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Assessment of Subsidization Strategies for Multi-Objective Optimization of Energy Efficiency Measures for Building Renovation at District Scale

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Abstract: In recent years, public authorities around the world have used incentive strategies to encourage the renovation of the existing building stock to meet the set carbon neutrality targets. However, the design of the incentives typically does not consider that the subsidized energy efficiency measures should result in robust long-term improvements with respect to various objectives. Moreover, building energy retrofit analyses are commonly conducted at the individual building level rather than at urban scale, which could instead significantly accelerate the renovation rate. In this context, the current research aims to combine these different factors to support the design of building energy retrofit programs. We developed 21 subsidization strategies and their impact was evaluated on a parametric multi-objective optimization with respect to energy, economic, and environmental performance for a district located in Bolzano, Northern Italy. The optimization was performed considering a set of energy efficiency measures, pertaining to building envelope, climate change, economic scenarios, and two types of energy supplies. The results showed that (1) the impact of climate change is limited for the climate of Bolzano; (2) the type of energy supply strongly influences the economic feasibility of the retrofit investments; (3) when the investment is profitable, the optimal solutions include those measures with the largest impact on energy efficiency; and (4) subsidization strategies modify the number and composition of the Pareto solutions.

Keywords: subsidization strategies; urban building energy modeling; urban simulation; CitySim; building energy retrofitting; multi-objective optimization; climate change

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1. Introduction

The European Union (EU) has been active in building decarbonization policies for many years, adopting one of its main legislative acts about 20 years ago, i.e., the Directive 2002/91/EC [1]. Despite this, the estimated energy consumption associated with the building sector in the EU has remained substantially unchanged in this period, being equal to about 40% of the total energy demand of all Member States [2,3]. In this framework, the EU Green Deal is the latest strategy developed to achieve the EU's 2030 climate goals and climate neutrality by 2050 [4]. Furthermore, the Renovation Wave initiative has been launched specifically for buildings [3], in order to at least double the annual renovation rate by 2030 and to promote deep energy renovation [5]. In this framework, the European Parliament recently voted on the revision of the Energy Performance of Building Directive with the following objectives: (i) ensuring that all new buildings are zero-emission by 2028; (ii) reaching class E energy performance by 2030 and class D by 2033 for residential buildings; and (iii) attaining the same ratings for non-residential and public buildings by 2027 and 2030, respectively [6].

As regards the technical aspects, Building Performance Simulation (*BPS*) can support the building renovation process, for instance, by assessing the efficacy of several Energy Efficiency Measures (*EEMs*), facilitating the identification of the most suitable and effective ones. This can be verified either with simple approaches, i.e., manually running several simulation alternatives, or by combining *BPS* with optimization techniques. While the former methodology leads to the evaluation of a defined number of scenarios [7], which may not include the optimal solution, the latter one can guarantee that optimal or near-optimal solutions are actually found. Among the many optimization methods employed in the field of *BPS* [8], multi-objective optimization is the most widely used because it can find the solutions satisfying competing criteria influencing environment, occupants, and economical aspects, such as energy needs, indoor thermal comfort, and operational costs [9].

Although the retrofit cost objective (along with energy) is the most widely used [10], and many public authorities currently provide several subsidization strategies for renovating the building stock, there is no general consensus on the best form of incentives [11]. Several studies have focused on the effectiveness of incentive schemes for building energy retrofitting. While these studies have examined various aspects of subsidies, it is important to note that they primarily analyze existing incentive schemes rather than exploring new subsidization strategies. Moreover, given the multidisciplinary nature of the energy policy field, subsidies in building energy retrofitting have been often studied from different perspectives. Trotta and Spangenberg [12] compared residential energy efficiency policies and private initiatives in five European countries, underlining the importance of policy design and its role to overcome different barriers and succeed in various target segments. Following this concept, Cremer and Weber [13] assessed the effectiveness and robustness of policy instruments by introducing the concept of net-benefit curves (quantification of the relationship between the reduction in carbon dioxide emissions at the macro level and the economic viability-based retrofit decision at the micro level), to help to identify those changes in policies parameters leading to substantial and economically attractive retrofits. Moving toward the analysis of the impact of incentives on specific case studies, De Masi et al. [14] studied the Italian "Superbonus" mechanism, which provides a tax deduction of 110% over 5 years, by analyzing energy, environmental, and economic performance of a real representative building. Similarly, Mayer et al. [15] examined the incentive effects of the German energy retrofit funding schemes for single-family houses built just before the first national thermal insulation legislation. To evaluate the financial attractiveness of incentive schemes in different countries, Menicou et al. [16] conducted a comparative analysis of the funding schemes in Cyprus, in Greece, and in the United Kingdom. Finally, Penna et al. [17] investigated to which extent the incentives on different typologies of *EEMs* can improve the performance of the optimal retrofit solutions, considering residential building modules in two climatic contexts representative of Italy.

