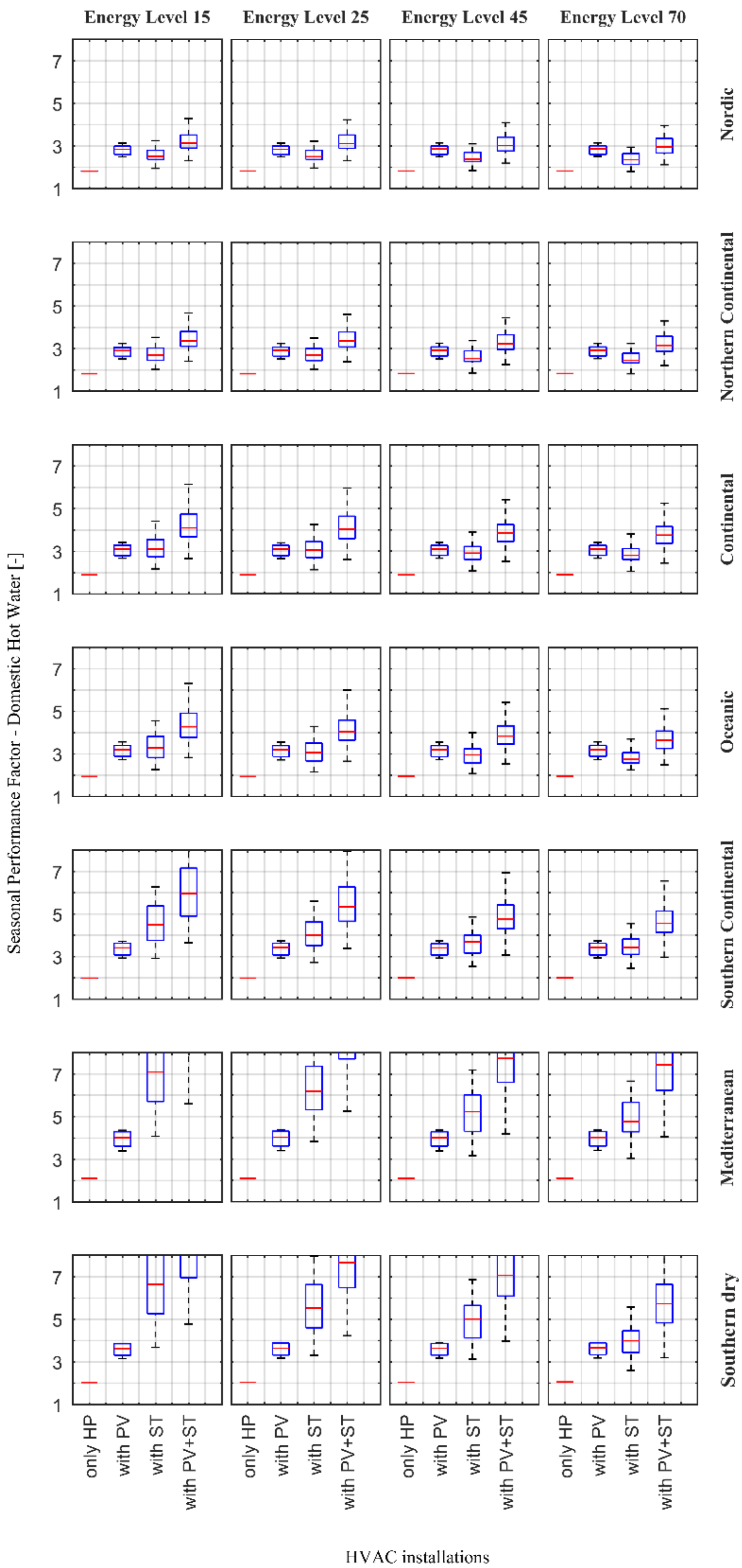

Figure 56 – Seasonal Performance Factor for Domestic Hot Water

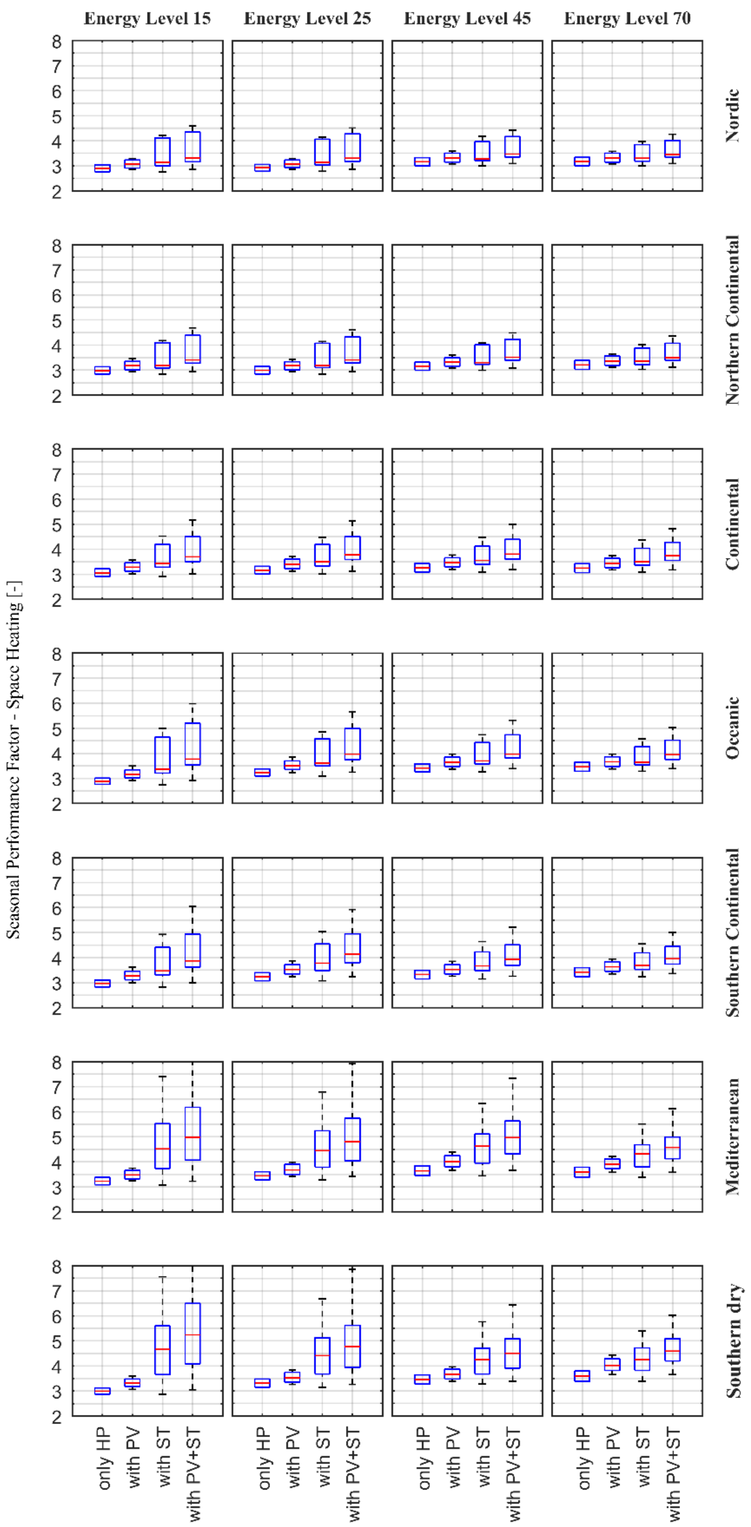

Figure 57 – Seasonal Performance Factor for Space Heating

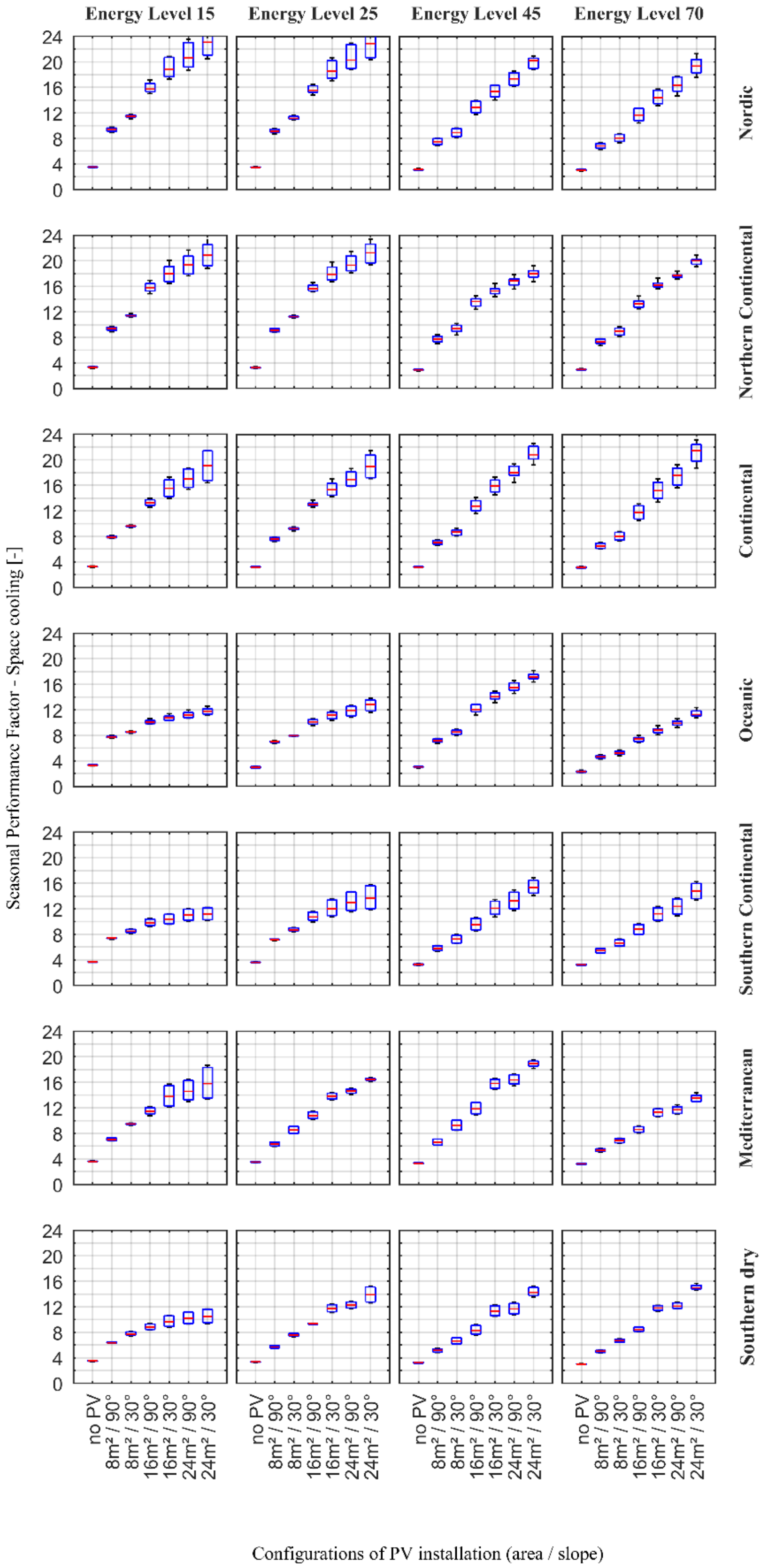

Figure 58 – Seasonal Performance Factor for Space Cooling

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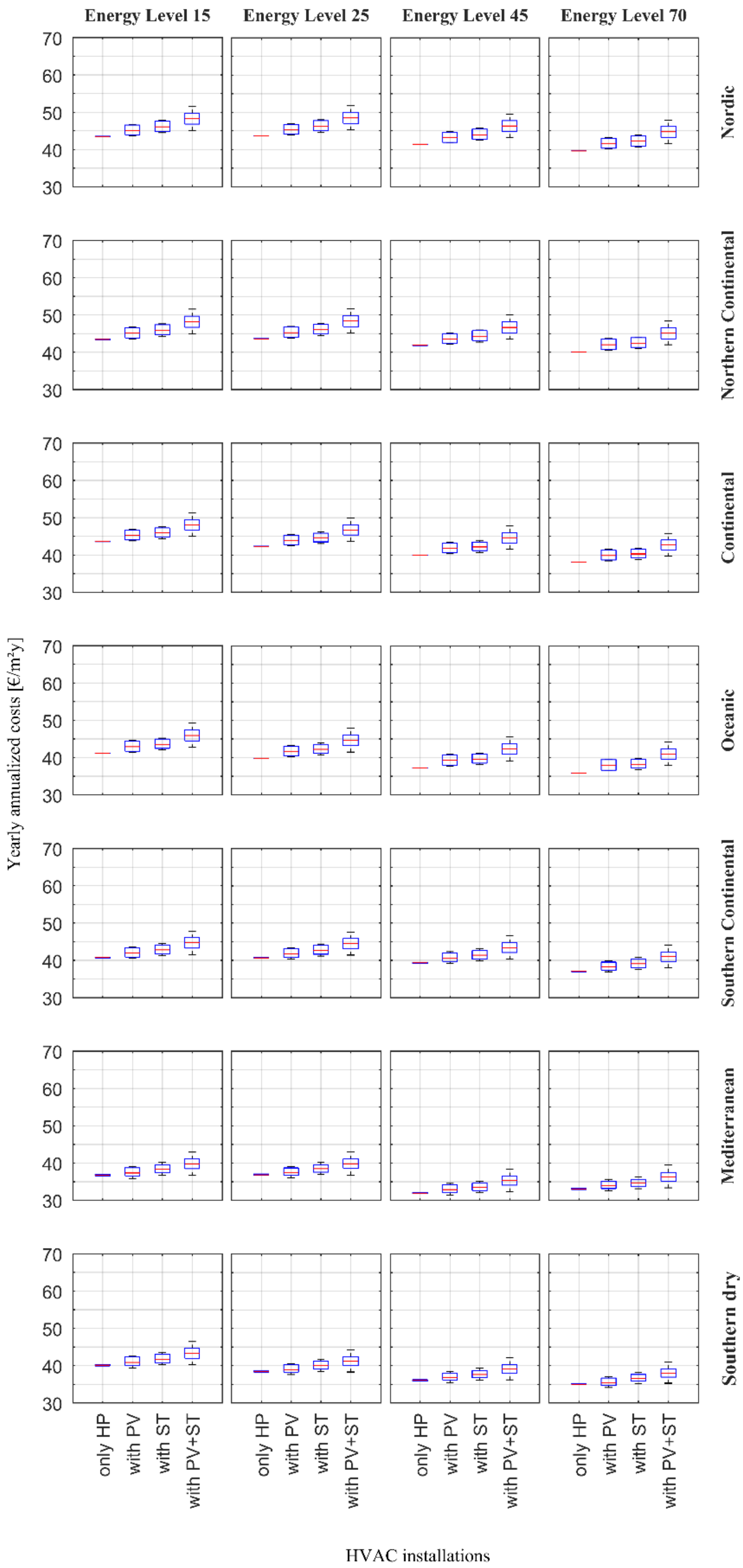

Figure 59 – Yearly annualised costs distribution for variants with solar systems

3.2 Single Family Houses - Ground source heat pump + radiant ceilings

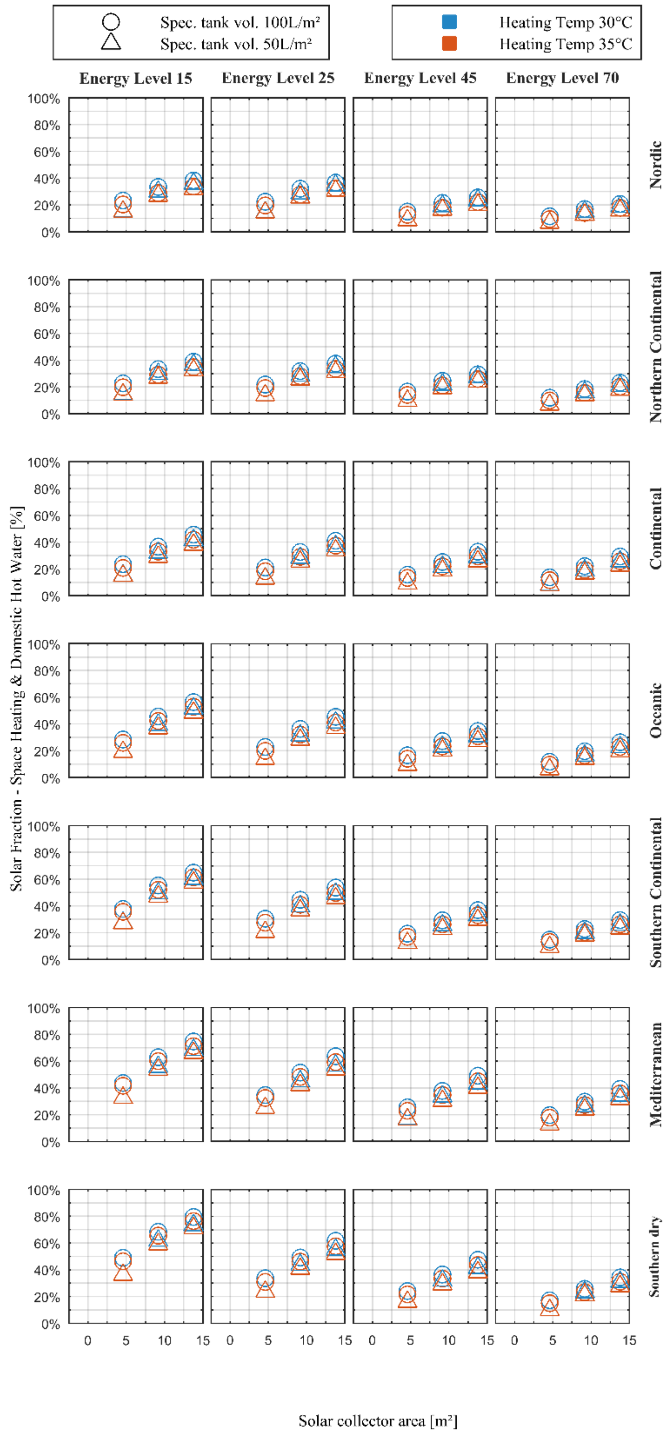

Figure 60 – Solar fraction for Domestic Hot Water with solar collectors in the main façade.

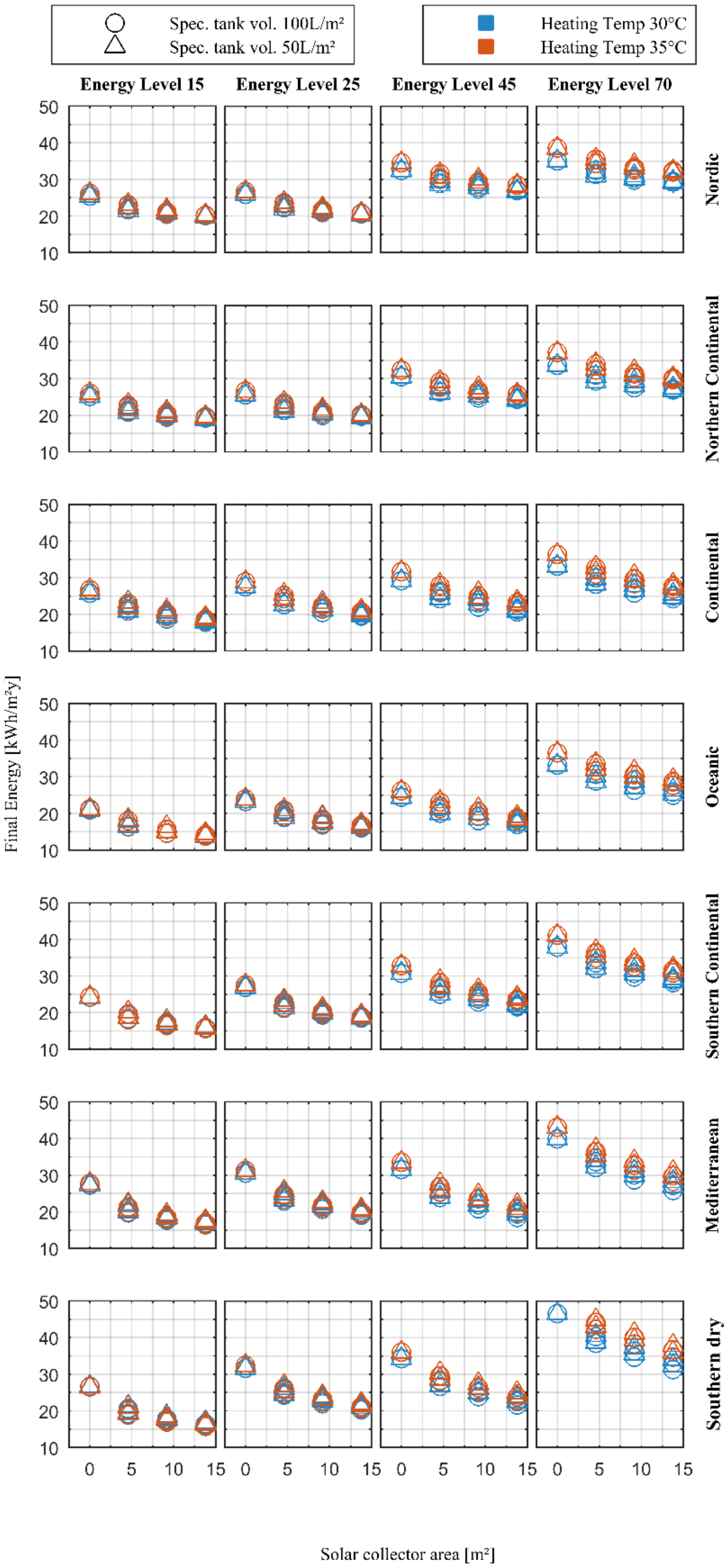

Figure 61 – Total final energy for several variants air-source heat pump and solar thermal system