Regardless of the adopted objectives and economic perspective, the common target remains the improvement of the energy performance of the existing building stock toward the standard of nearly-Zero or Zero Energy Buildings. However, the robustness of the proposed solution is a critical aspect to take into consideration in renovation study. Indeed, in the context of climate change with evolving microclimatic conditions, selected measures are expected to be suitable not only for the current scenario but also for the long term. While some studies have considered this aspect by incorporating future weather files into their optimization analyses, research in this direction remains limited to a few cases. For instance, in order to consider the effect of climate change on building retrofitting, Mostafazadeh et al. [18] introduced a novel simulation-based multi-objective optimization approach and applied it to a residential building in Tehran, Iran, considering different scenarios with future climate change and energy price variation. Likewise, to cope with the same problem and overcome the shortcomings of standard optimization techniques, Ma et al. [19] developed a dynamic intelligent building retrofit decision-making model in response to climate change.

At this point, it has been outlined that when it comes to building retrofitting, both incentives and climate change should be included in a multi-objective optimization study, in order to make informed decisions and provide robust designs for the long term. However, in order to accelerate the renovation process, it is necessary to incorporate all of these aspects into urban-scale analyses. In fact, moving from the current step-by-step renovation to district-level retrofit interventions can increase the renovation rate to at least 3%, thus meeting the requirements set by the EU [20]. Furthermore, addressing energy efficiency challenges at the urban scale allows for the implementation of solutions that would be otherwise unattainable by focusing solely on individual buildings [21]. Examples include the design of smart districts and the integration of buildings into energy communities [22]. Finally, urban-scale approaches can be used to assess which *EEMs* are most prominent in existing buildings, and thus which are most worth investing in.

In conclusion, when implementing new design solutions in buildings, another important aspect that is usually overlooked in favor of energy consumption reduction is the total amount of saved CO_2 emissions, considering also the global warming potential of the introduced *EEMs*. Indeed, as buildings become more and more energy efficient and their associated operational carbon emissions decrease, the embodied carbon in the life cycle can become significant [23]. In this regard, embodied carbon is an essential aspect when focusing on environmental sustainability in a comprehensive way, and there are very few studies in the literature aiming at finding a trade-off between embodied and operational carbon [24]. Furthermore, accounting for the embodied carbon in the decision-making process could lead to the adoption of more environmentally friendly materials while still guaranteeing satisfying energy efficiency improvements [25].

In this context, the present study aims to integrate all these aspects in order to support the definition of retrofitting policies for the building stock at the district level and to study the influence of different incentives on the results. A parametric multi-objective optimization with respect to environmental, energy, and economic performance is run for a district located in the city of Bolzano, Northern Italy, considering a set of *EEMs* related to the building envelope. Twenty-one different subsidization strategies are developed and studied and their impact on the optimization results evaluated. The effects of climate change, cost of energy, and *EEMs* are also considered to provide long-term insights.

2. Methodology

As mentioned in the introduction, this study aims at accounting for the effect of several aspects on the outcome of a parametric multi-objective optimization for building retrofitting at district scale. The methodology focused on applying to the considered case study a set of *EEMs* along with several simplified subsidization approaches, while evaluating different scenarios in terms of (a) climate change, (b) type of energy supply, and (c) cost.

2.1. Case Study

In this research, the same case-study neighborhood employed in a previous work by Haneef et al. [26] was used to analyze and discuss all aspects mentioned above. The selected district is located in Bolzano, Italy, an Alpine city characterized by a heating-dominated climate. It consists of 95 residential buildings built between 1990 and 1995 using similar materials, and thus having comparable thermal envelope properties. The district was chosen because it is connected to the district heating system serving part of the city, making it easier to collect actual energy consumption data and perform calibration and validation of the developed urban building energy model.

The geometrical model of the neighborhood was created with reference to several sources. The official Geographic Information System (*GIS*) of the City of Bolzano was used to retrieve the footprints of each building. Then, the Digital Surface Model (*DSM*) and Digital Terrain Model (*DTM*) of the area were compared to calculate the height of each building. Assuming a floor height of 3 m, the resulting building heights were checked on

Google 3D Maps for consistency. Windows were modeled using the window-to-floor ratio, assuming a value of 1/8 in accordance with the current Italian regulation.

As for the non-geometric characteristics, they were obtained from the energy performance certificates of the buildings provided by the local energy agency, i.e., the Klimahaus Agency. Rather than assigning to each building the properties found in the certificates, three envelope archetypes were generated according to the procedure proposed by Haneef et al. [26]. The average thermal transmittances of the building components for each building envelope archetype are reported in Table 1, while a detailed description of their composition and the other properties characterizing the case study can be found in the previous contribution [26]. The remaining model inputs were set in agreement with technical standards [27,28].

Table 1. Average thermal transmittances of the building components (W m^{-2} K^{-1}) for the three building envelope archetypes.

	Wall	Roof	Floor	Windows
Archetype1 A1	0.60	0.32	0.39	3.2
Archetype2 A2	0.64	0.24	0.46	3.2
Archetype3 A3	0.52	0.35	0.43	3.2

The district was modeled by using CitySim as the modeling tool, and its heating needs were calibrated using a k-fold cross-calibration–validation method, achieving deviations within ±5% of the metered energy needs at the district level. Figure 1 shows the 3D geometrical model of the case-study district developed.

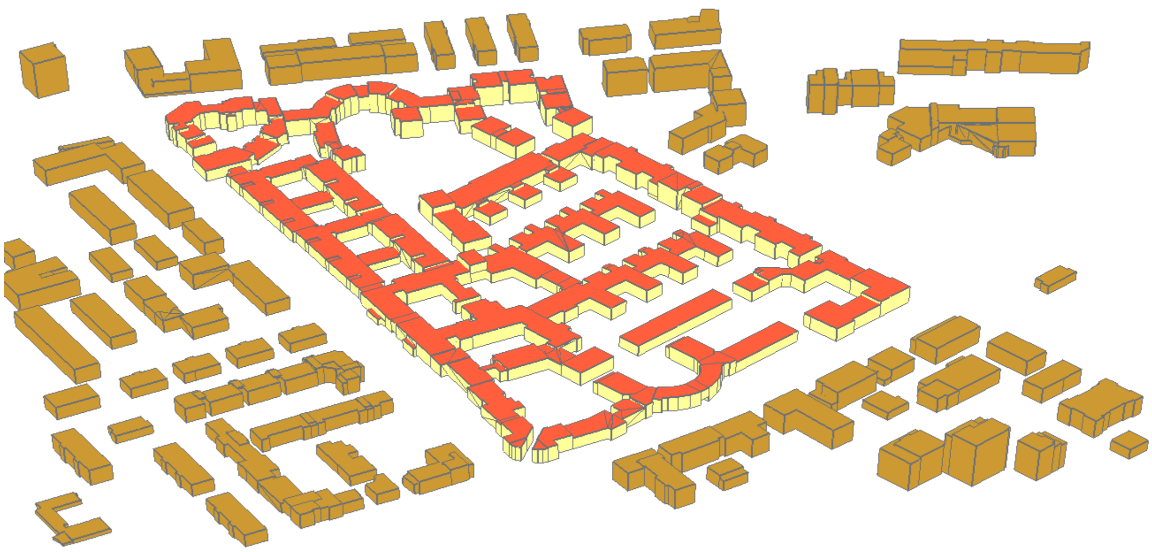

Figure 1. CitySim semantic model of the case-study district with shading surfaces in brown, walls and roofs of the studied buildings respectively in yellow and orange.