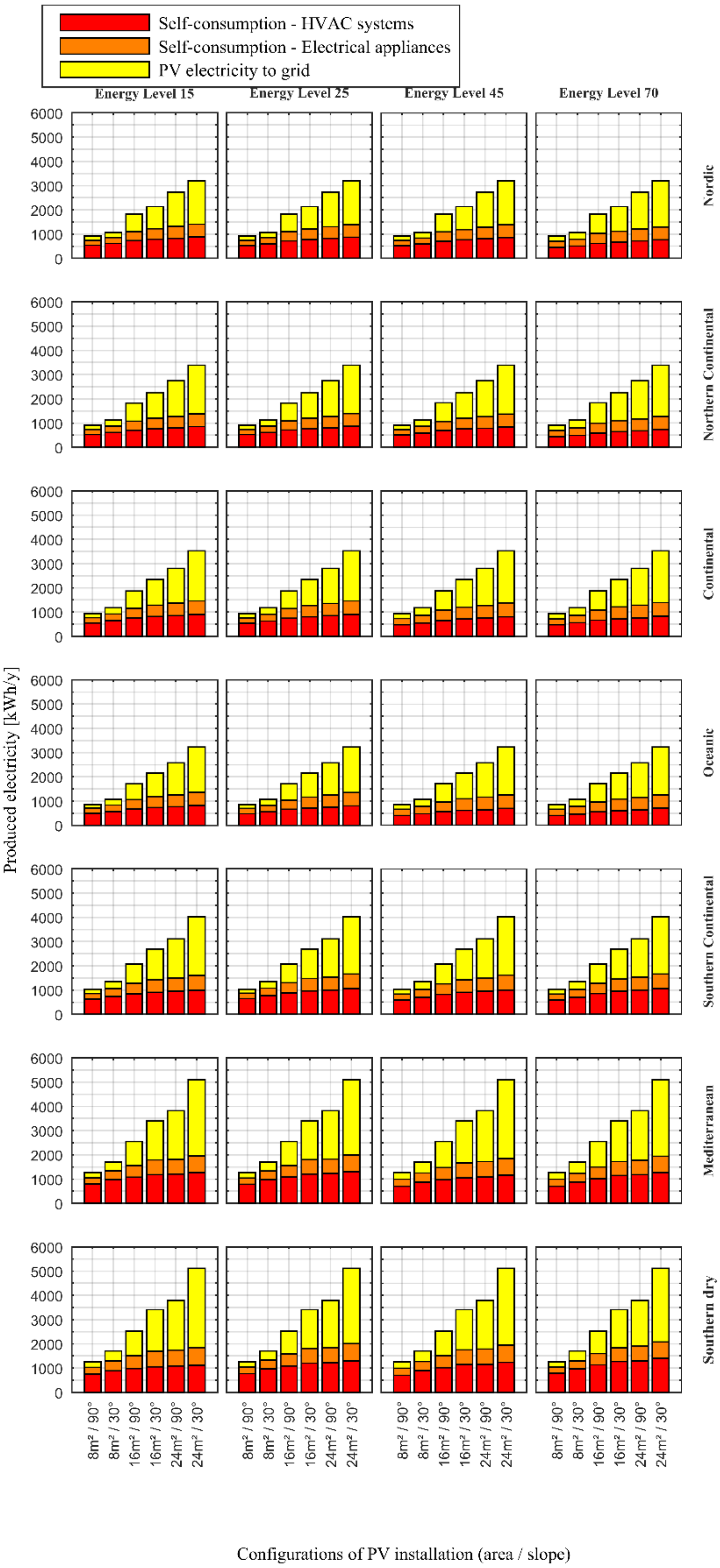

Figure 62 – Photovoltaic electricity production

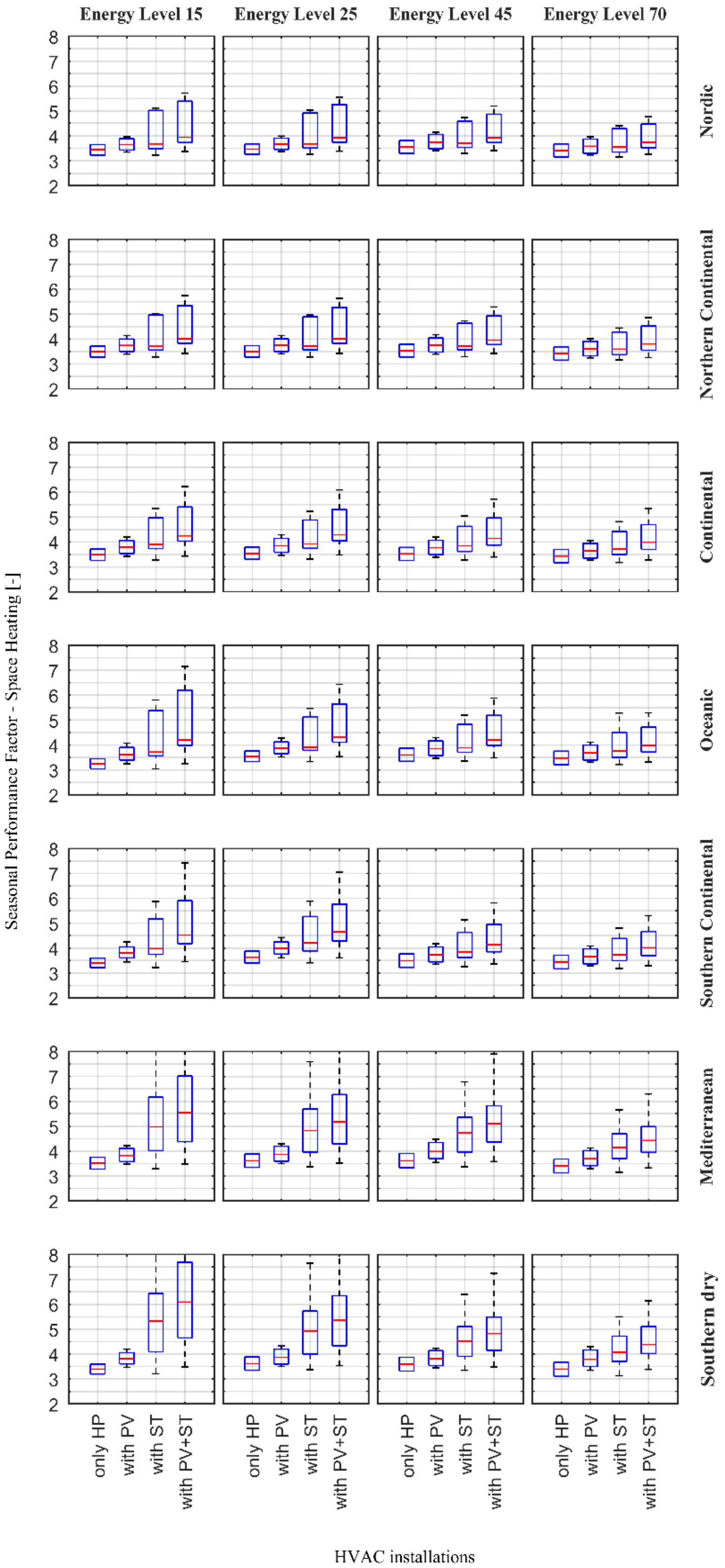

Figure 63 – Seasonal Performance Factor for space heating

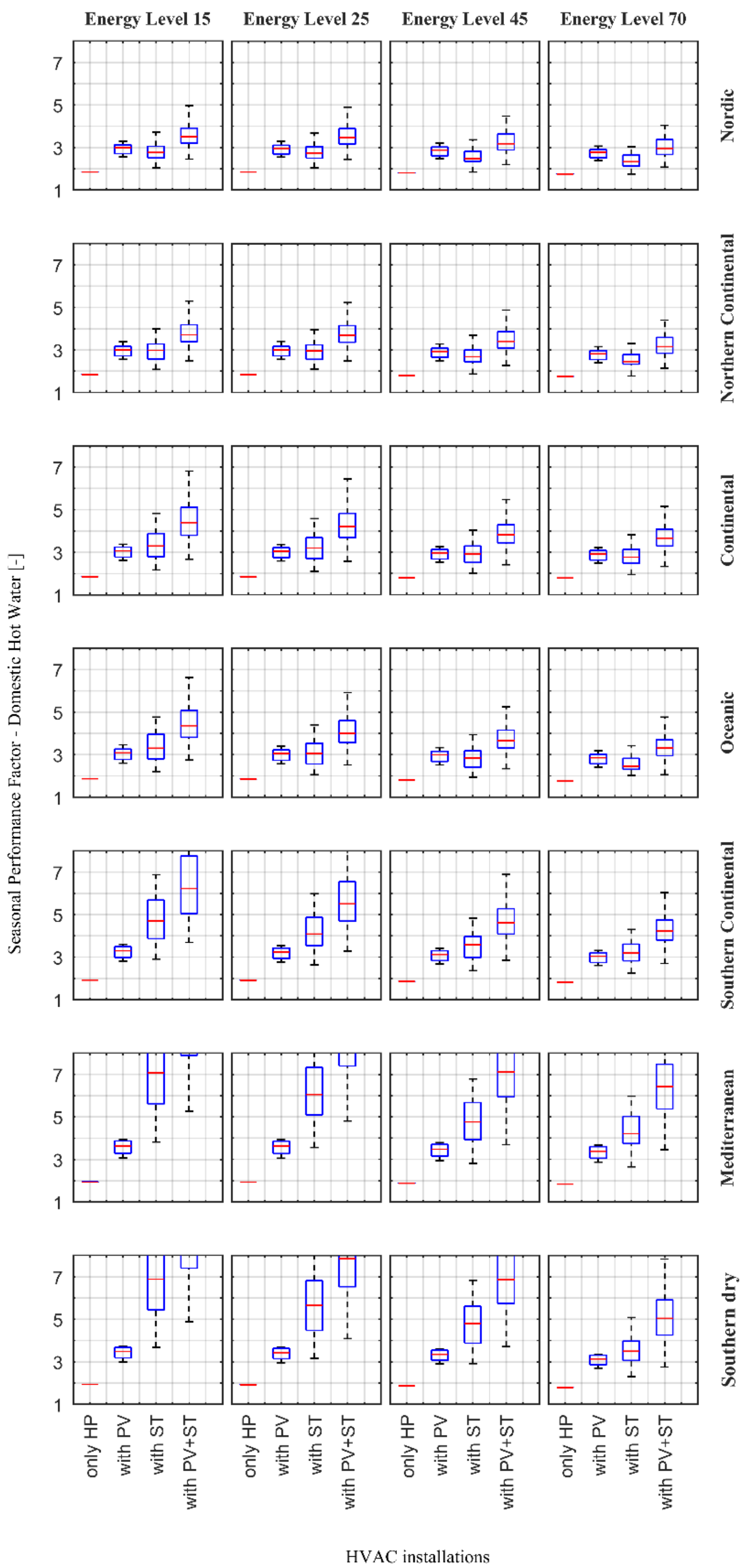

Figure 64 – Seasonal Performance Factor for DHW production

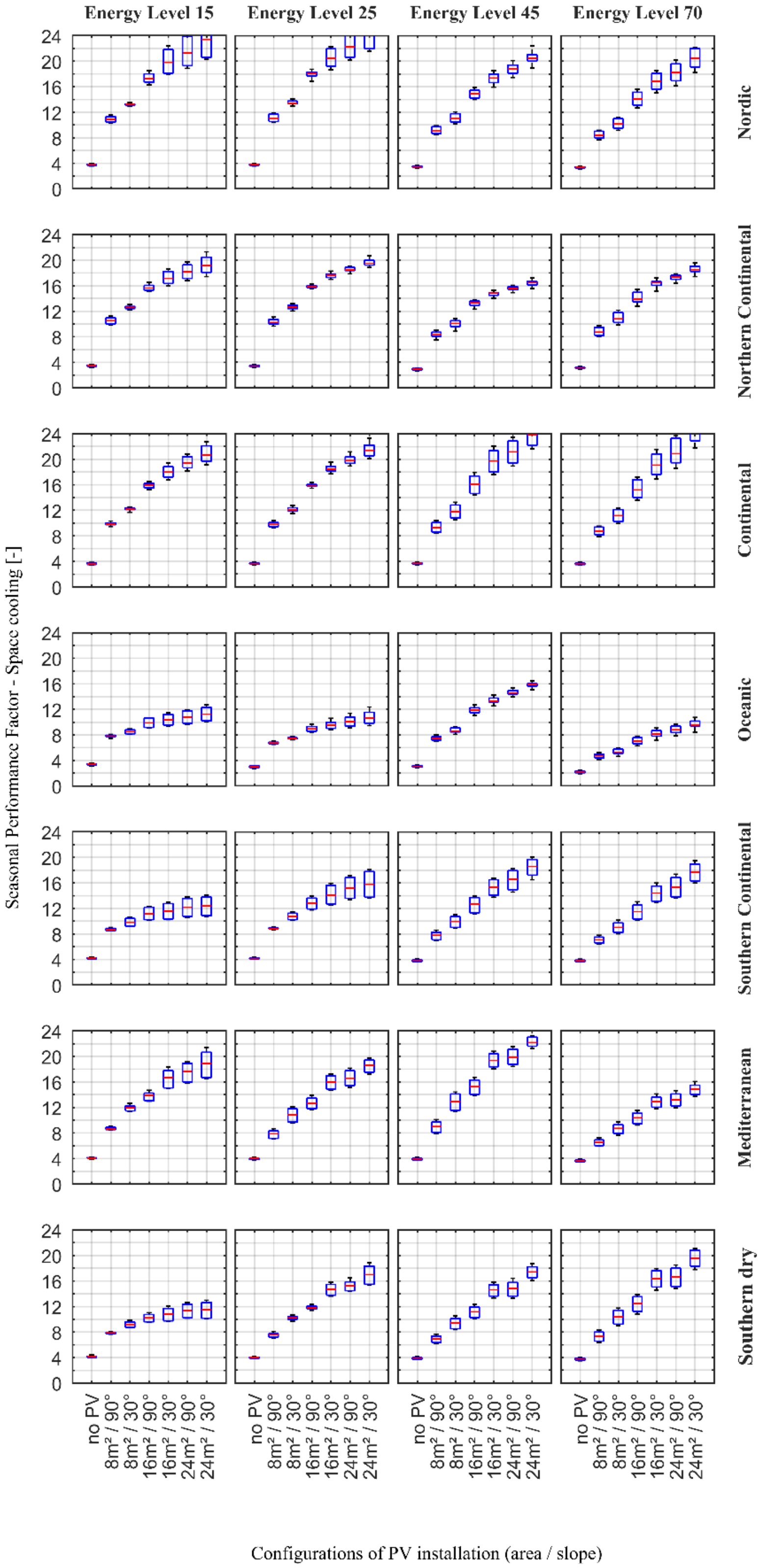

Figure 65 – Seasonal Performance Factor for Space Cooling

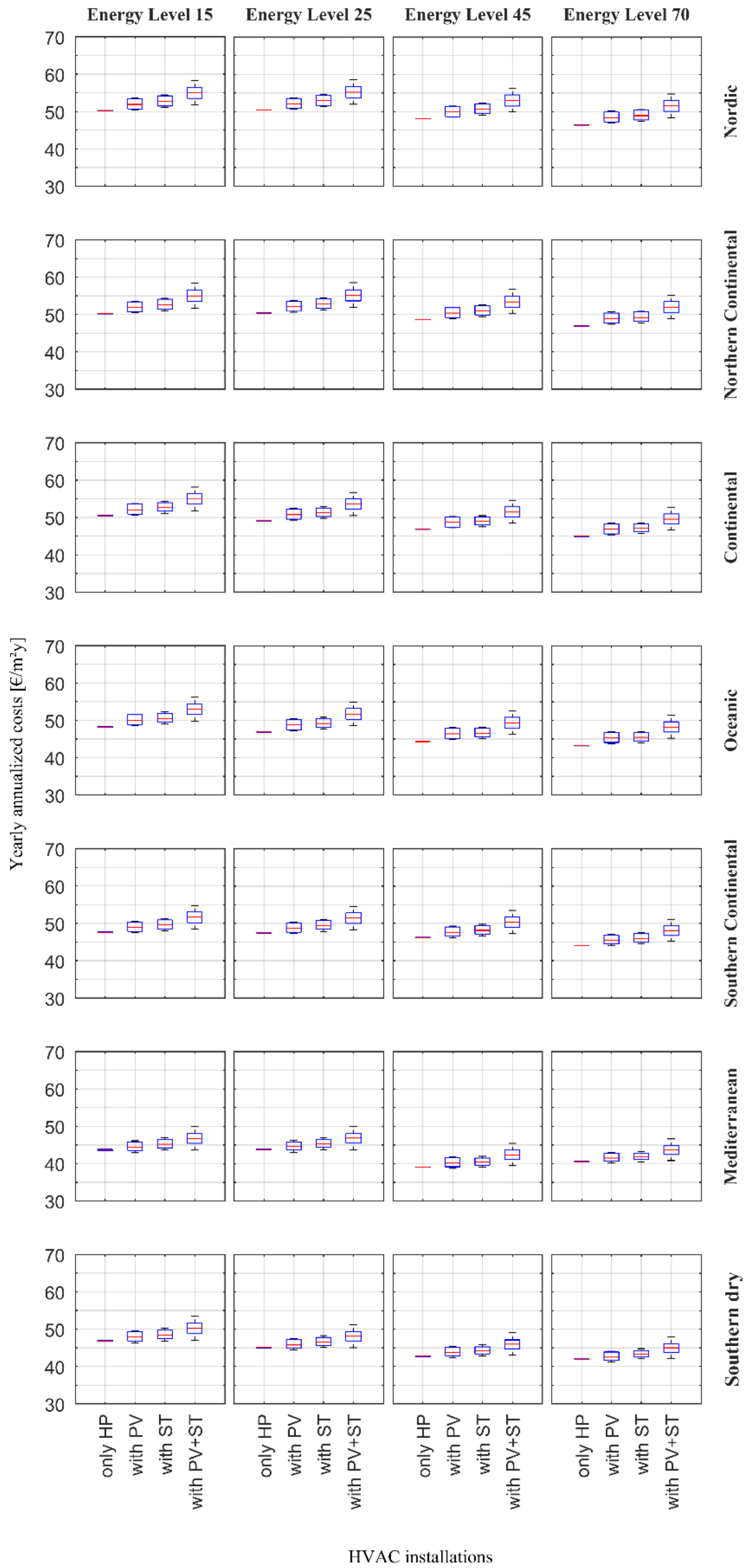

Figure 66 – Yearly annualised costs distribution for variants with solar systems

3.3 Single Family Houses – Gas boiler + radiant ceilings

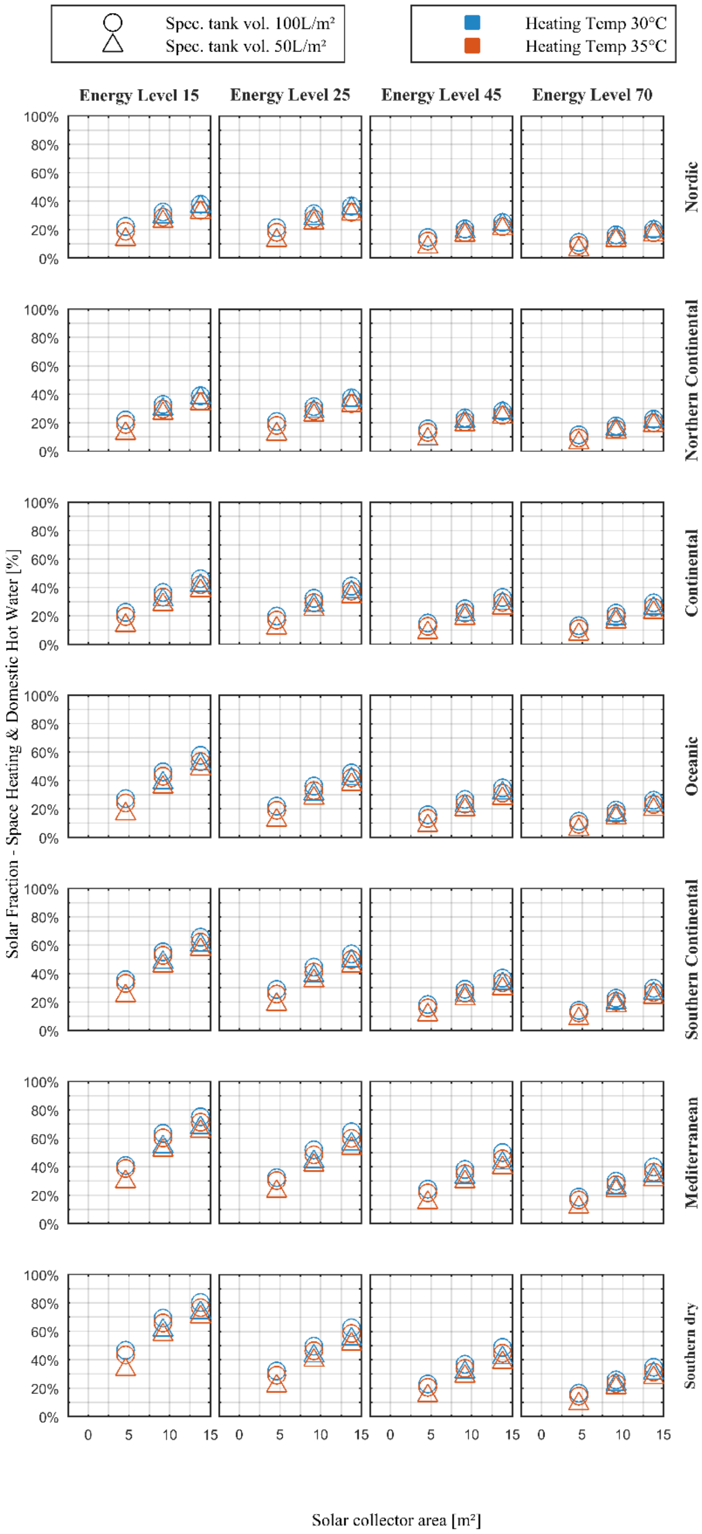

Figure 67 - Solar fraction for Domestic Hot Water and Space Heating with solar collectors in the main façade