2.2. Scenarios

2.2.1. Climate Scenarios

Since this research aims at providing guidelines that can be reliable in the long term, simulations were carried out with two different weather files and results compared to assess the influence of climate change. Specifically, we used (i) a standard Typical Reference Year (*TRY*, heating degree days with base temperature equal to 18 °C HDD_{18} = 2178 K d, cooling degree days with base temperature equal to 18 °C CDD_{18} = 504 K d, calculated according to ASHRAE 169 [29]), and (ii) a 2050 future climate of the city of Bolzano (HDD_{18} = 2115 K and CDD_{18} = 701 K d). The latter one was generated with Meteonorm according to the A2

Business as Usual climate change scenario of the emission scenarios report for the period 1961–2100 by the Intergovernmental Panel on Climate Change (*IPCC*) AR4 [30].

2.2.2. District Scenarios

Since in Italy, more than two-thirds of households use natural gas as an energy source for space heating [31], in order to make the findings of this work easier to generalize, a fictitious alternative residential district, not connected to the district heating network but served by standard gas boilers, was created. To obtain the required natural gas consumption of the boiler district, the simulated final uses in the case of district heating were increased considering the minimum efficiencies required from existing standard boiler systems reported in the local regulation (DGP 235/2020) [32].

2.2.3. Energy Efficiency Measures and Economic Scenarios

Only *EEMs* aiming at improving the energy performance of the envelope were selected and applied simultaneously to the entire building fabric; i.e., partial renovation strategies using only some *EEMs* were not considered. Moreover, the chosen *EEMs* are known to improve occupants' thermal comfort (e.g., leading to higher mean radiant indoor temperatures in winter) while still guaranteeing satisfactory indoor air and environmental quality, assuming that the same ventilation rate is adopted by the occupants.

Two types of windows were used:

- Double glazing (*DH*) with high Solar Heat Gain Coefficient (*SHGC*) (U_{gl} = 1.14 W m^{-2} K^{-1}, *SHGC* = 0.61).
- Triple glazing (*TH*) with high *SHGC* (U_{gl} = 0.61 W m^{-2} K^{-1}, *SHGC* = 0.58).

Both window alternatives were chosen with high *SHGC* because this research focuses only on the heating performance of buildings in an Alpine climate, where high *SHGC* windows are generally preferred.

Two insulation materials were selected:

- Extruded polystyrene (*XPS*) with a thermal conductivity λ = 0.035 W m^{-1} K^{-1}, a density ρ = 30 kg m^{-3}, and a specific thermal capacity c = 1450 J kg^{-1} K^{-1}.
- Wood fiber with λ = 0.045 W m^{-1} K^{-1}, ρ = 160 kg m^{-3}, c = 2000 J kg^{-1} K^{-1}.

The insulation thickness was also selected according to two possibilities, such as the minimum requirement to comply with the law and 20 cm. The minimum value to meet the legal requirements changes according to the type of insulation material and the type of surface on which it is applied, i.e., wall or roof, as shown in Table 2. On the other hand, the choice for the maximum value of 20 cm was twofold. First, the rules about construction and urban planning compliance that are in place in Italian urban environments make it often difficult to install very thick insulation layers in building retrofits. Indeed, insulation thickness for this kind of intervention rarely exceeds 15 or 20 cm in the local dense urban context. Second, adding 20 cm of insulation leads to low thermal transmittances for both considered materials, equal to around 0.15 W m^{-2} K^{-1} for vertical walls, which are significantly lower than what it is typically expected in local standard retrofittings.

Table 2. Minimum insulation thicknesses to meet the law requirements for walls and roofs for each building archetype.

Type of Insulation	Element	Archetype1 A1	Archetype2 A2	Archetype3 A3
XPS	Wall	8 cm	8 cm	7 cm
	Roof	5 cm	2 cm	6 cm
Wood fiber	Wall	10 cm	11 cm	9 cm
	Roof	7 cm	2 cm	8 cm

A unitary investment cost *C*, including installation costs, was assigned to each *EEM* after an analysis of the costs present in the Official Regional Price List of the neighboring Province of Trento. In order to make the present work more robust for long-term evaluations in consideration of the recent economic uncertainty and inflation growth, a pre-pandemic economic scenario and two post-pandemic scenarios were evaluated. Thus, the Official Regional Price List of 2018 and 2021 were used to obtain the equations reported in Table 3 for the calculation of the unitary investment costs, respectively, for the pre-pandemic scenario and the post-pandemic scenario 1. For the insulation, the unitary investment cost was found in the function of the insulation thickness *s* in meters.

Table 3. Pre- and post-pandemic prices scenarios for the unitary investment cost *C* regarding insulation and windows. For the insulation, *s* represents the insulation thickness in meters.

Economic Scenario	Insulation		Windows	
	XPS	Wood Fiber	Double Glazing	Triple Glazing
Pre-pandemic scenario	$112.5{\cdot}s + 55.6$ EUR m^{-2}	$363.7{\cdot}s + 74.6$ EUR m^{-2}	421.7 EUR m^{-2}	463.9 EUR m^{-2}
Post-pandemic scenario 1	$288.3{\cdot}s + 52.0$ EUR m^{-2}	$373.6{\cdot}s + 76.9$ EUR m^{-2}	448.4 EUR m^{-2}	492.4 EUR m^{-2}
Post-pandemic scenario 2	$551.0{\cdot}s + 43.7$ EUR m^{-2}	$383.7{\cdot}s + 74.8$ EUR m^{-2}	476.8 EUR m^{-2}	522.7 EUR m^{-2}

As regards the post-pandemic scenario 2, expected to represent a third extreme inflation case, the *EEMs'* post-pandemic prices were increased at the same rate they increased between the pre- and post-pandemic periods.

In addition, the environmental impact of the proposed *EEMs* was expressed in terms of Global Warming Potential (*GWP*), i.e., in kilograms of CO_2 equivalent, according to the Swiss building materials database "Oekobilanzdaten im Baubereich" by KBOB [33]. For the insulation, 14.5 $kg_{CO2\text{-}e}$ kg^{-1} and 0.257 $kg_{CO2\text{-}e}$ kg^{-1} were used as *GWP* for the *XPS* and the cellulose fiber, respectively. For the windows, a *GWP* value of 18.02 $kg_{CO2\text{-}e}$ kg^{-1} was calculated for the double glazing (assuming 77% of glazed area) and 25.62 $kg_{CO2\text{-}e}$ kg^{-1} for the triple glazing (assuming 73% of glazed area), in agreement with Hoellinger et al. [34]. As regards the cost of energy in the different scenarios, it was also determined differently for the two simulated districts (i.e., the actual neighborhood served by the local district heating network and the fictitious one with natural gas boilers).

In the case of district heating, the average tariff calculated from the energy supply price lists remained approximately the same before and after the pandemic outbreak, due to the fact that the district heating of the city of Bolzano is fueled by municipal solid waste and it is not particularly influenced by the fluctuations of the energy market. As a consequence, an energy cost equal to 0.064 EUR kWh_t^{-1} was applied to all three economic scenarios [35]. On the other hand, the average price of natural gas increased significantly in Italy, from 0.0728 to 0.1005 EUR kWh_t^{-1} (38% increase) before and after the pandemic, respectively [36]. As regards the post-pandemic scenario 2, a further increase of 50% for the price of natural gas was considered. This was undertaken in order to define an extreme inflation scenario characterized by a non-linear increase for the energy vector price and differential inflation compared to pre-pandemic and post-pandemic 1 scenarios.

For all energy source prices, the fixed parts of the energy price were not accounted for in the economic analyses, since they are independent of the impact of the *EEMs*; i.e., the final consumers pay the same amount for the fixed part of the energy cost in all scenarios. Furthermore, the accounted value-added tax was equal to 10%, in agreement with the current Italian law [37].