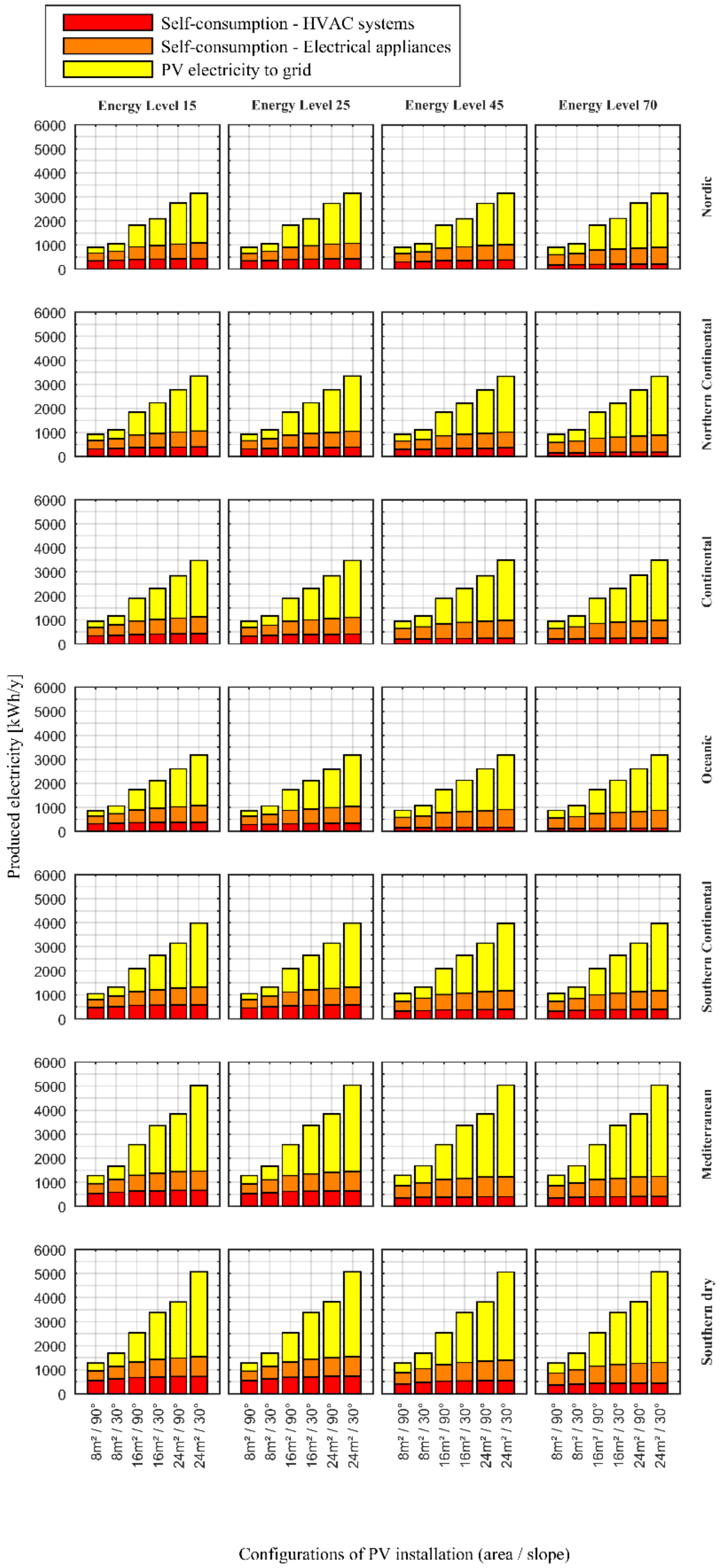

Figure 68 - Photovoltaic electricity production

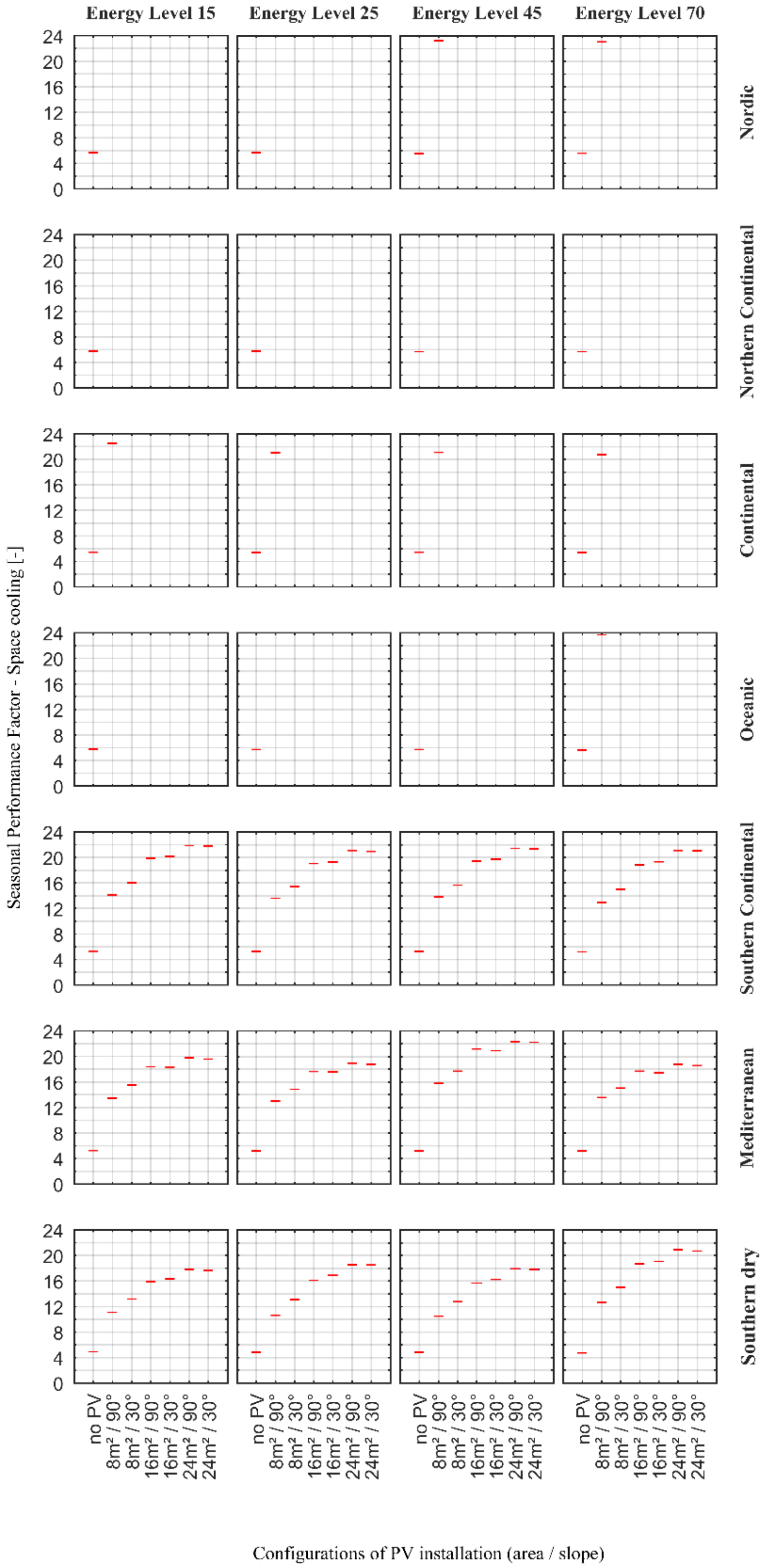

Figure 69 - Seasonal Performance Factor for Space Cooling

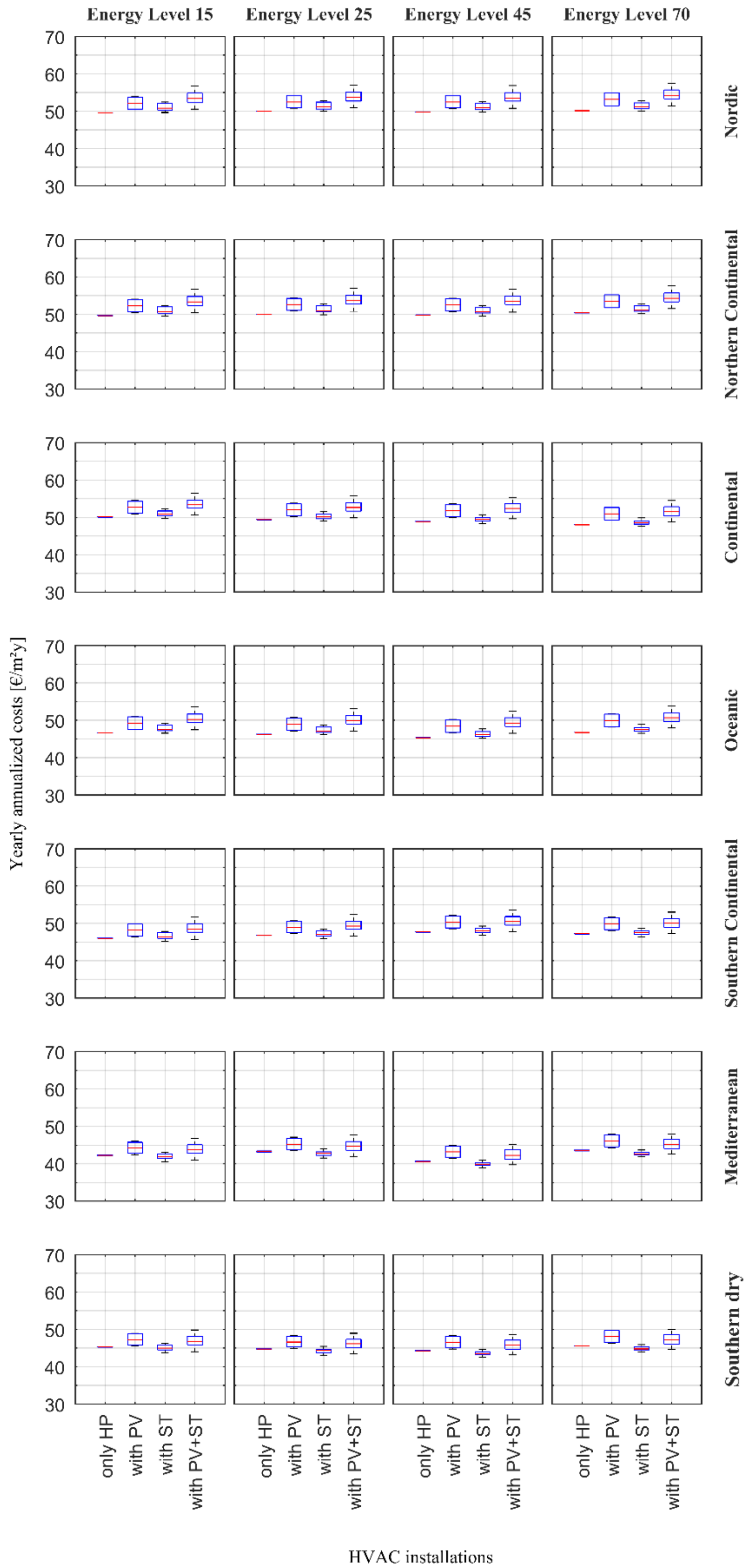

Figure 70 - Yearly annualised costs distribution for variants with solar systems

3.4 Single Family Houses – Pellet boiler + radiant ceilings

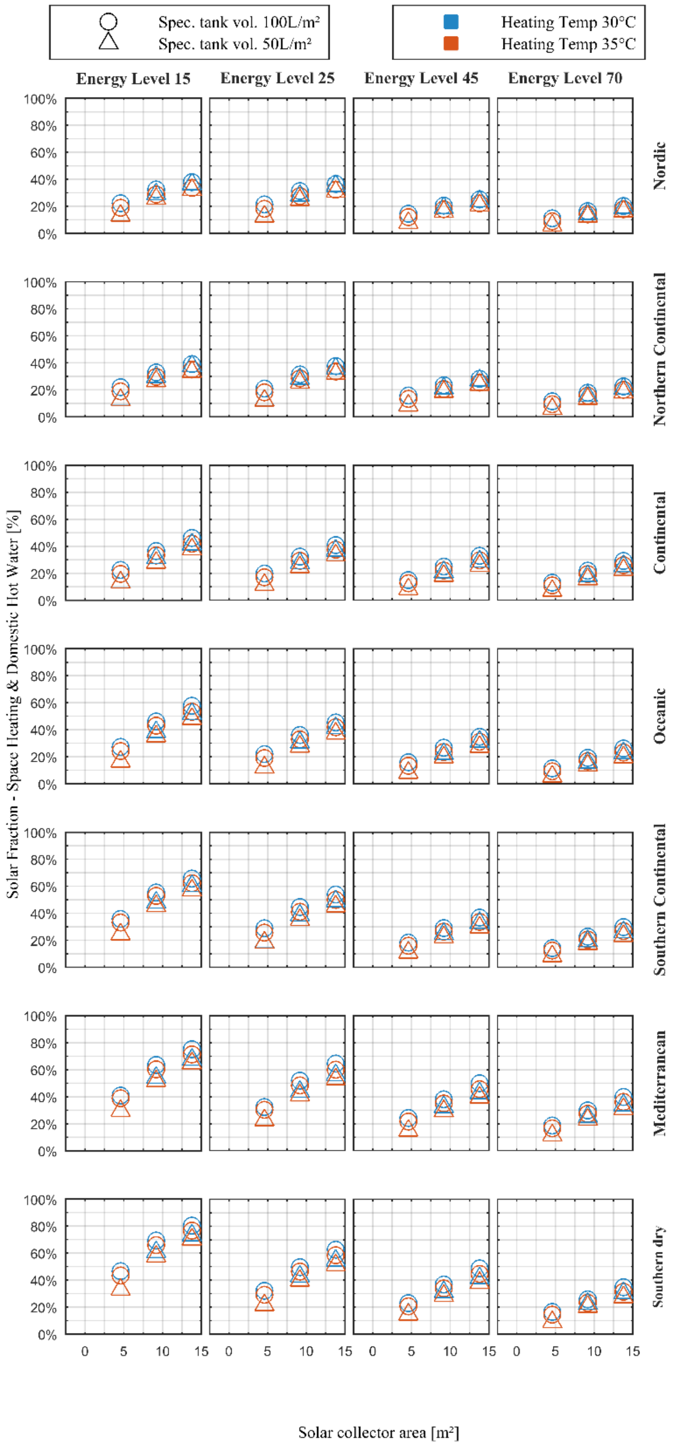

Figure 71 - Solar fraction for Domestic Hot Water and Space Heating with solar collectors in the main façade

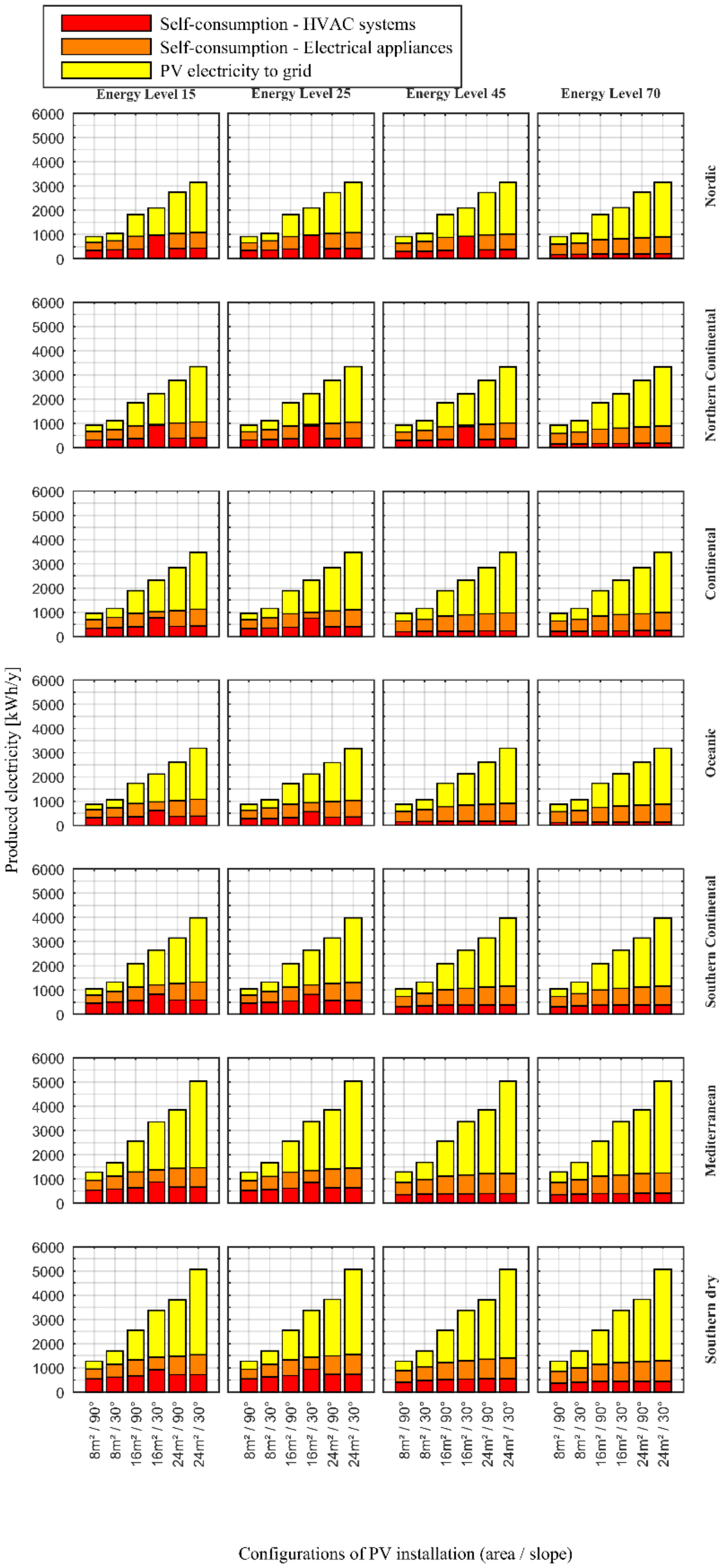

Figure 72 - Photovoltaic electricity production

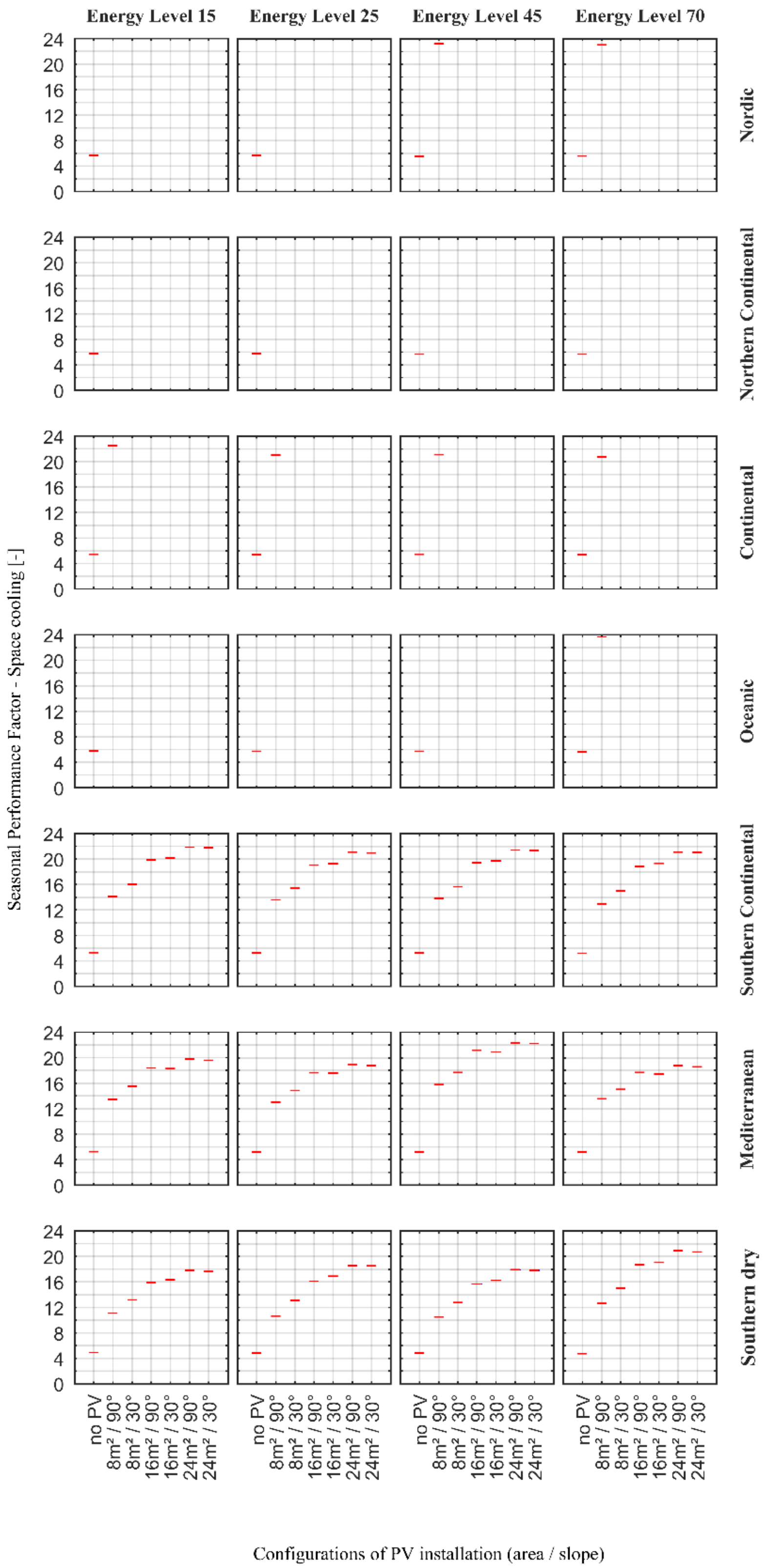

Figure 73 - Seasonal Performance Factor for Space Cooling

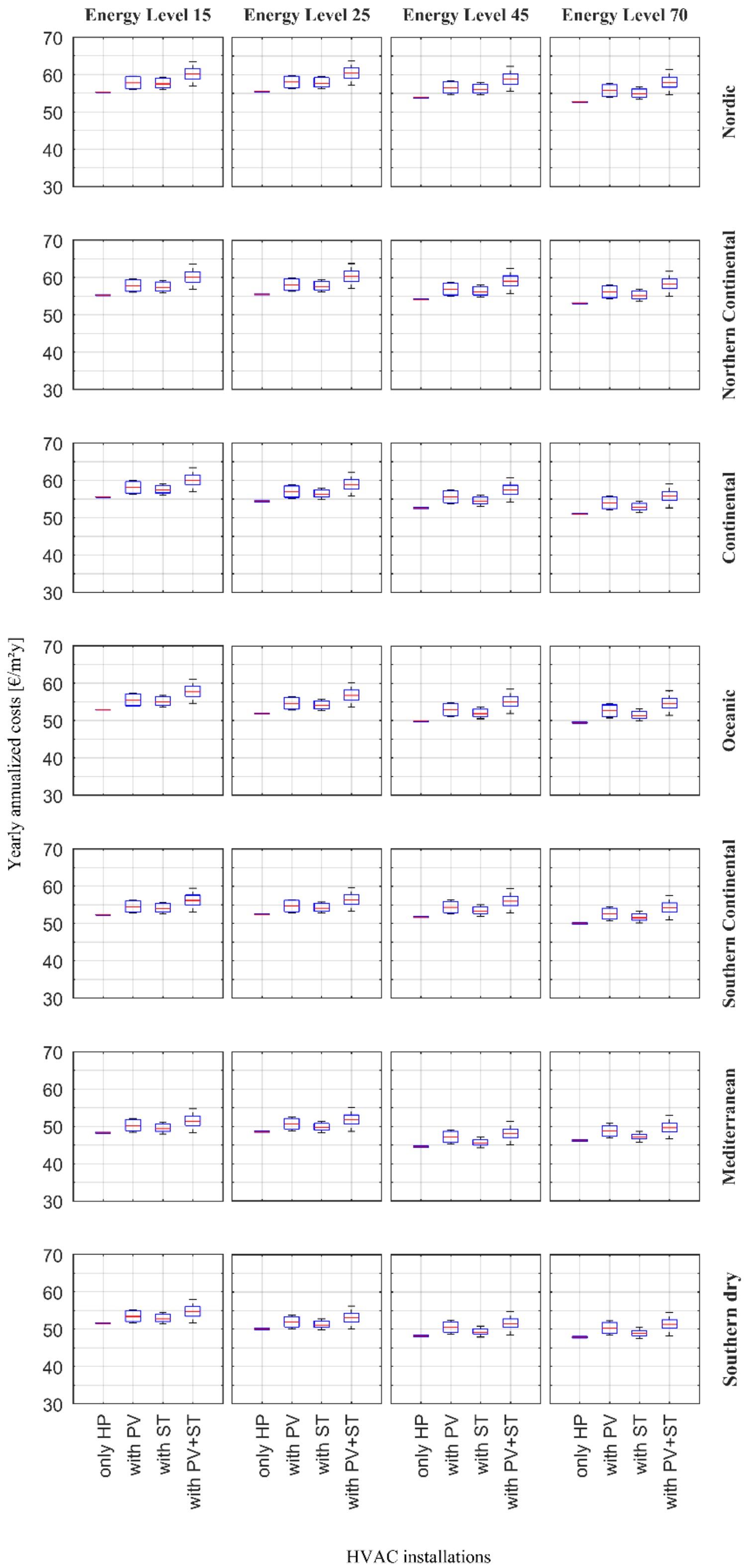

Figure 74 - Yearly annualised costs distribution for variants with solar systems

3.5 Single Family Houses – Air to water heat pump + fan coils

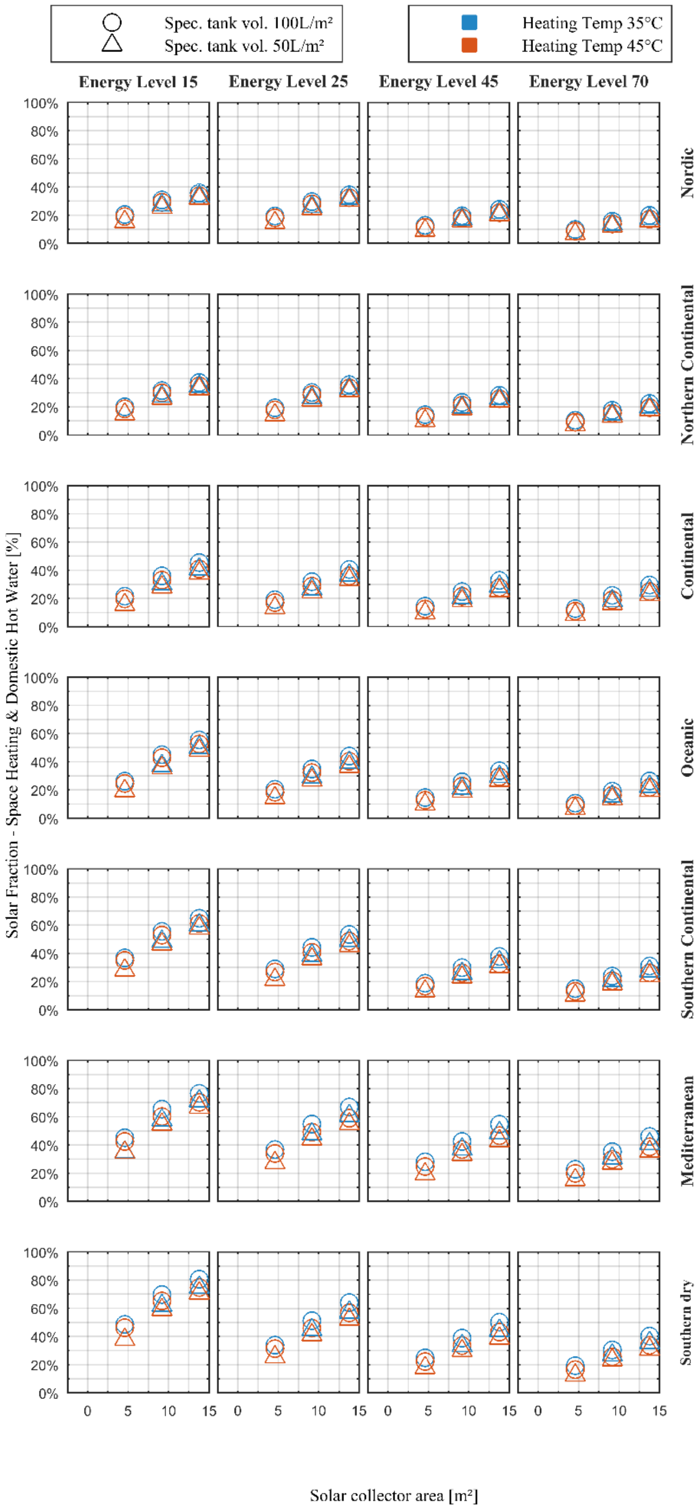

Figure 75 – Solar fraction for heating production with solar collectors in the main façade

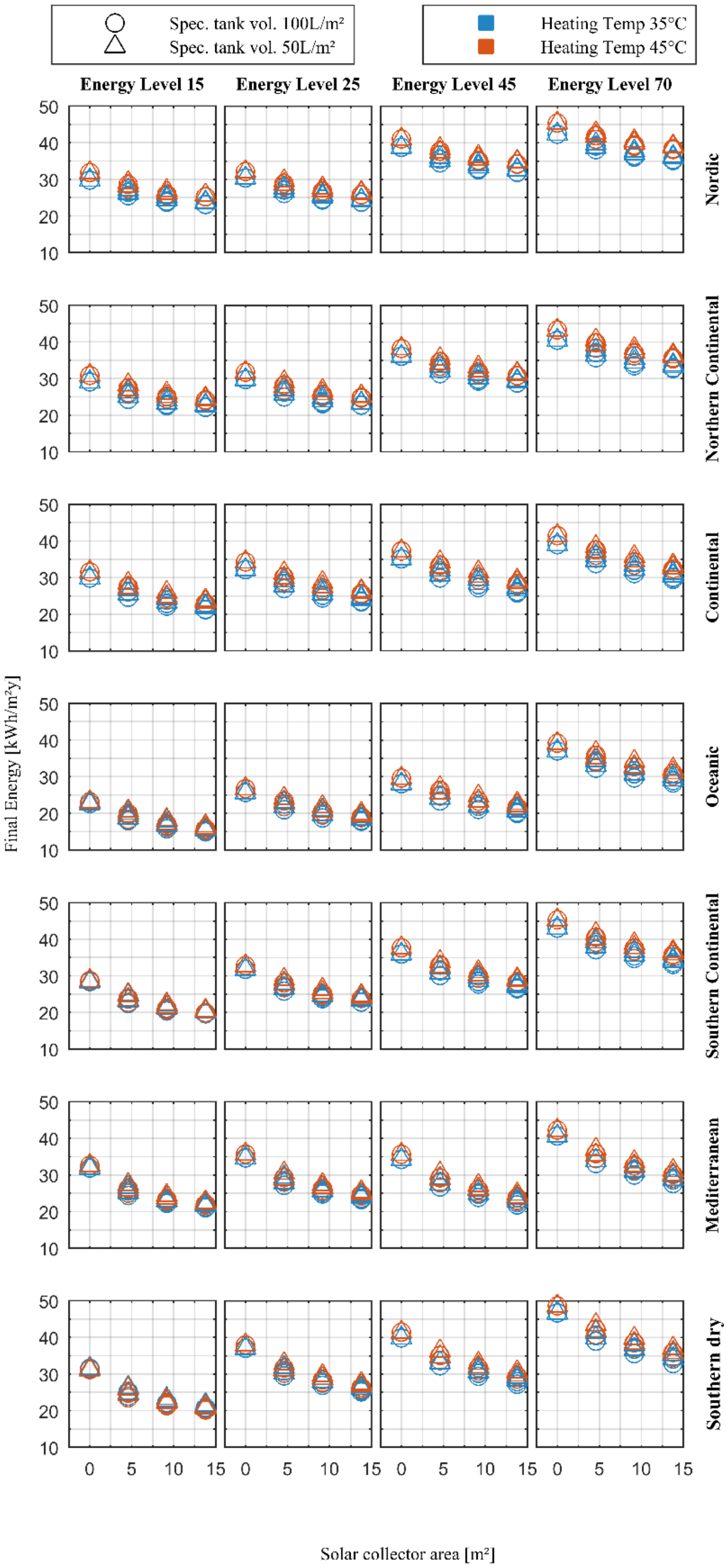

Figure 76 – Total final energy for several variants air-source heat pump and solar thermal system

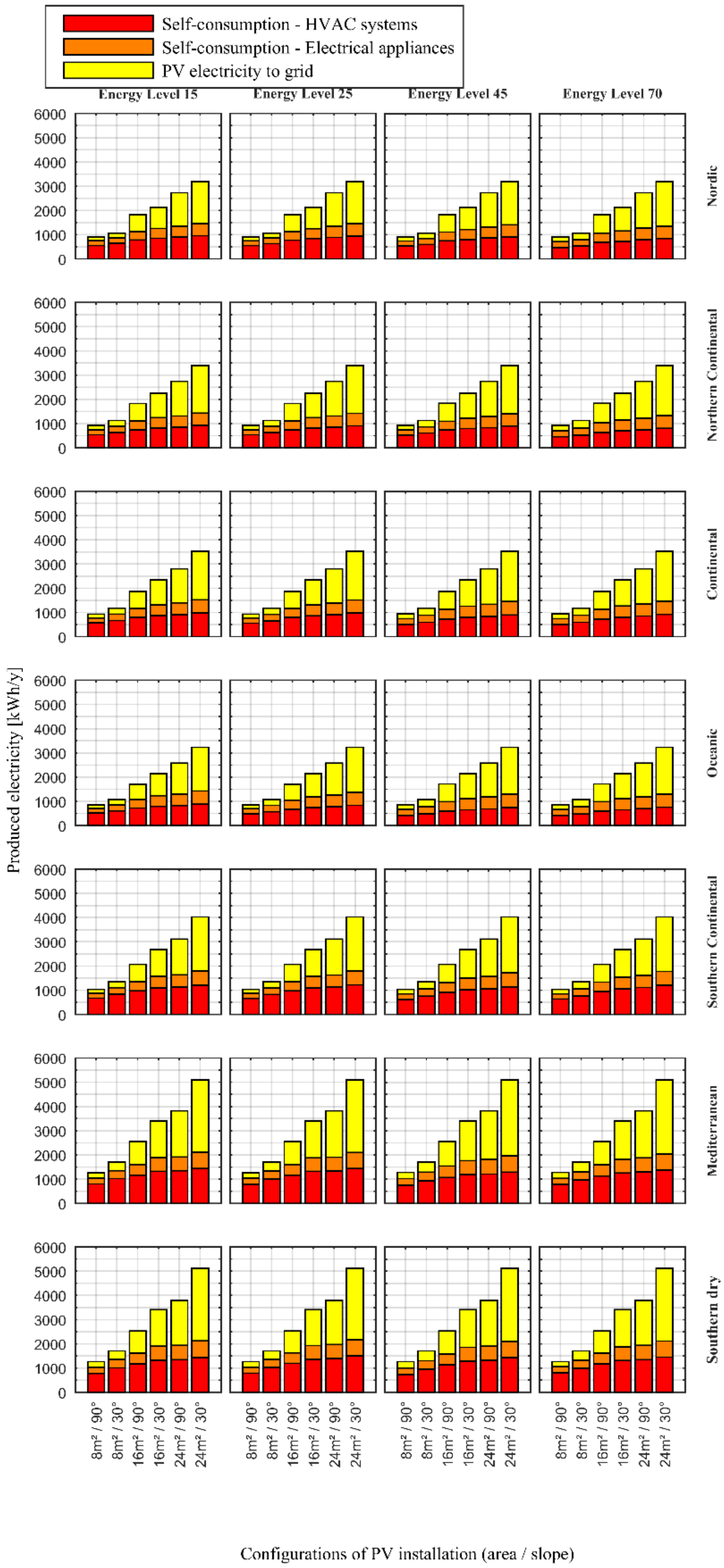

Figure 77 – Photovoltaic electricity production

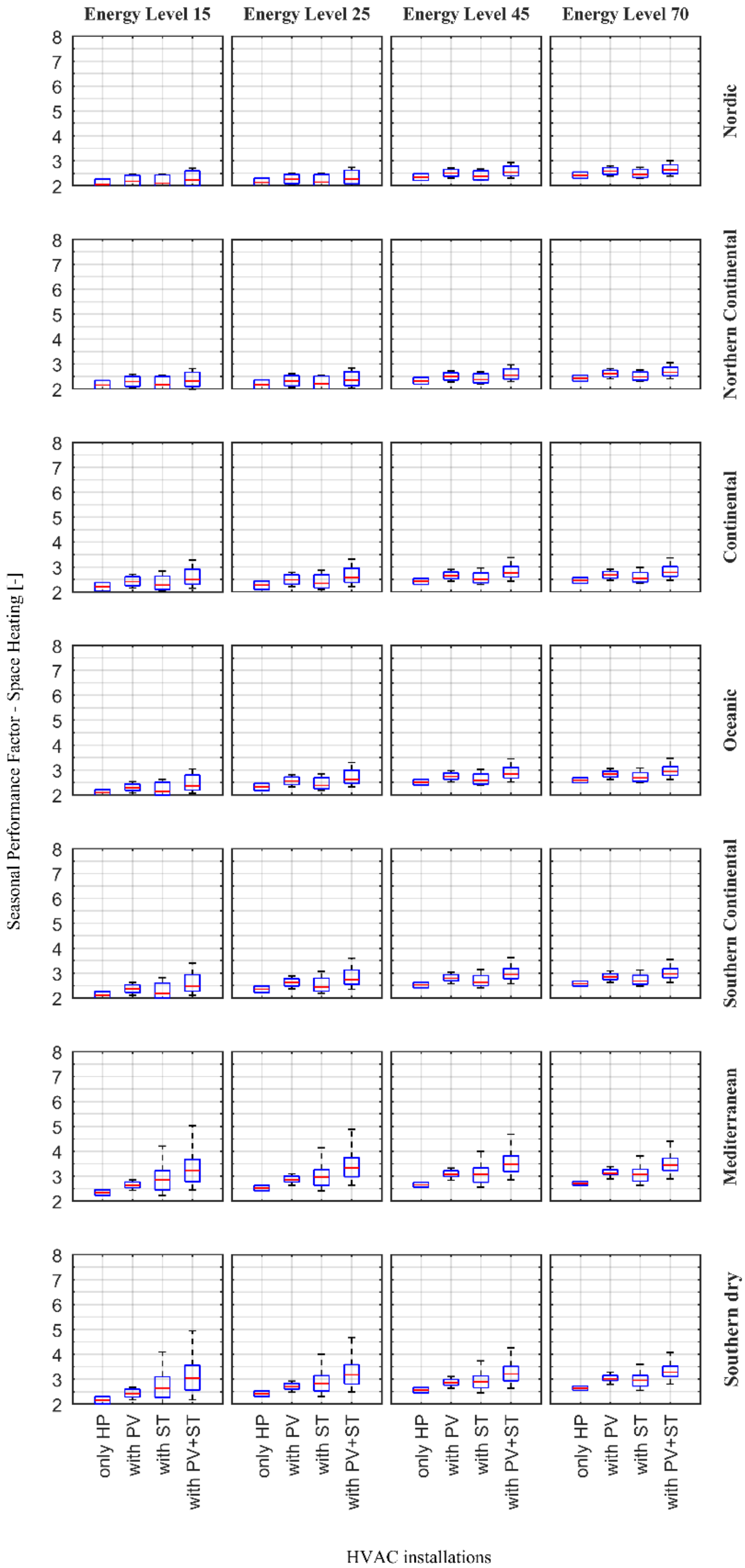

Figure 78 – Seasonal Performance Factor for space heating production

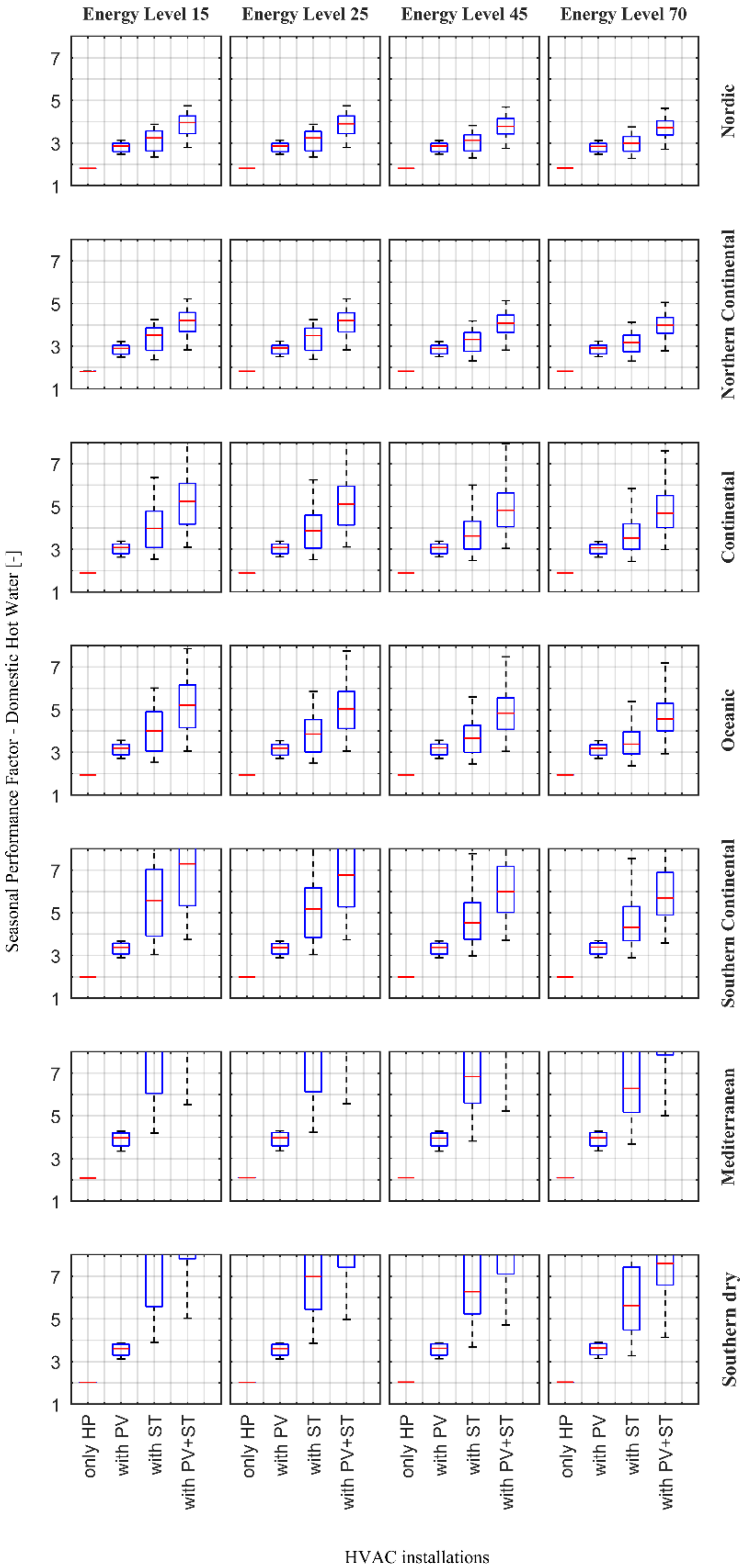

Figure 79 – Seasonal Performance Factor for DHW production

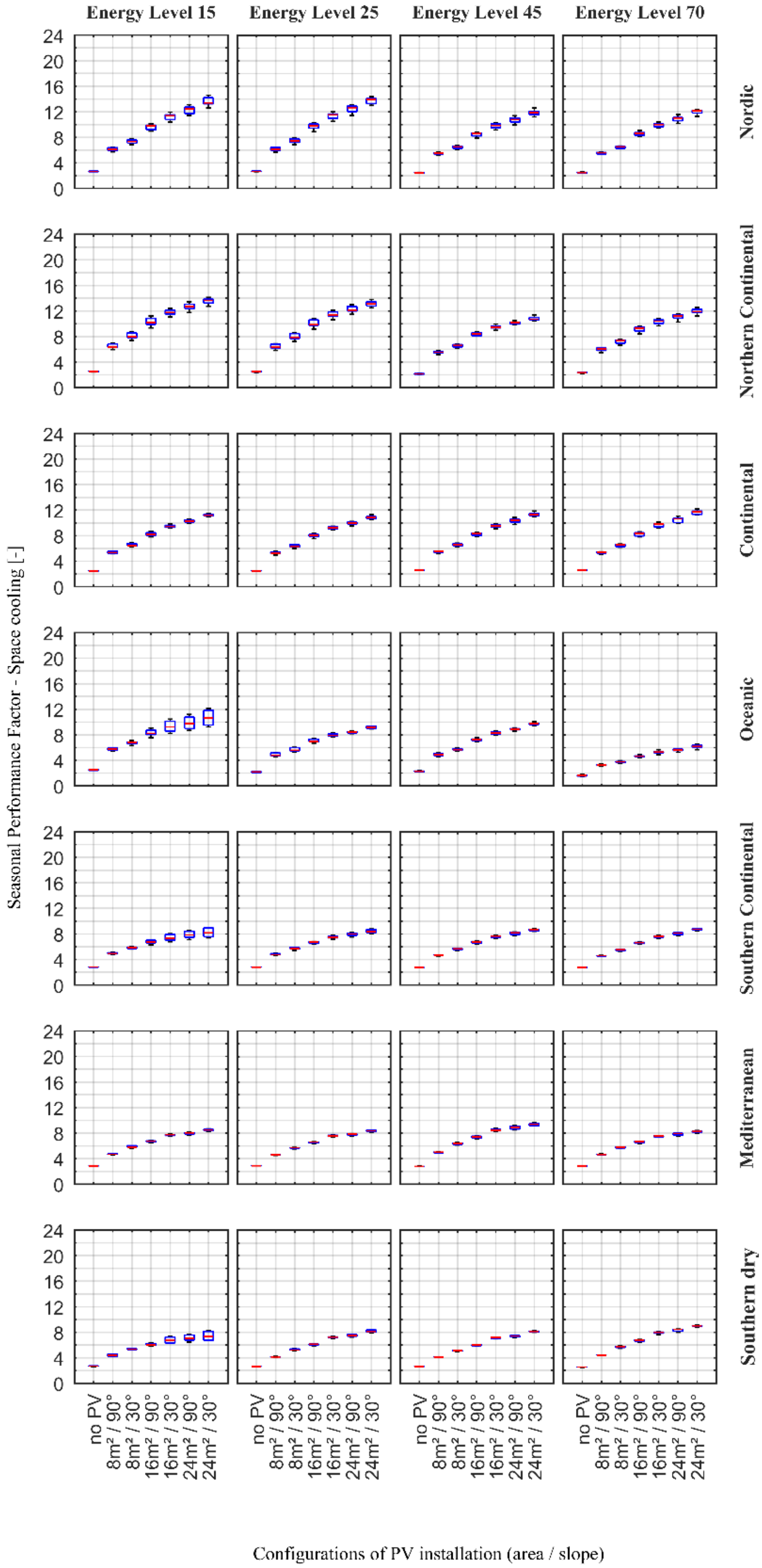

Figure 80 – Seasonal Performance Factor for Space Cooling

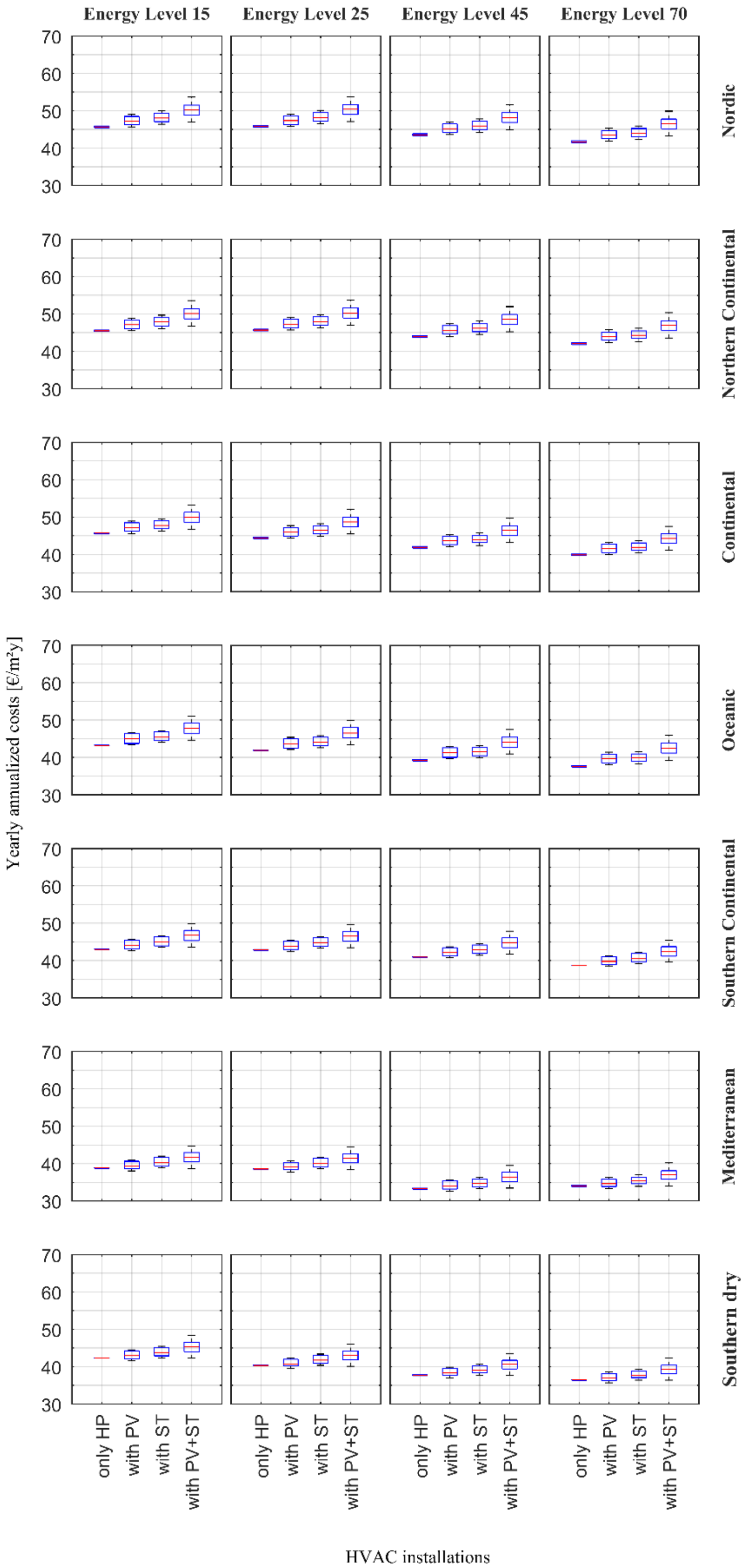

Figure 81 – Yearly annualised costs distribution for variants with solar systems

3.6 Single Family Houses – Ground source heat pump + fan coils

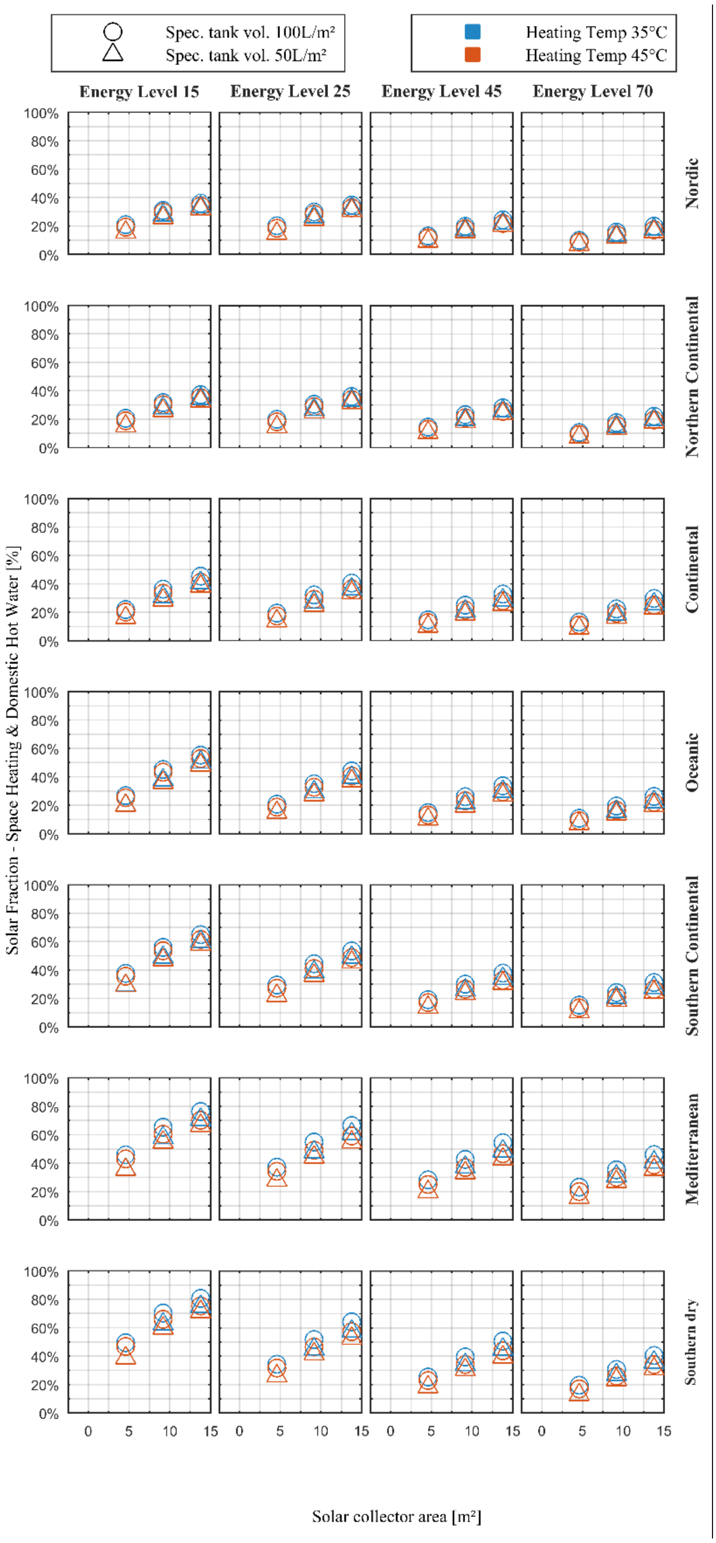

Figure 82 – Solar fraction for DHW + space heating with solar collectors in the main façade.