2.2.4. Subsidization Strategies

In Haneef et al. [26], it was found that no retrofit scenario would be economically sustainable for the same district under consideration in the current research. Thus, a wide range of simplified subsidization strategies was analyzed to discuss whether they could be used to promote building energy renovation and, in some cases (such as from cases 10 to 19), to support the choice of more environmentally friendly, although expensive, solutions (Table 4):

Table 4. Summary of subsidization strategies with incentives color-coded according to the payment period (green: subsidization paid immediately; blue: subsidization paid in 5 years; red: subsidization paid in 10 years).

Case	Contribution for *XPS* (%)	Contribution for Wood Fiber (%)	Contribution for Windows (%)
1	25	25	25
2	25	25	25
3	25	25	25
4	50	50	50
5	50	50	50
6	50	50	50
7	75	75	75
8	75	75	75
9	75	75	75
10	25	75	50
11	25	75	50
12	25	75	50
13	50	75	50
14	50	75	50
15	50	75	50
16	25	75	50
17	25	75	50
18	50	75	50
19	50	75	50
20	110	110	110
21	110	110	110

0. No public contributions.
1. A total of 25% of public contribution for all the *EEMs*, paid immediately.
2. A total of 25% of public contribution for all the *EEMs*, paid in 5 years.
3. A total of 25% of public contribution for all the *EEMs*, paid in 10 years.
4. A total of 50% of public contribution for all the *EEMs*, paid immediately.
5. A total of 50% of public contribution for all the *EEMs*, paid in 5 years.
6. A total of 50% of public contribution for all the *EEMs*, paid in 10 years.
7. A total of 75% of public contribution for all the *EEMs*, paid immediately.
8. A total of 75% of public contribution for all the *EEMs*, paid in 5 years.
9. A total of 75% of public contribution for all the *EEMs*, paid in 10 years.
10. A total of 25% for *XPS* and 75% for wood fiber, 50% for windows, paid immediately.
11. A total of 25% for *XPS* and 75% for wood fiber, 50% for windows, paid in 5 years.
12. A total of 25% for *XPS* and 75% for wood fiber, 50% for windows, paid in 10 years.
13. A total of 50% for *XPS* and 75% for wood fiber, 50% for windows, paid immediately.
14. A total of 50% for *XPS* and 75% for wood fiber, 50% for windows, paid in 5 years.
15. A total of 50% for *XPS* and 75% for wood fiber, 50% for windows, paid in 10 years.
16. A total of 25% for *XPS* and 50% for windows, paid in 5 years; 75% for wood fiber, paid immediately.

17. A total of 25% for *XPS* and 50% for windows, paid in 10 years; 75% for wood fiber, paid immediately.
18. A total of 50% for *XPS* and 50% for windows, paid in 5 years; 75% for wood fiber, paid immediately.
19. A total of 50% for *XPS* and 50% for windows, paid in 10 years; 75% for wood fiber, paid immediately.
20. A total of 110% of public contribution for all *EEMs*, paid in 5 years.
21. A total of 110% of public contribution for all *EEMs*, paid in 10 years.

Partial retrofitting strategies or mixing of different types of the same *EEMs* are not considered in this work. Thus, the corresponding contributions are assigned based on the material used for each specific case of renovation.

In the subsequent analysis, a subsidization strategy was considered to be economically sustainable if at least one combination of *EEMs* led to a positive Net Present Value, calculated as described in Section 2.3.

2.3. Objective Functions and Simulation

Three objectives were considered in the parametric multi-objective optimizations: energy performance, economic performance, and sustainability performance.

The energy performance was determined as the annual energy needs for space heating of the whole district.