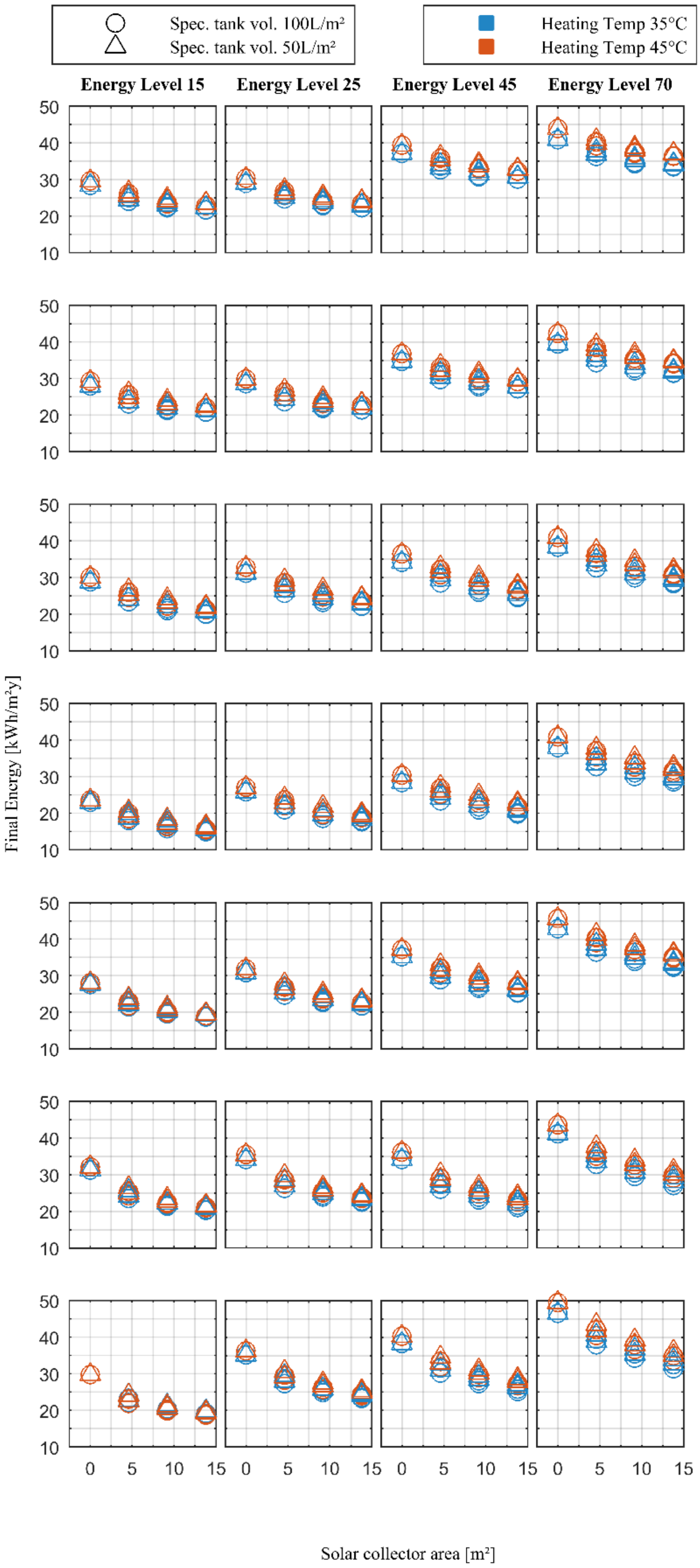

Figure 83 – Total final energy with solar thermal system

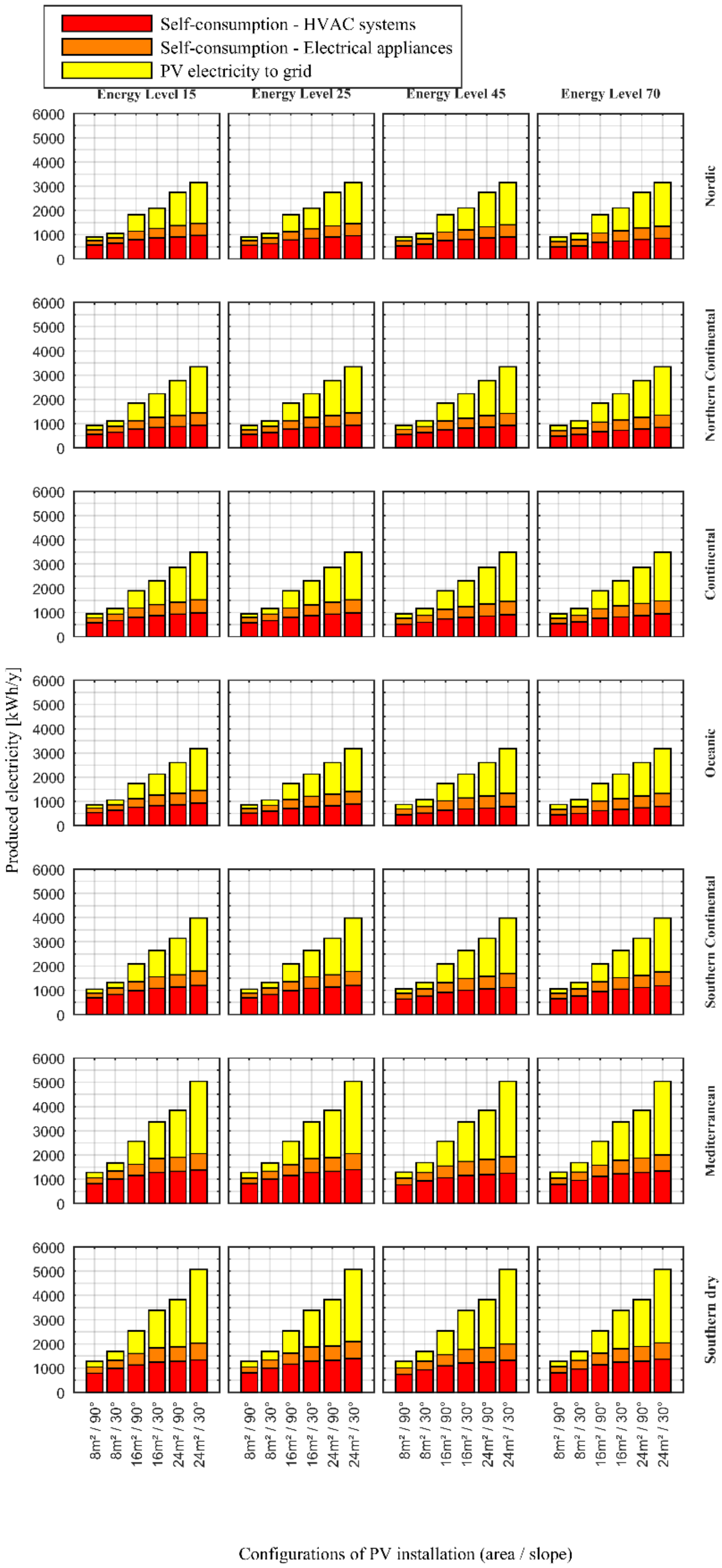

Figure 84 – Photovoltaic electricity production

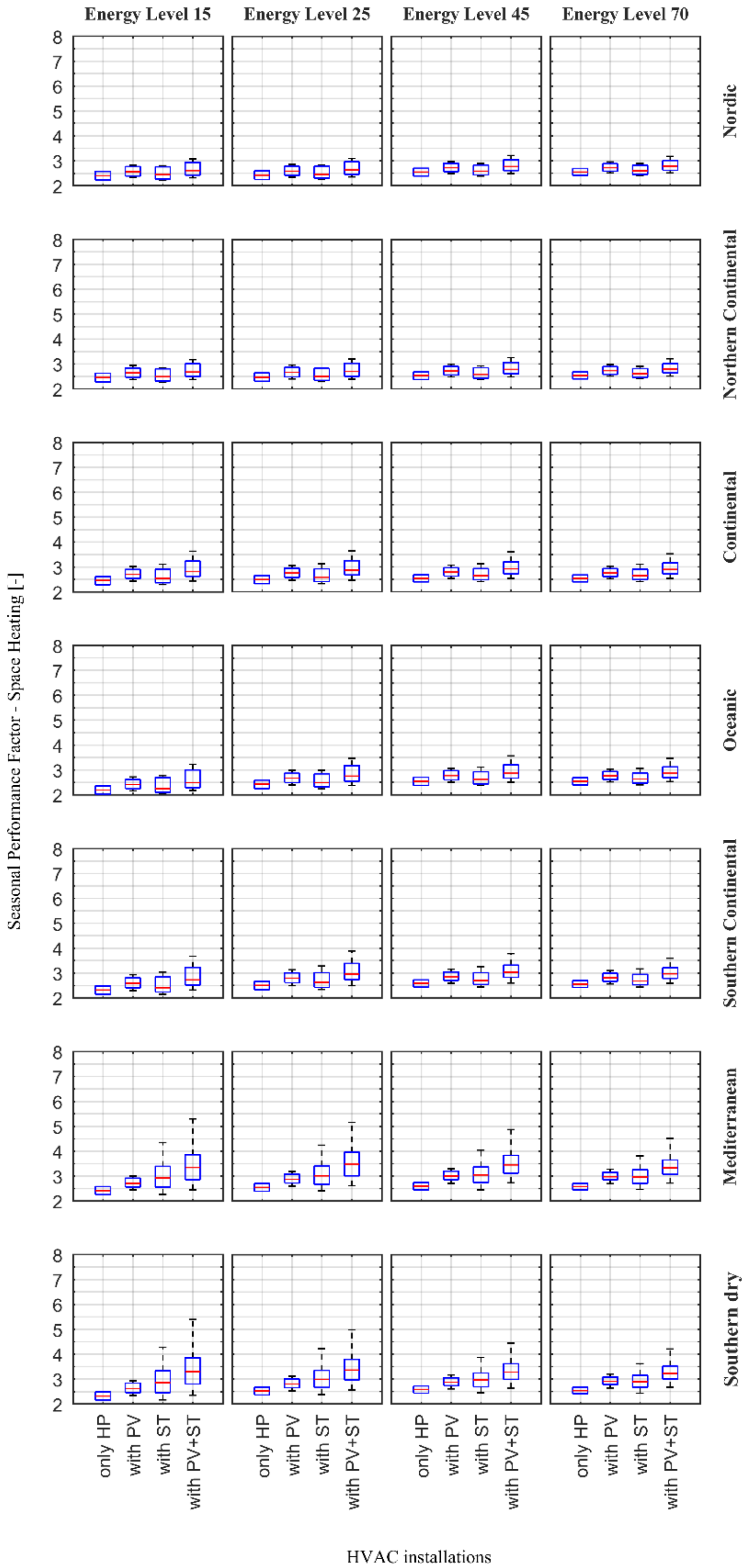

Figure 85 – Seasonal Performance Factor for space heating

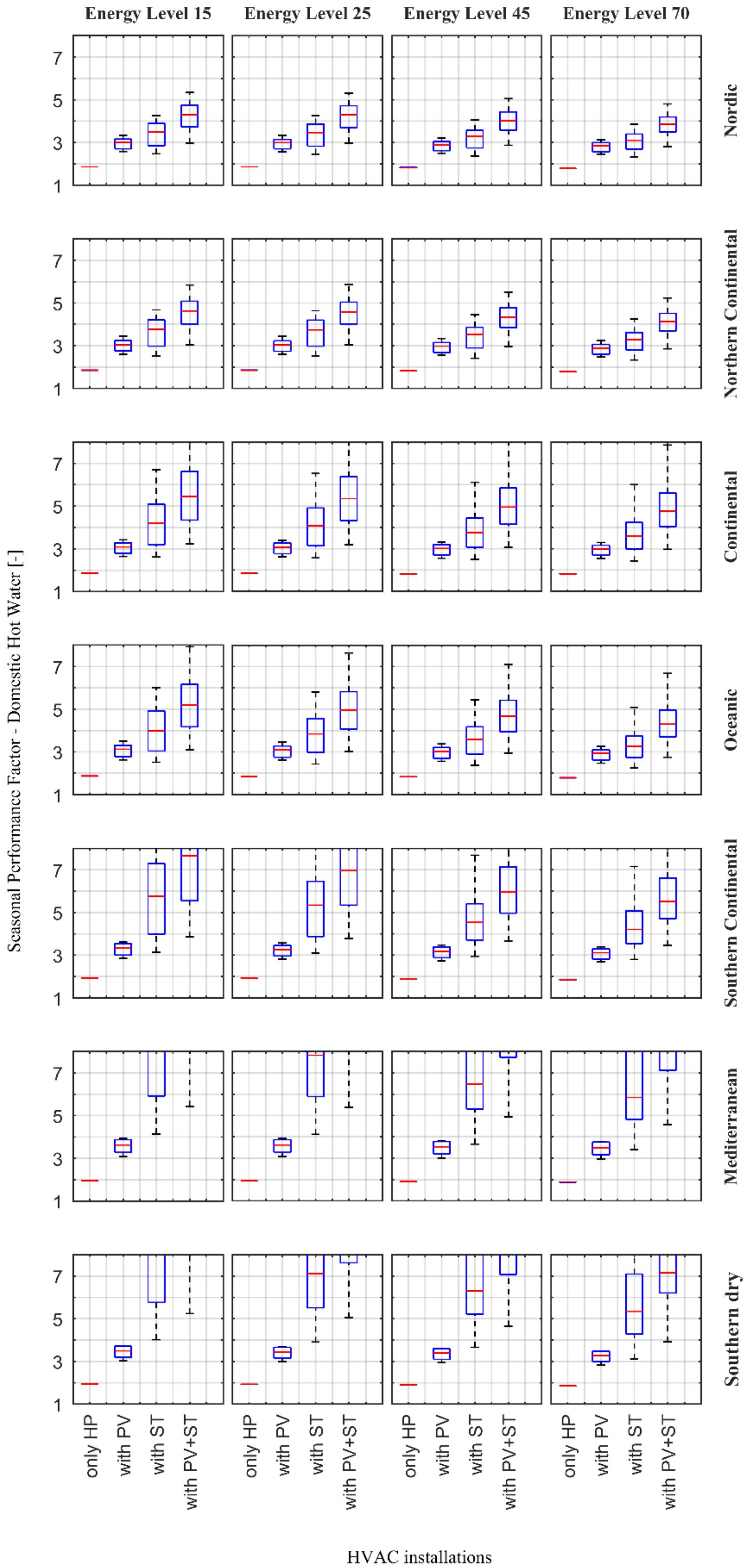

Figure 86 – Seasonal Performance Factor for DHW production

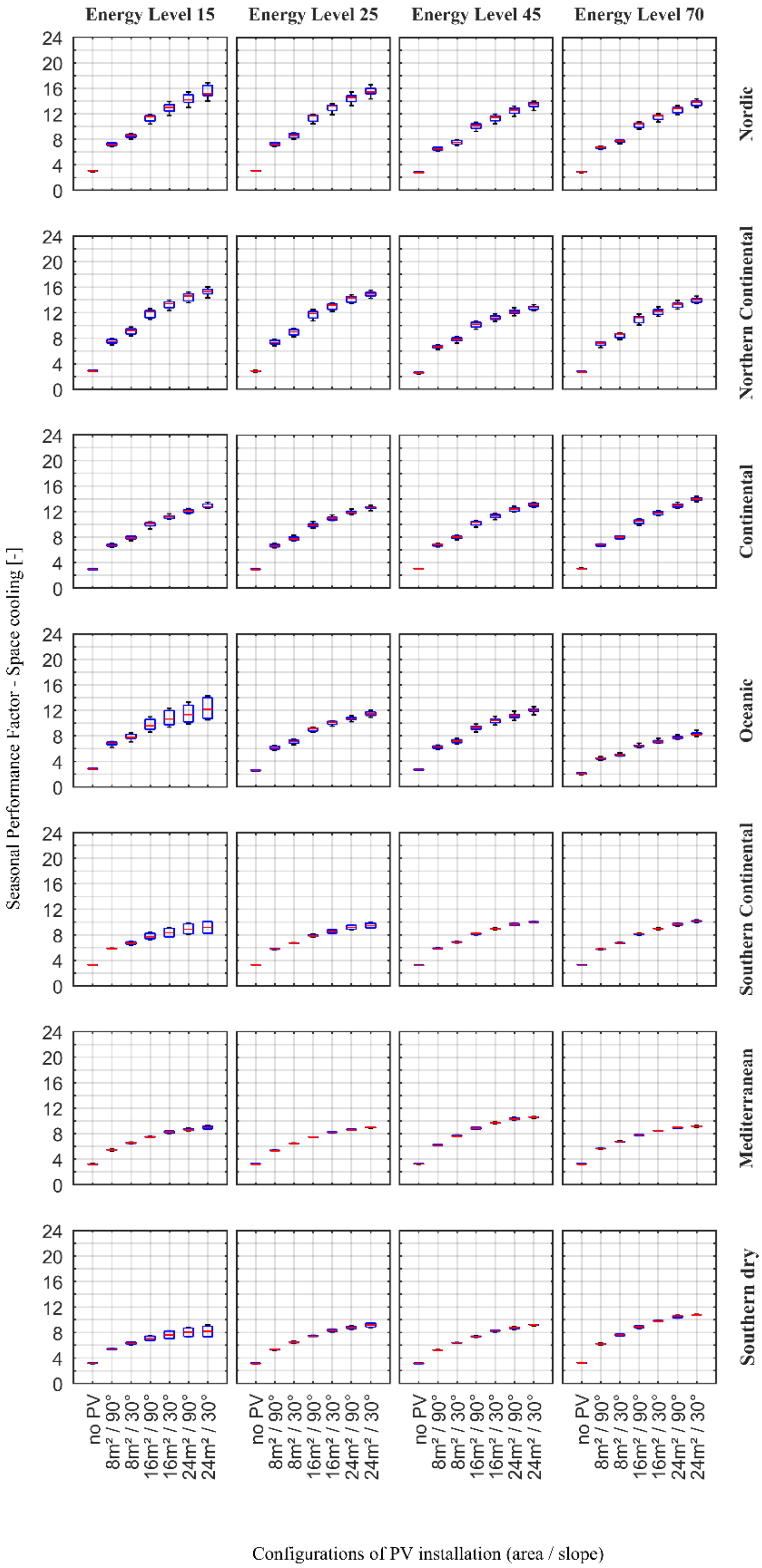

Figure 87 – Seasonal Performance Factor for Space Cooling

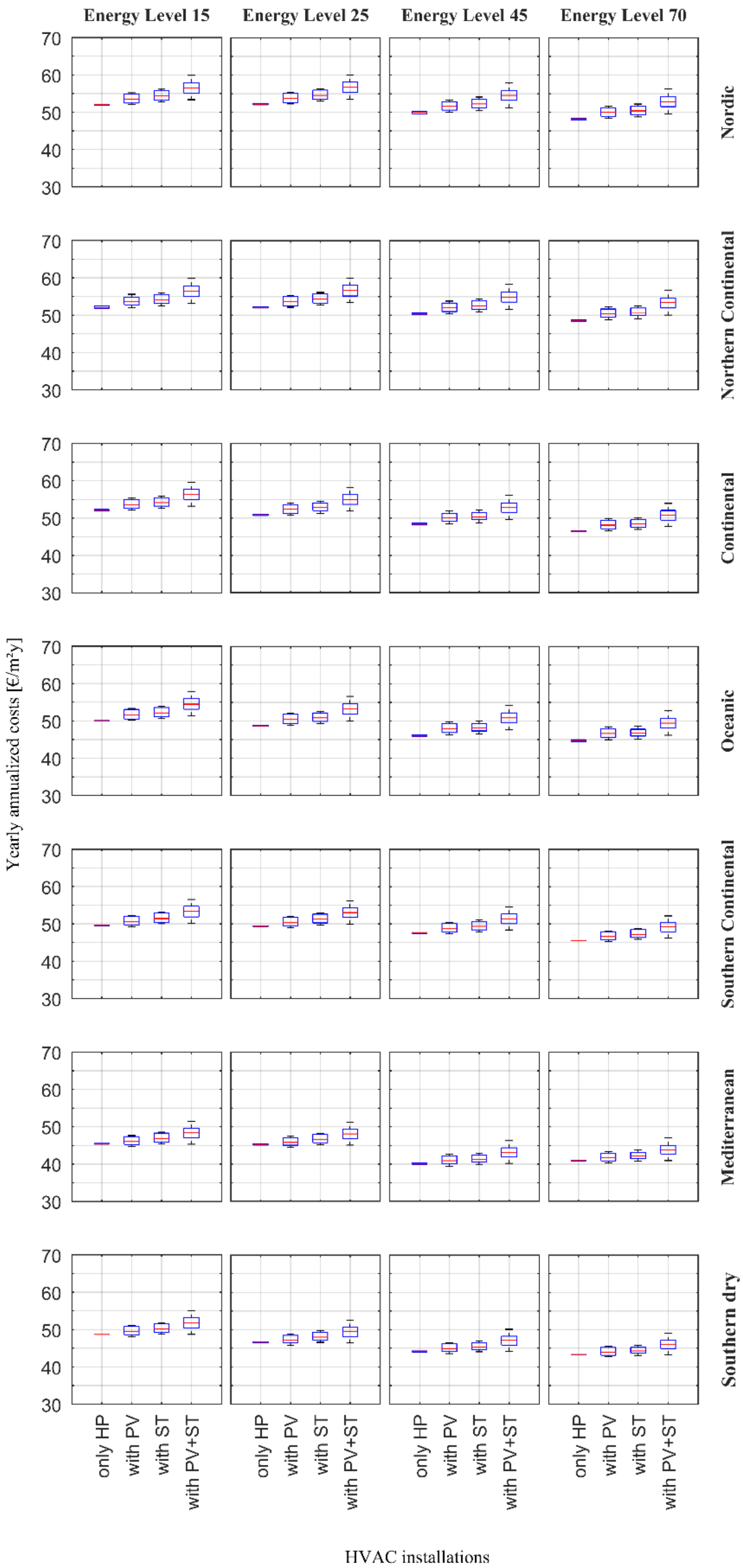

Figure 88 – Yearly annualised costs distribution for variants with solar systems

3.7 Single Family Houses – Gas boilers + fan coils

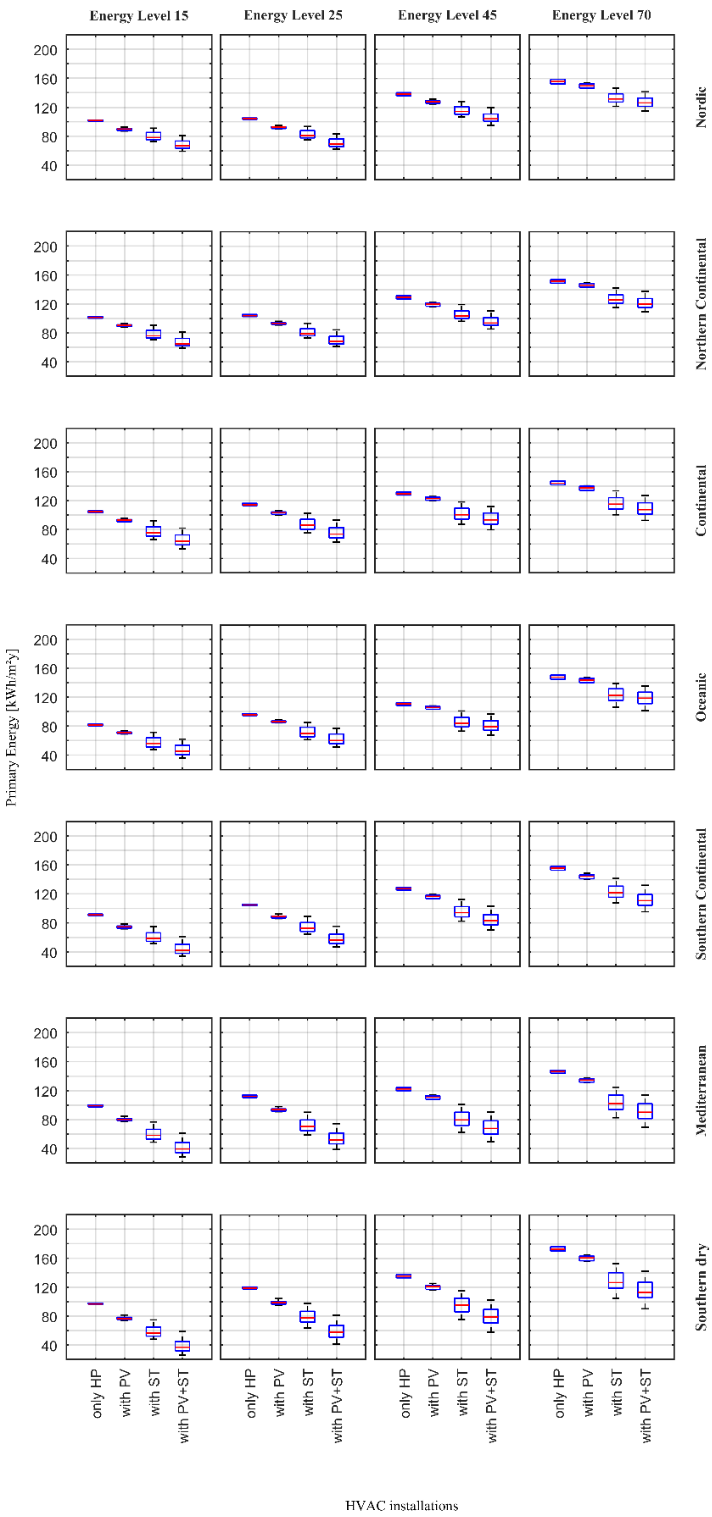

Figure 89 - Total primary energy for different HVAC installation types

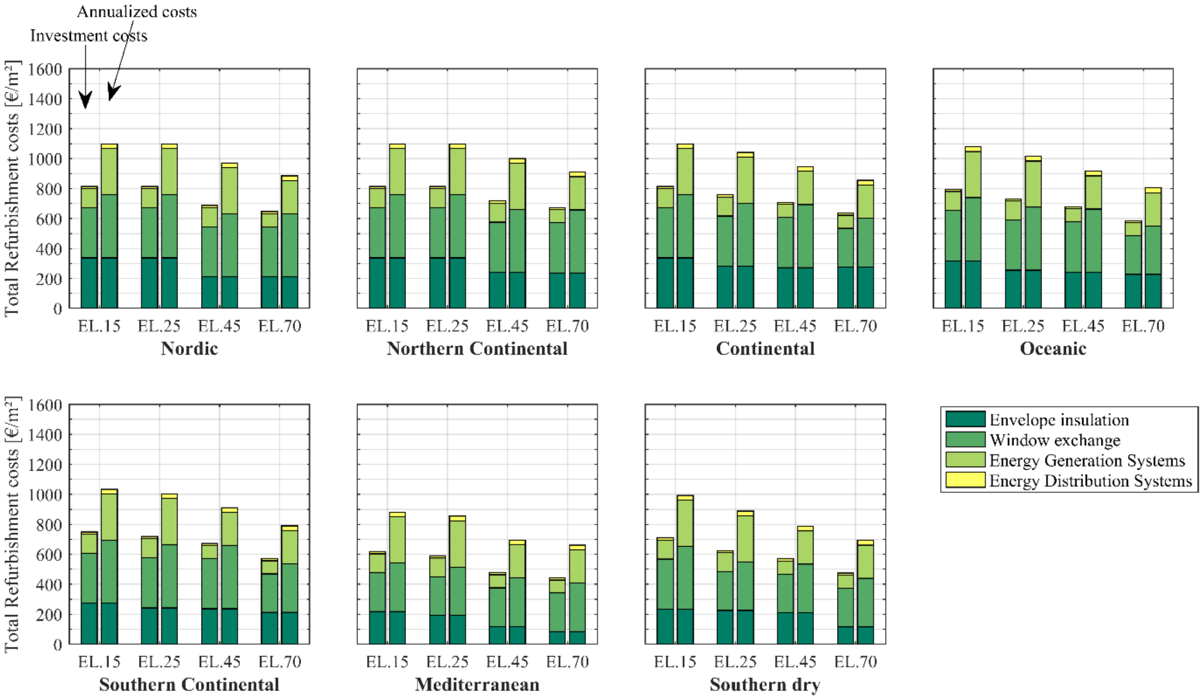

Figure 90 - Yearly annualised costs distribution for variants without solar systems

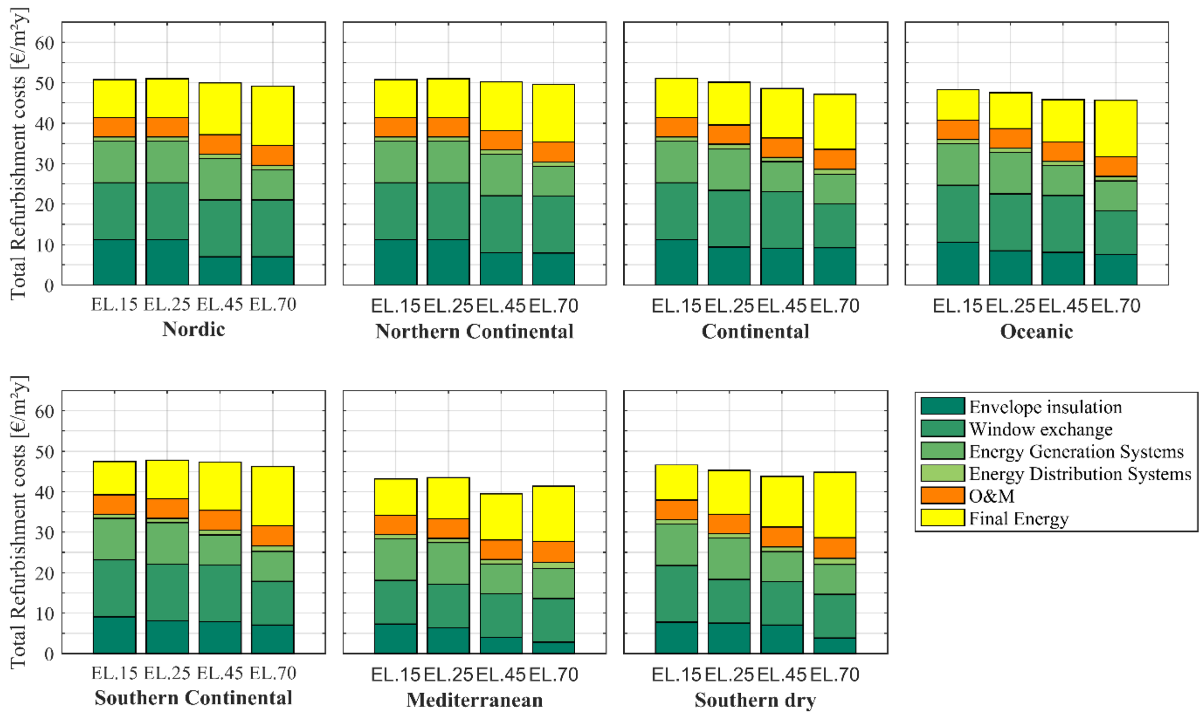

Figure 91 - Yearly annualised costs distribution for variants without solar systems

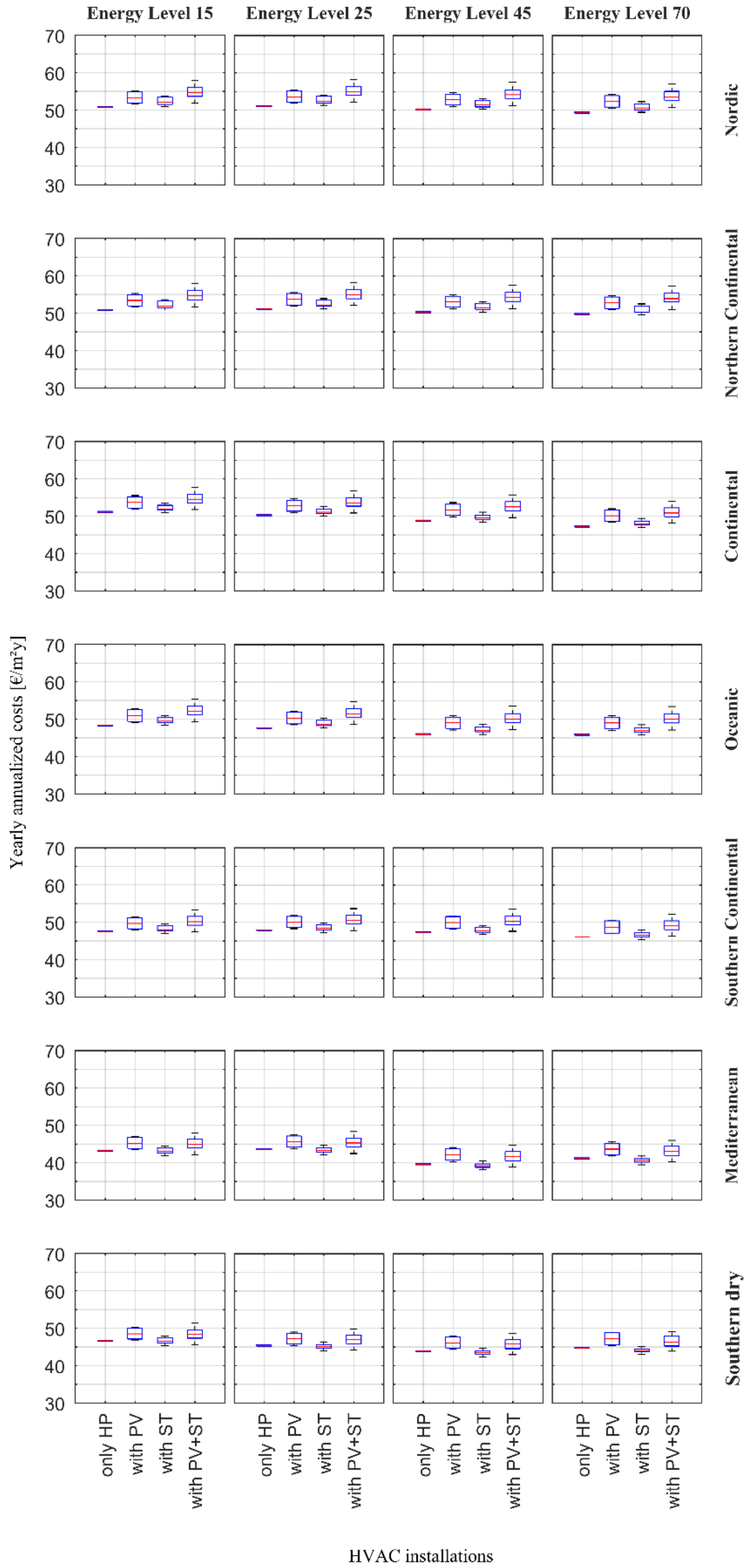

Figure 92 - Yearly annualised costs distribution for variants with solar systems

3.8 Single Family Houses – Pellet boilers + fan coils

3.8 Single Family Houses – Pellet boilers + fan coils

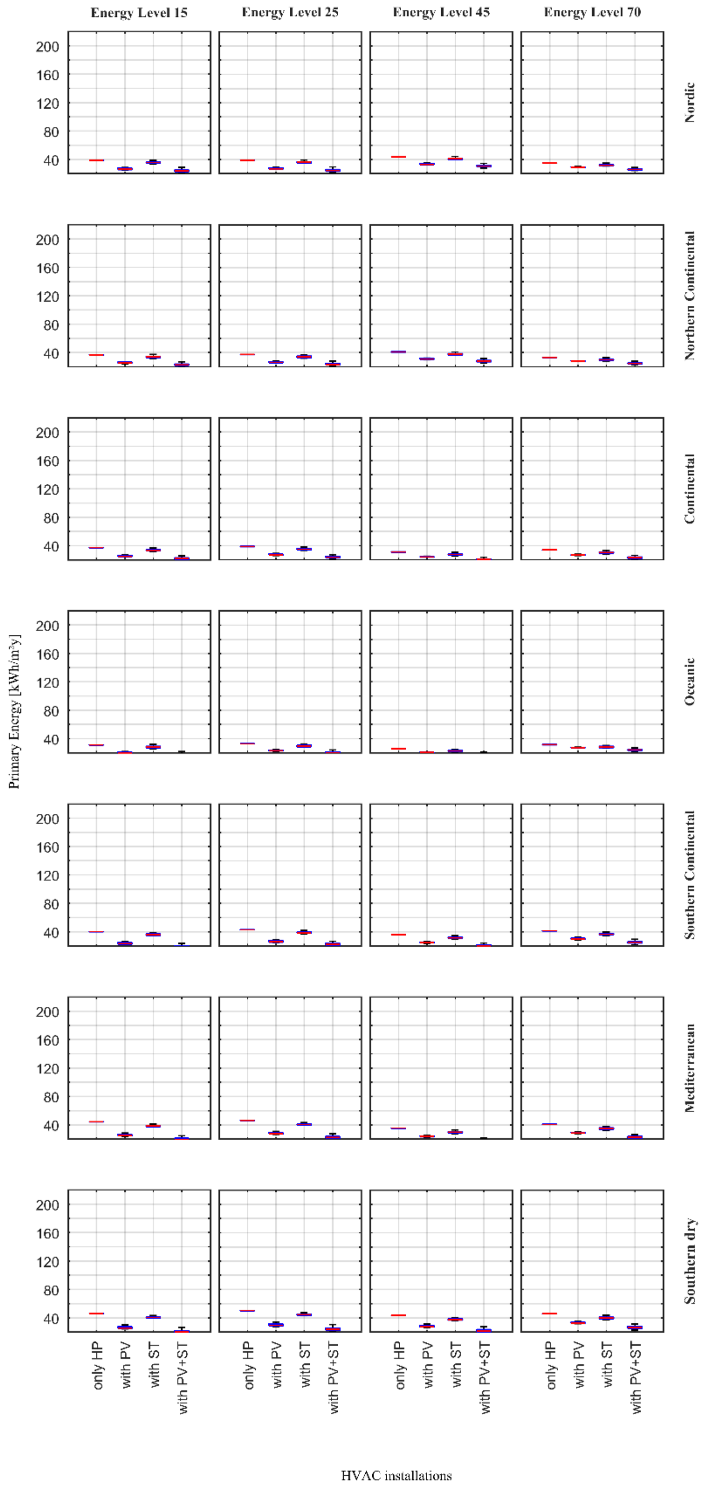

Figure 93 - Total primary energy for different HVAC installation types

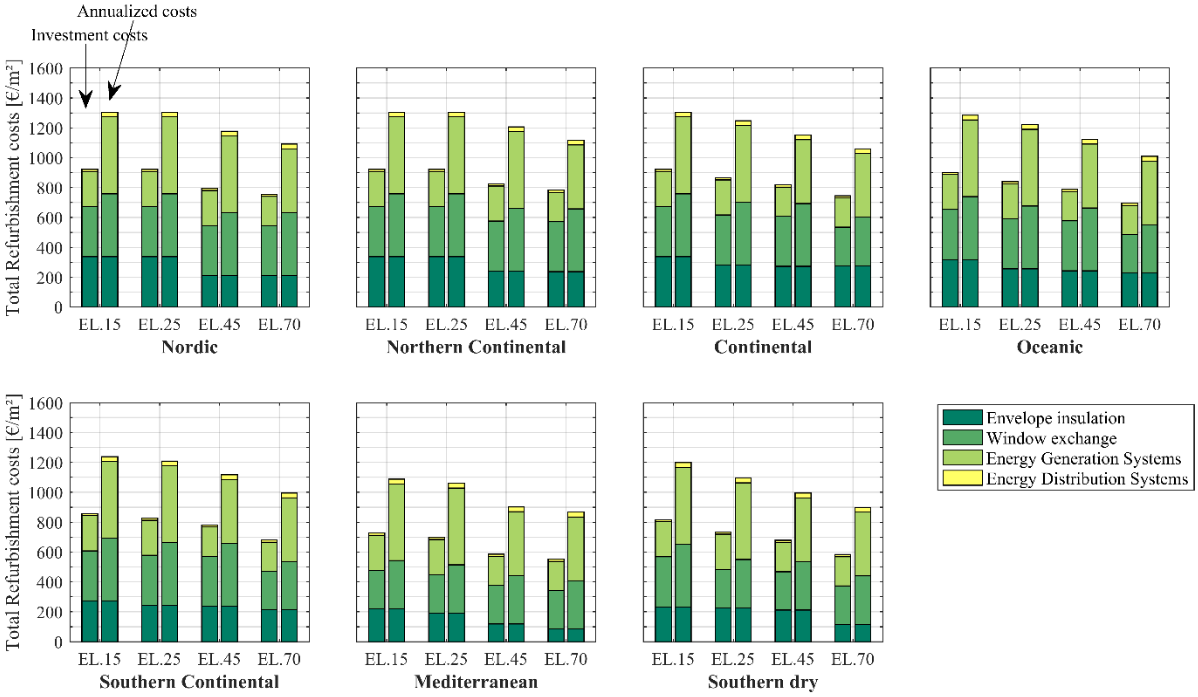

Figure 94 - Yearly annualised costs distribution for variants without solar systems

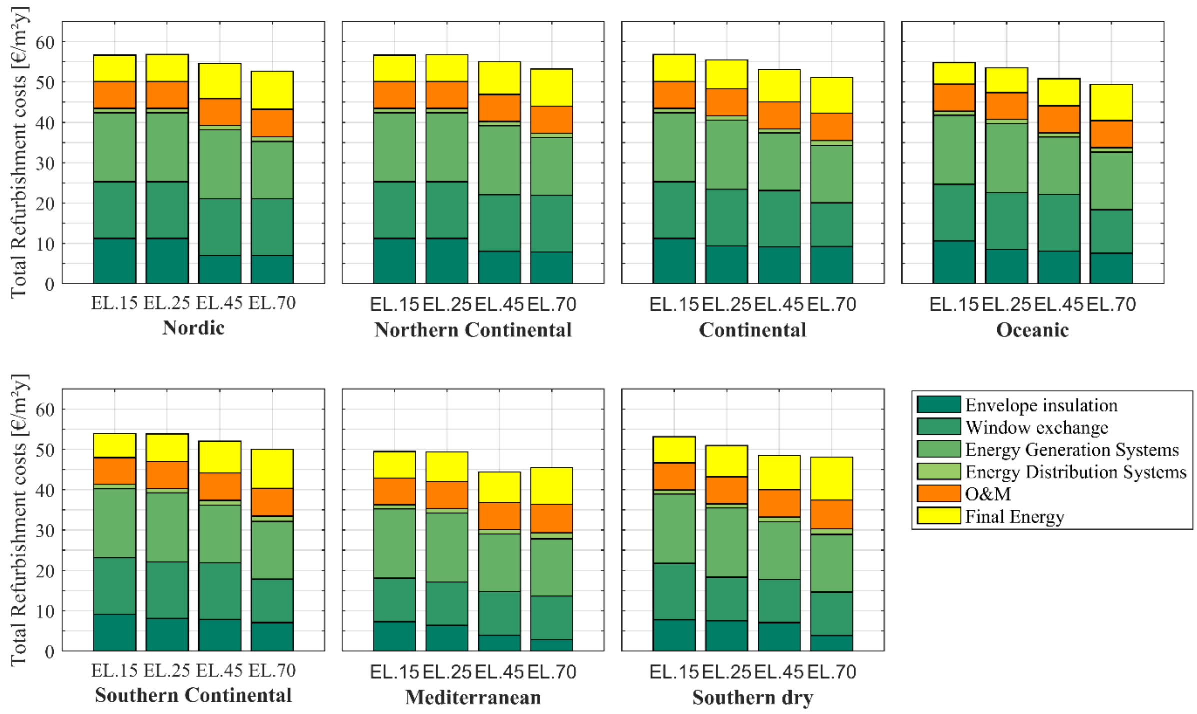

Figure 95 - Yearly annualised costs distribution for variants without solar systems

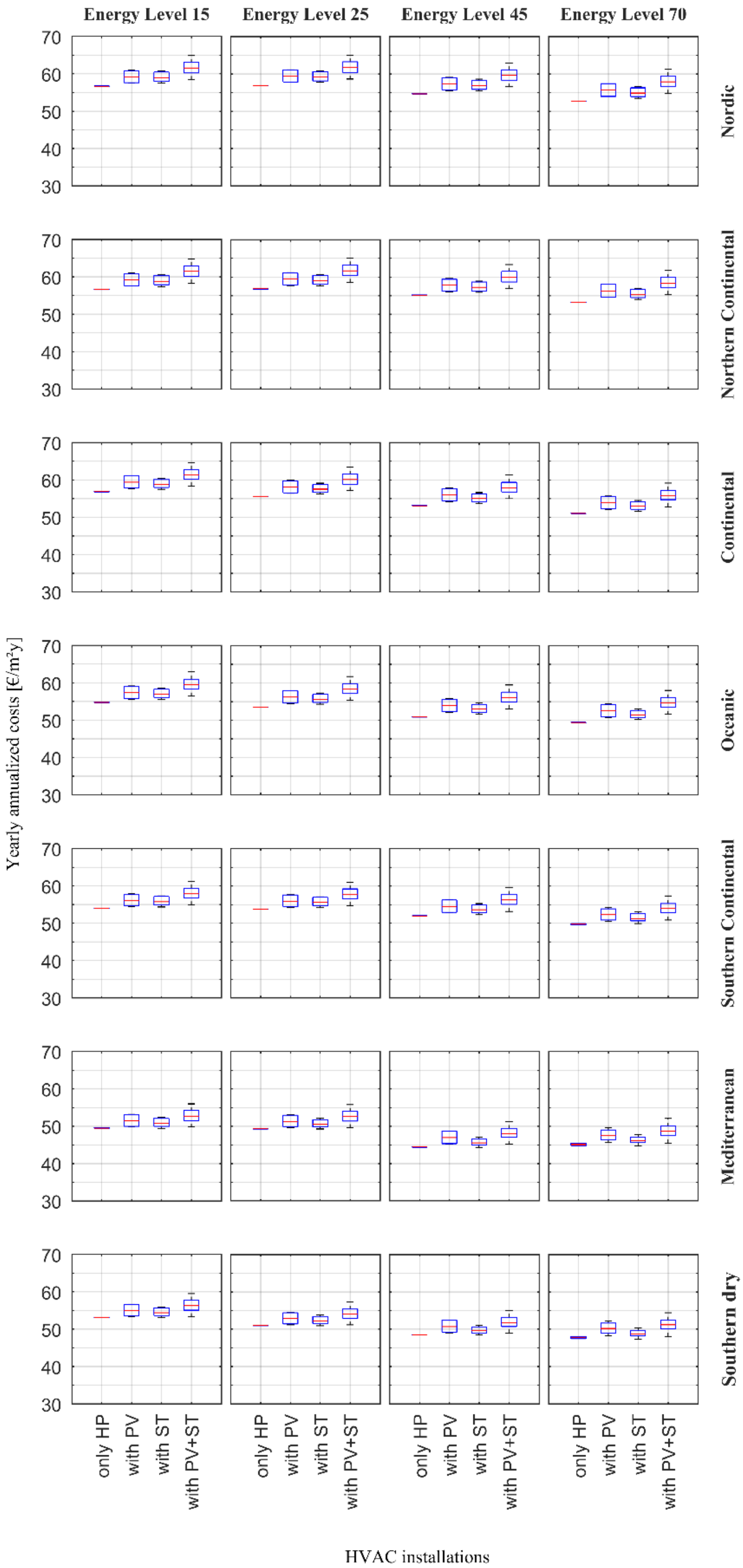

Figure 96 - Yearly annualised costs distribution for variants with solar systems

3.9 Single Family Houses – Air to water heat pump + radiators

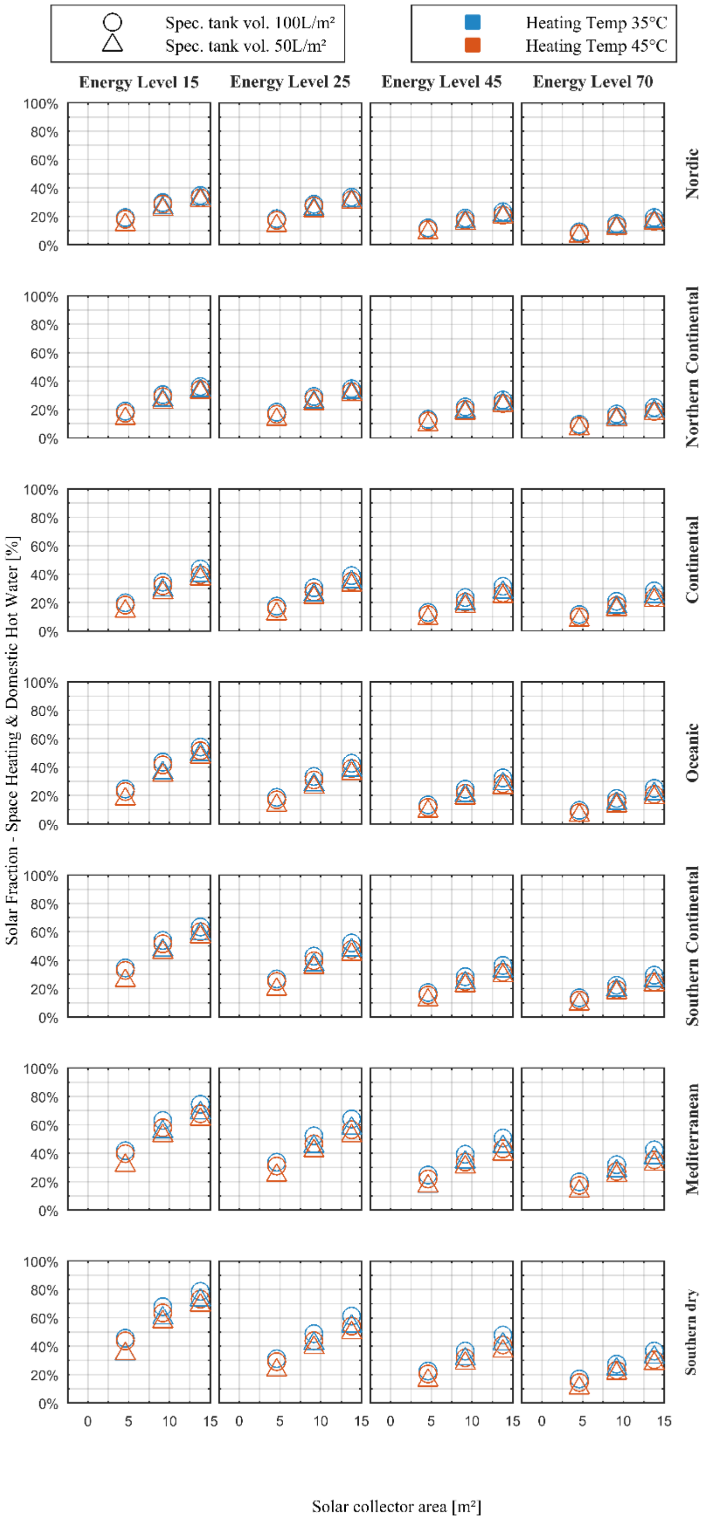

Figure 97 – Solar fraction for heating production with solar collectors in the main façade.