The economic performance of the investigated *EEMs* was evaluated by calculating the differential Net Present Value (*NPV*) of each retrofit case with respect to the base case, in which no renovation scenarios were pursued, by means of the calculation presented in EU Commission Delegated Regulation 244/2012 [38]. The *NPV* was calculated over a period of 30 years using a discount rate i = 3%. The initial investment costs I were computed according to the selected *EEMs* and economic scenario (see Section 2.2.3) and accounted as negative cash flows. Annual savings C_{saved} were calculated as the difference between the annual costs for space heating in the case with no retrofitting actions and those of the retrofitted case, summed to the corresponding public contribution for that year, if provided. Differently from the initial investment, annual savings and public contributions were accounted as positive cash flows.

Then, the *NPV* of each retrofit solution was computed according to the following formula:

$$NPV(i, N) = I + \sum_{t=0}^{30} \frac{C_{saved,t}}{(1+i)^t}$$

Due to the way in which the cash flows were defined, profitable investments have a positive *NPV*; hence, those are the cases in which the savings are greater than the initial investment cost.

The sustainability performance was assessed as the net cumulative CO_2 emissions saved (S_{CO2}) over the same 30-year-long analysis period as the economic analysis.

In the two district configurations, the neighborhood is served by a district heating network fueled by waste heat recovery, as in the real case, or by natural gas boilers as in the fictional case. In both scenarios, the saved CO_2 emissions were calculated by multiplying the energy savings by the reference emission factors of 0.17 $kg_{CO2\text{-}e}\ kWh_t^{-1}$ and 0.21 $kg_{CO2\text{-}e}\ kWh_t^{-1}$ for district heating and natural gas, respectively, as indicated in the local law DGP 235/2020 [32]. In addition, the embodied and installation CO_2 emissions GWP_{tot} were also considered in the 30-year balance with a negative sign, unlike the CO_2 saved, which was given a positive sign.

$$S_{CO_2} = GWP_{tot} + \sum_{t=0}^{30} CO_{2,saved,t}$$

Although the selected energy and sustainability performance metrics are related, it was decided to include them both as targets because, by calculating the cumulative net CO_2 emissions saved, they can properly account also for the effect of using more sustainable materials in the post-retrofit building life cycle. Once the *EEMs* and the objective functions were defined, it was possible to proceed with the simulation of the cases and scenarios. In this work, a full factorial parametric evaluation was performed in order to properly compare the results, rather than employing an optimization algorithm. Given the *EEMs* and their discretization, a total of 512 (2^9) cases were simulated and employed in the multi-objective optimization to find the Pareto solutions for each scenario and subsidization strategy. Specifically, all of them were analyzed for 2 climate scenarios, 2 types of district scenarios, 3 economic scenarios, and 22 subsidization strategies (including no incentives at all), for a total of 135 168 cases.

3. Results and Discussion

To highlight the importance of implementing subsidization strategies in this study, the results of the pre-pandemic scenario without incentives are presented in Table 5. The findings clearly demonstrate that in all 512 cases, no combination of *EEMs* is profitable without subsidies, and the profitability gap is substantial.

Table 5. Results for the pre-pandemic scenario without incentives.

		Heating (kWh/m^2)	Differential *NPV* (EUR/m^2)	Cumulative-Saved-CO_2-Emissions (kg$_{CO2}$/m^2)
Boiler *TRY*	Maximum	74.48	−99.16	308.77
	Minimum	59.17	−196.26	185.93
	Average	67.30	−139.20	241.63
Boiler 2050	Maximum	70.09	−104.68	277.47
	Minimum	56.27	−203.02	154.93
	Average	63.61	−145.41	214.21
DH *TRY*	Maximum	64.80	−109.18	213.04
	Minimum	51.48	−206.89	97.91
	Average	58.55	−149.63	157.15
DH 2050	Maximum	60.98	−113.53	191.00
	Minimum	48.95	−212.84	76.08
	Average	55.34	−154.84	137.84

Table 5 further reveals a reduction in heating needs from the *TRY* to the 2050 scenario, aligning with expectations, along with a decrease in cumulative saved CO_2 emissions. Additionally, the lower energy requirements in the 2050 scenarios result in even lower *NPV*s compared to the *TRY* scenarios. Thus, since the energy retrofit of the considered district would not be economically sustainable without any subsidization strategy, the *NPV*s for all the considered scenarios are presented in order to assess whether any incentives could make the district renovation profitable. Given the large number of combinations of interventions for each scenario, the cases are presented using boxplots. A more detailed discussion of the most suited *EEMs* for this case study is provided below.