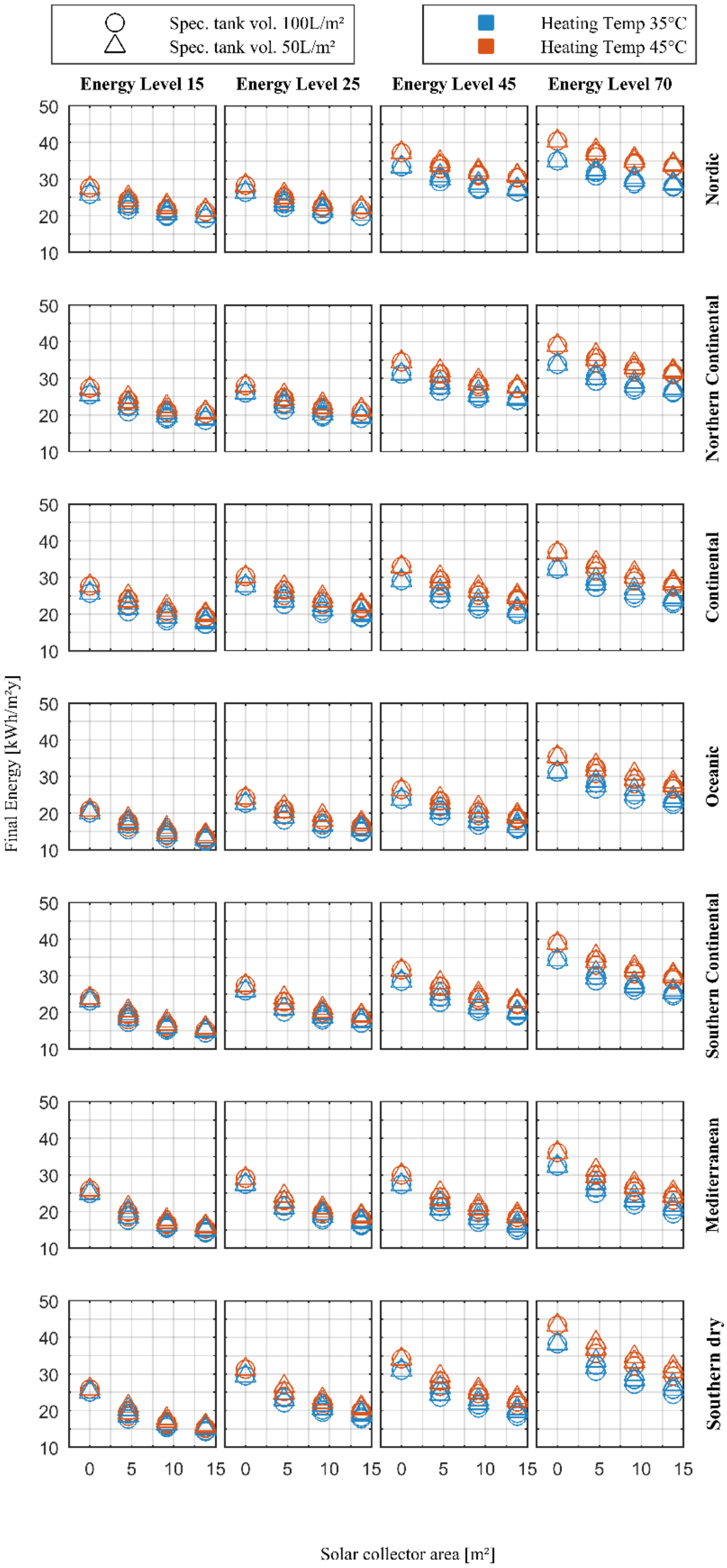

Figure 98 – Total final energy for several variants air-source heat pump and solar thermal system

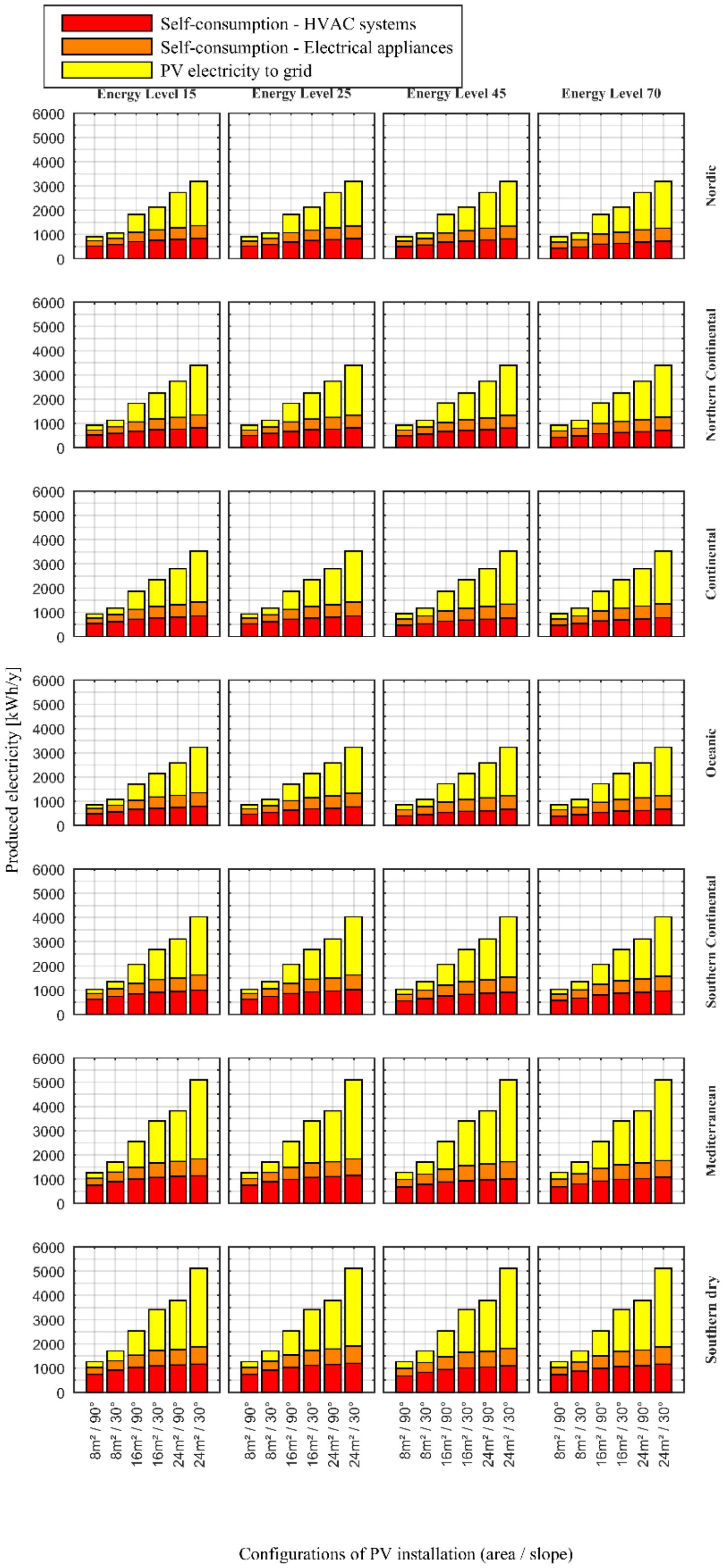

Figure 99 – Photovoltaic electricity production

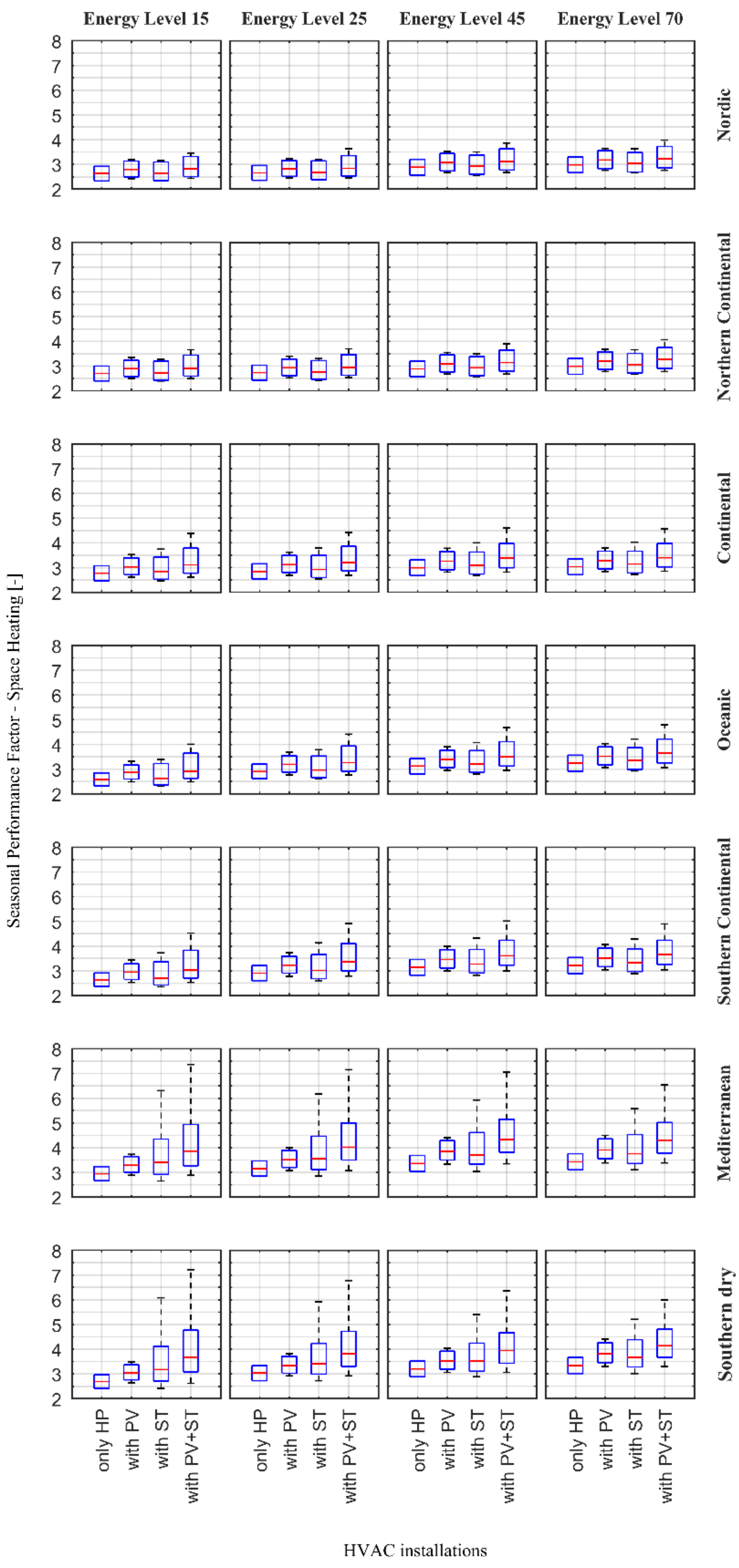

Figure 100 – Seasonal Performance Factor for space heating

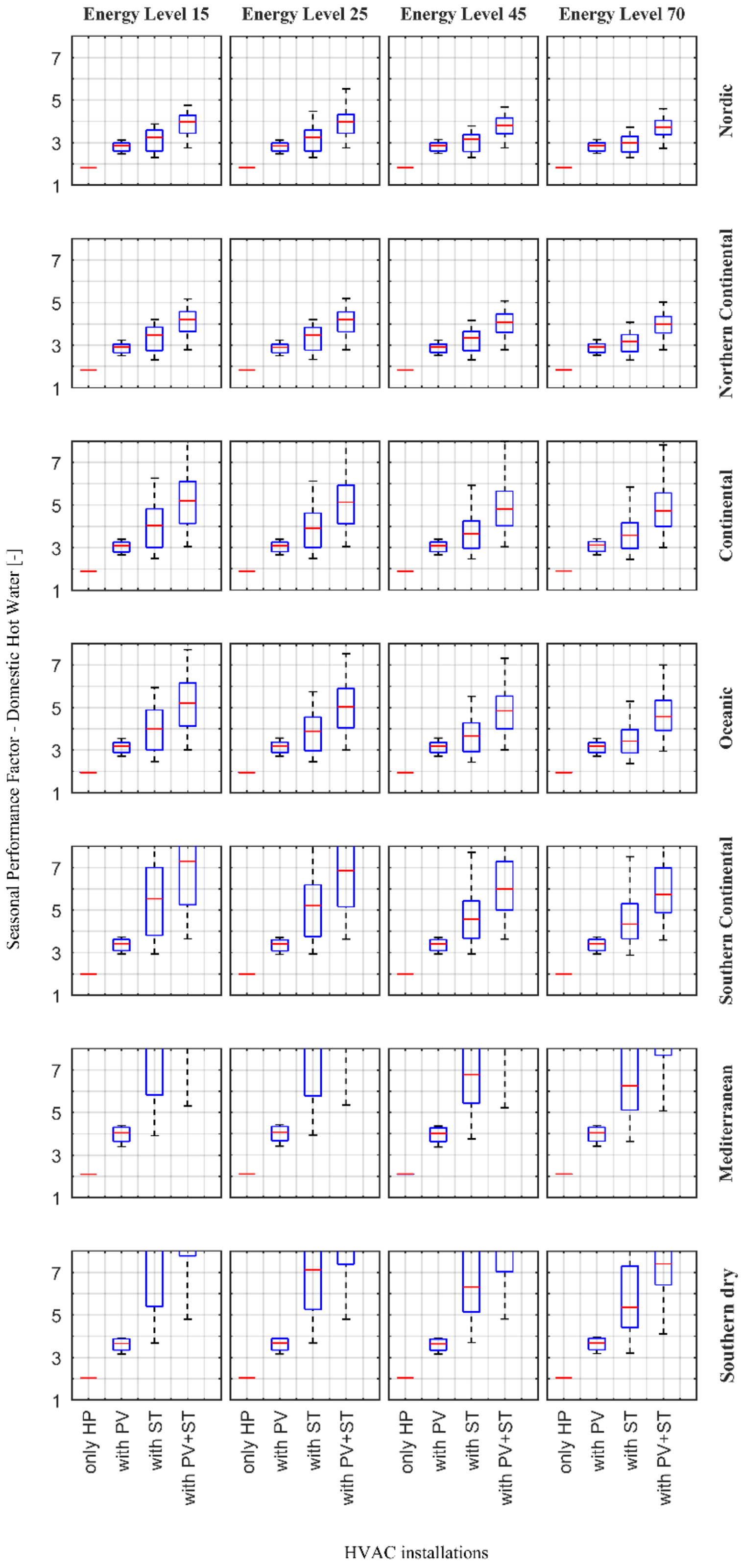

Figure 101 – Seasonal Performance Factor for DHW production

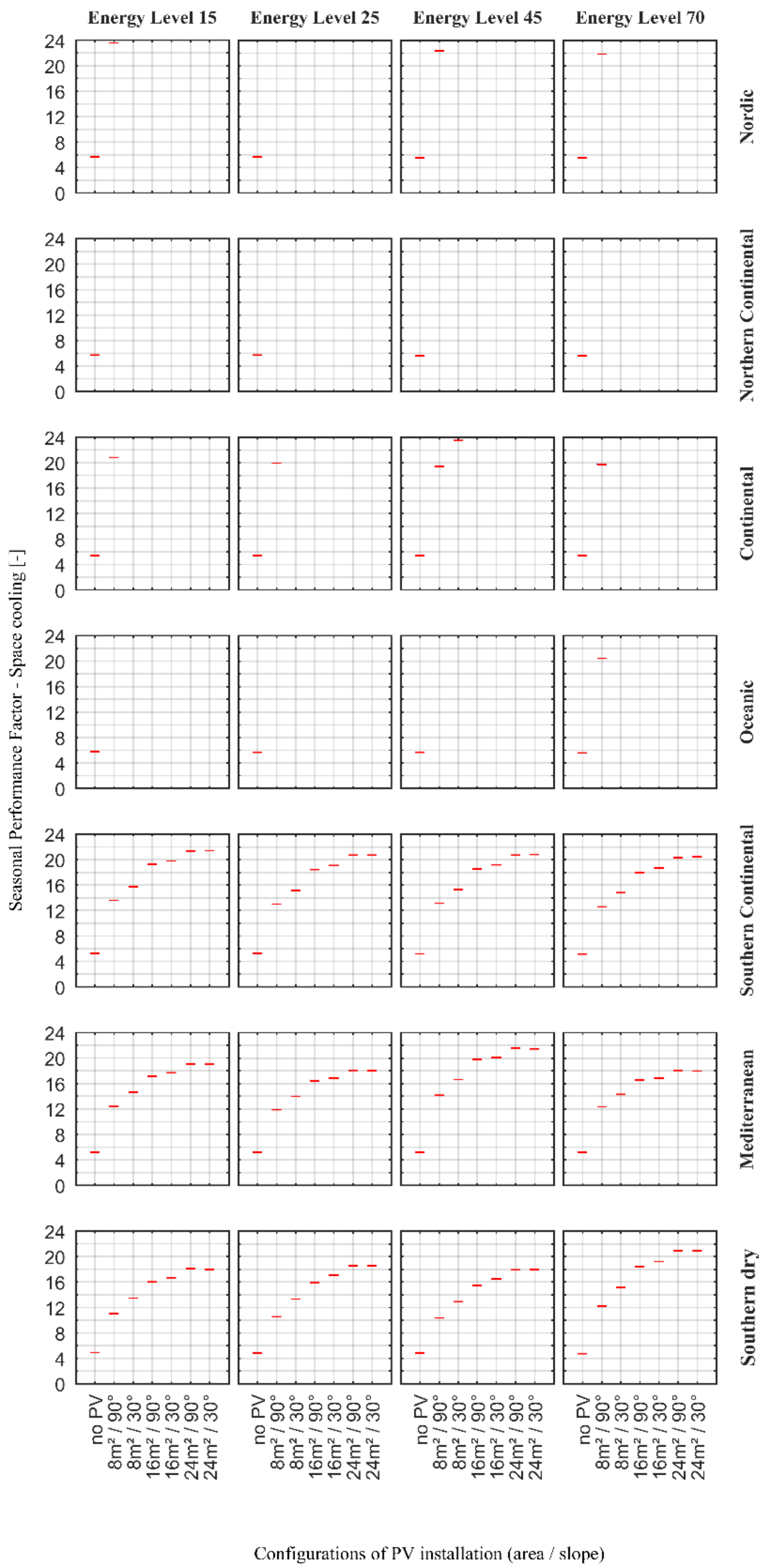

Figure 102 - Seasonal Performance Factor for Space Cooling

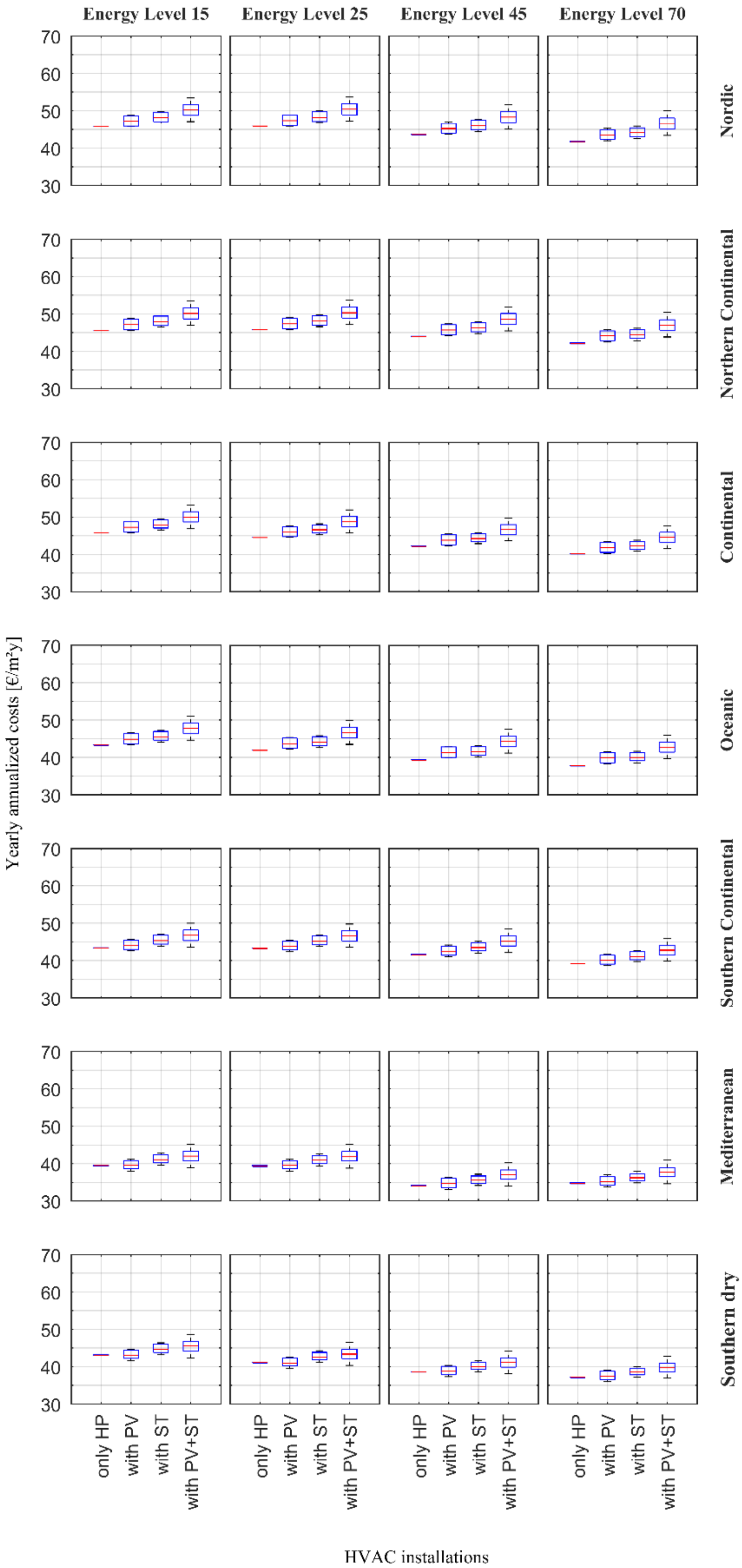

Figure 103 – Yearly annualised costs distribution for variants with solar systems

3.10 Single Family Houses – Ground source heat pump + radiators

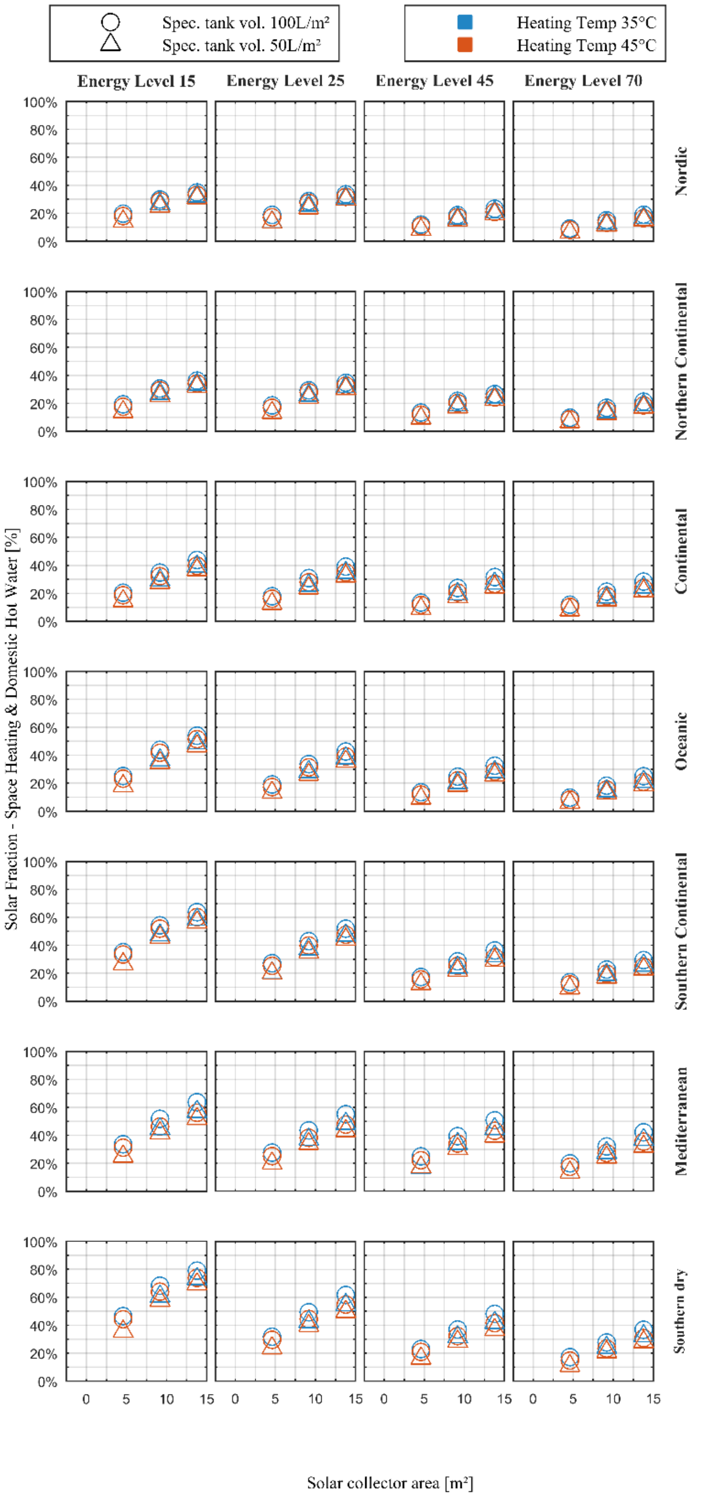

Figure 104 – Solar fraction for DHW + space heating with solar collectors in the main façade.

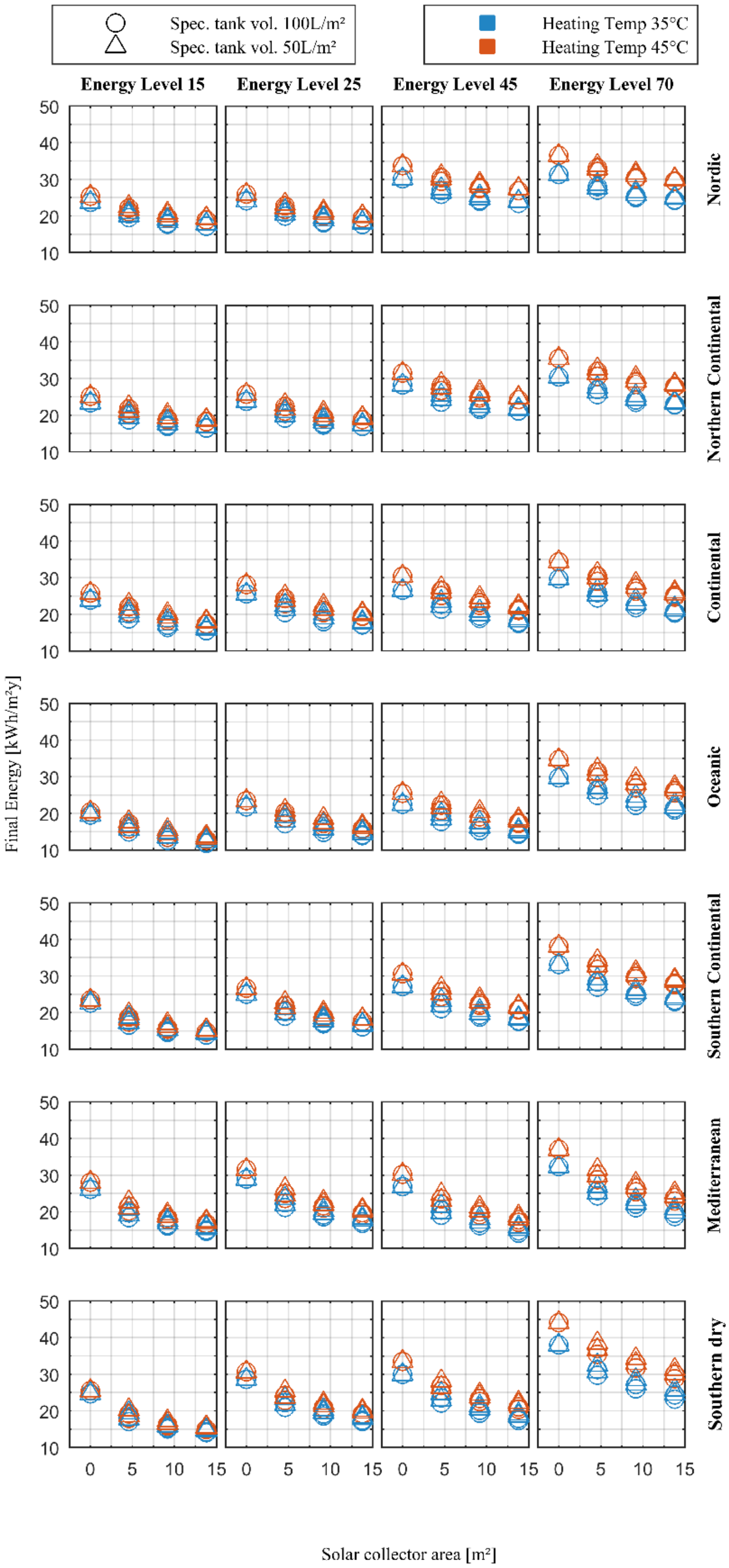

Figure 105 – Total final energy with solar thermal system

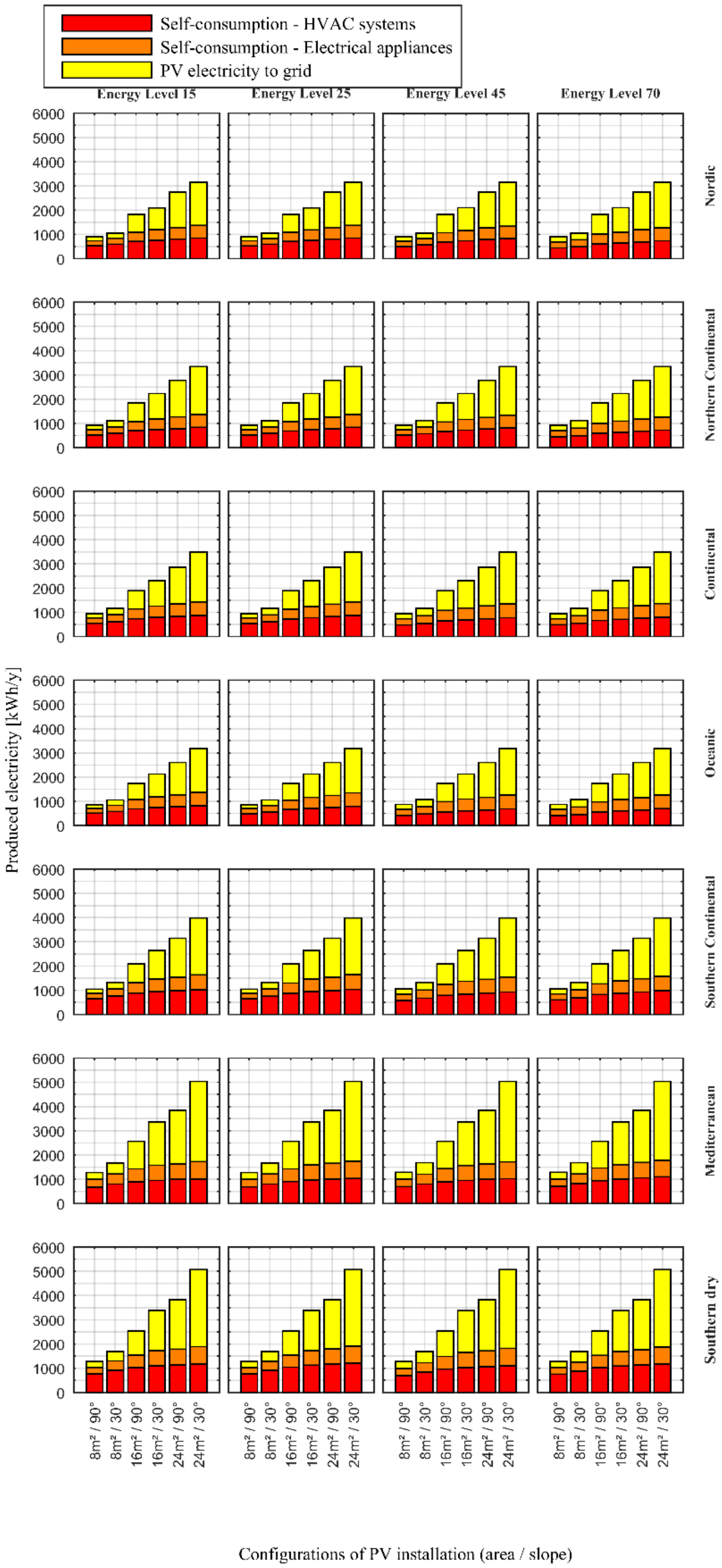

Figure 106 – Photovoltaic electricity production

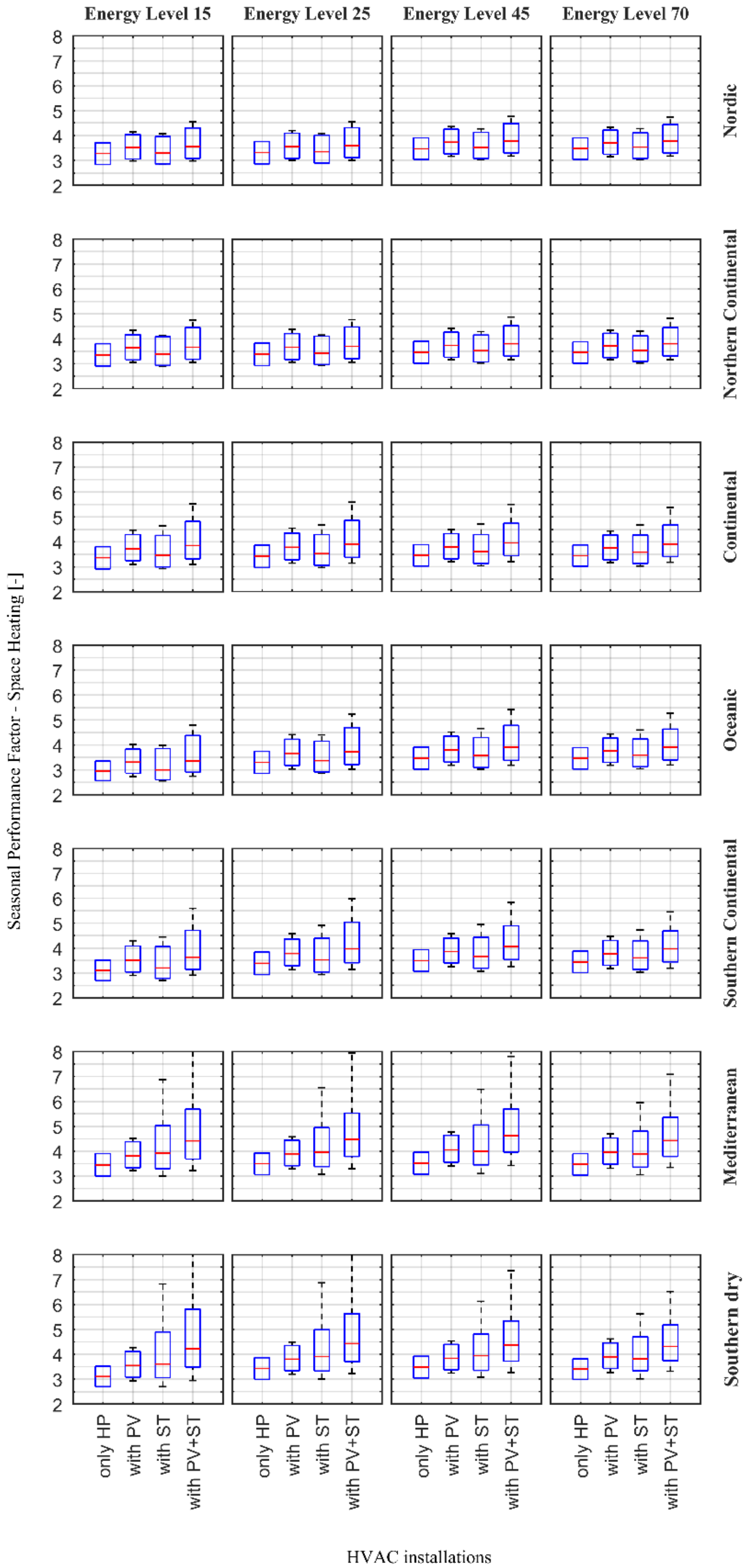

Figure 107 – Seasonal Performance Factor for space heating

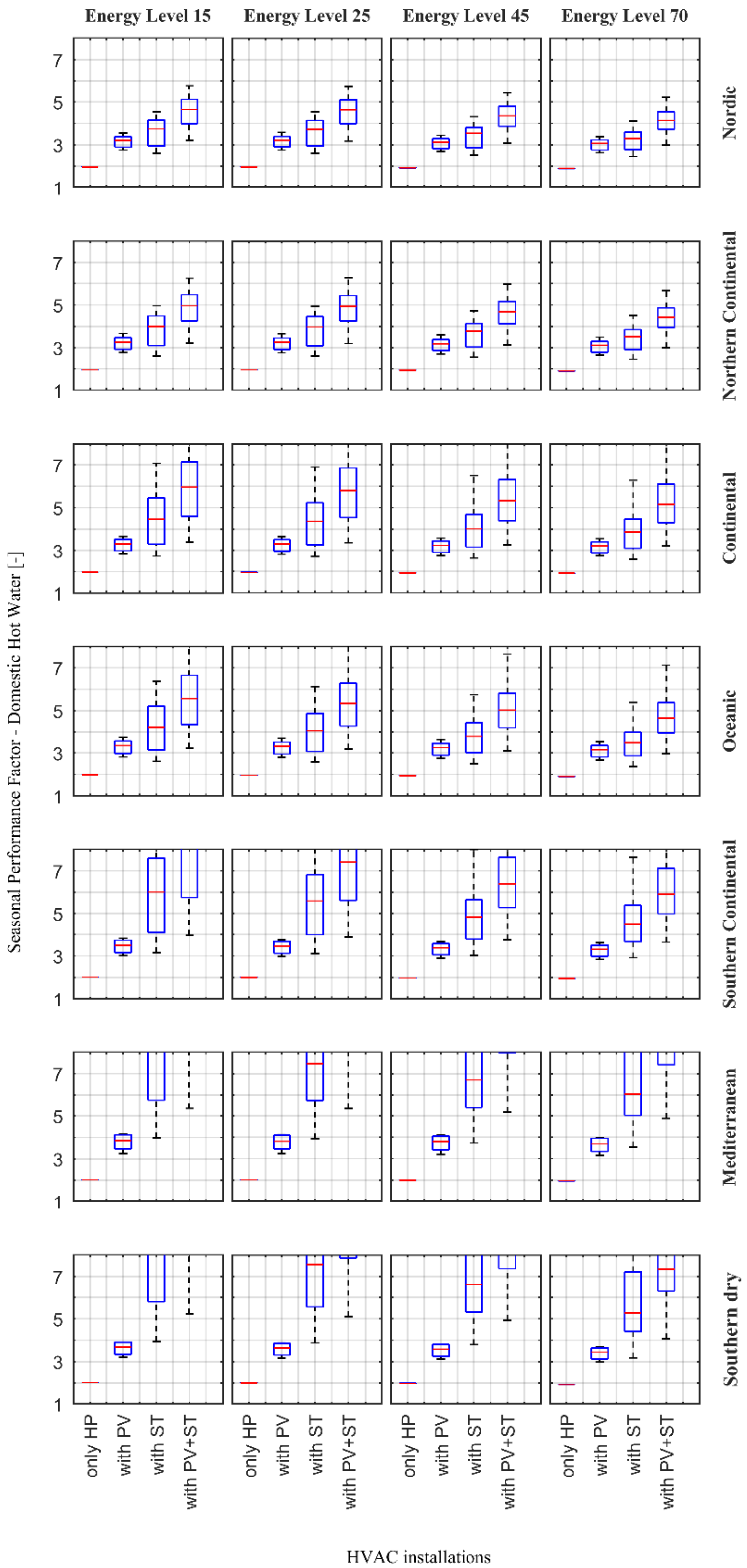

Figure 108 – Seasonal Performance Factor for DHW production

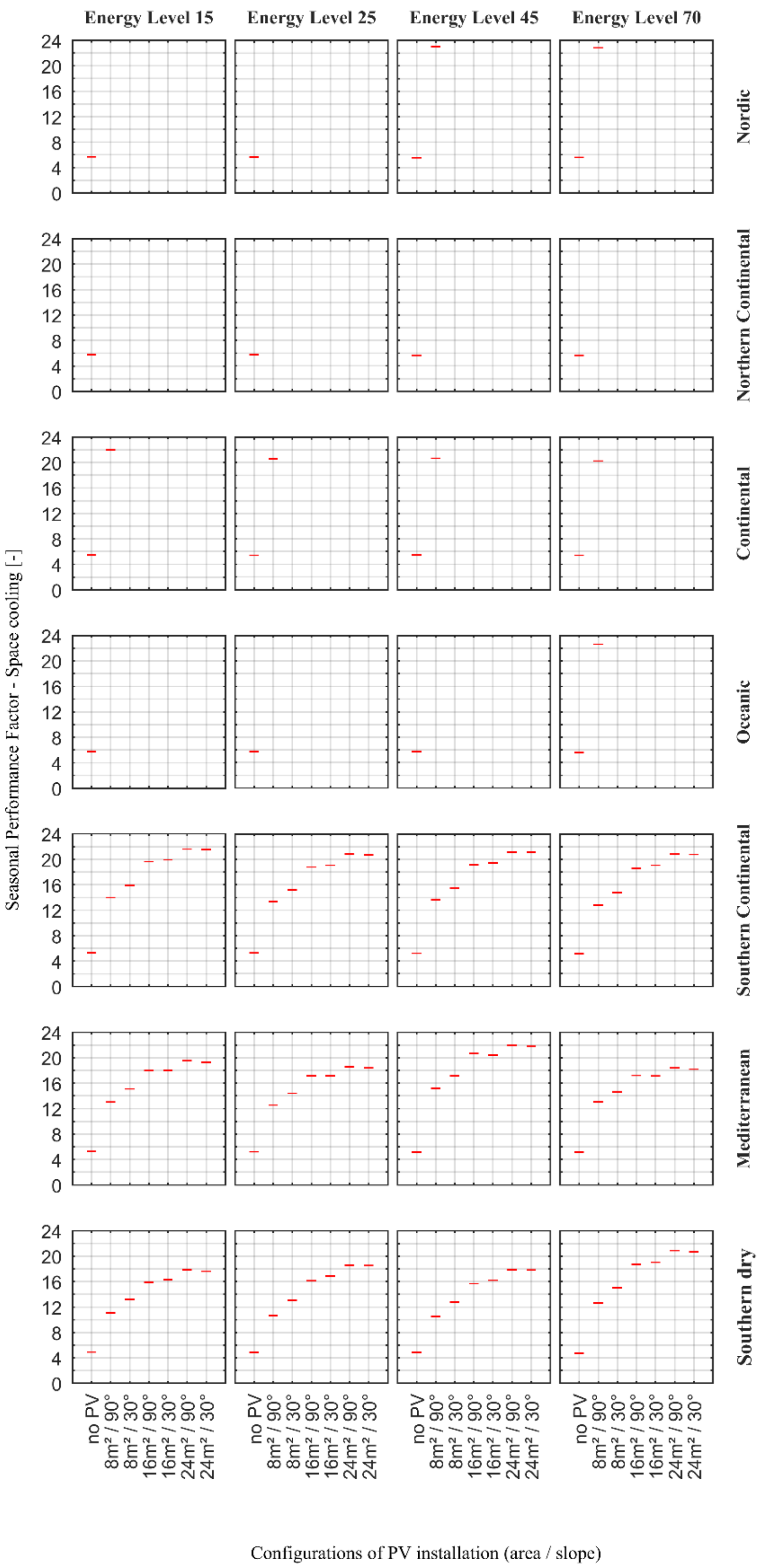

Figure 109 – Seasonal Performance Factor for space cooling

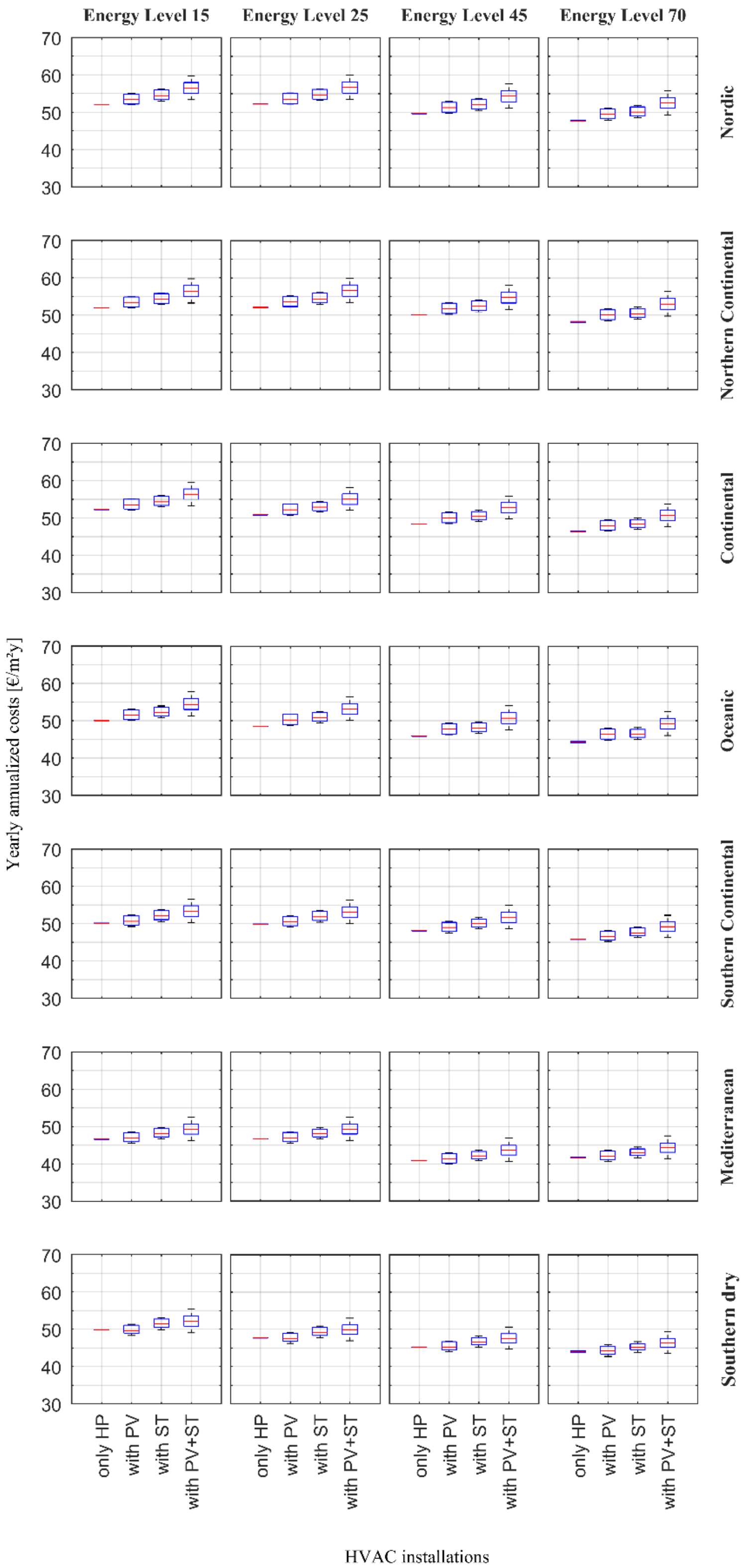

Figure 110 – Yearly annualised costs distribution for variants with solar systems

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