3.1. Economic Performance

In the pre-pandemic economic scenario shown in Figure 2, the results highlight that, for every subsidization strategy, the return on the investment for the fictitious neighborhood with boilers is higher than that for the neighborhood with district heating, due to the higher cost of the natural gas.

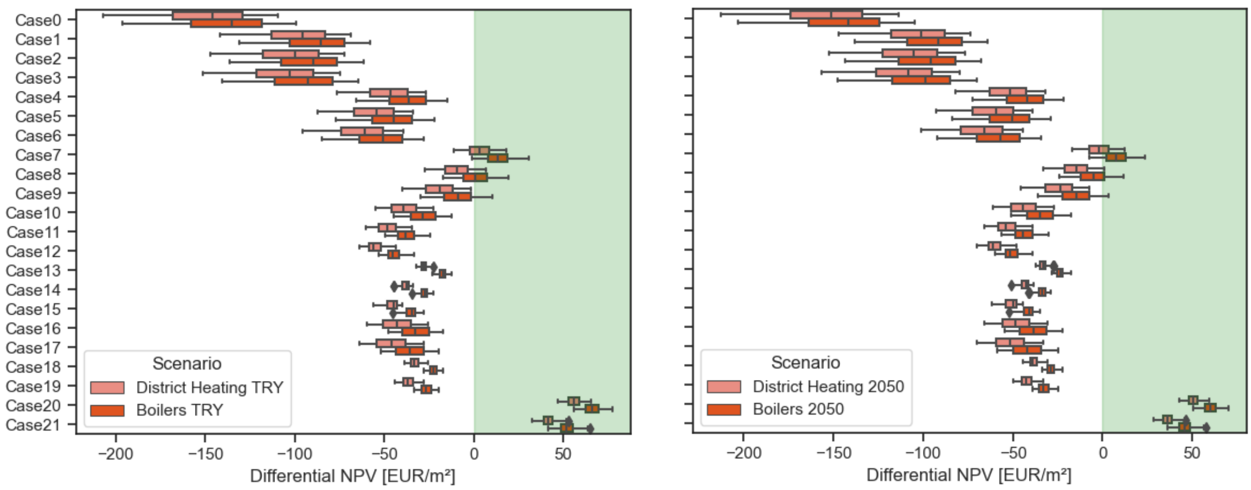

Figure 2. Pre-pandemic *NPV*s for the two climatic and district scenarios for each analyzed subsidization strategy (green area showing economic sustainability).

This trend is observed in both current and future climatic conditions, although in the simulated 2050 climate scenarios the space heating needs are expected to be lower and, consequently, all interventions are slightly less convenient, as previously outlined. The economic sustainability for the considered case-study district was verified in a limited number of subsidization strategies: cases 20 and 21 (i.e., a 110% incentive paid in 5 or 10 years), which are those with the highest *NPV* values, and cases 7, 8, and 9 (i.e., a 75% incentive paid immediately, in 5 or 10 years). It can be then concluded that, in the pre-pandemic economic context, it was necessary to cover at least 75% of the renovation costs in order to have positive *NPV*s, regardless of the type of HVAC system (district heating and boilers) and climatic condition (current or projected climate change scenario). Furthermore, it can be noted that, the sooner a public contribution is provided, the more convenient and sustainable is the energy renovation investment.

Figure 3 shows the same results considering the post-pandemic economic scenario 1. As a whole, it can be commented that the growth of the natural gas price (+38% in the post-pandemic scenario 1 while the district heating price is kept constant) has increased the differences between the economic performance registered for the neighborhood supplied by the district heating network and the one equipped with traditional boilers. Furthermore, the boxplots in the figure show that, for the former one, the subsidization strategies with convenient and positive *NPV*s are still limited, while, for the latter one, the investments are profitable in a broader range of cases.

Moreover, although the *EEM* investment costs also increased, their increment was not as steep as for the natural gas price. Indeed, focusing on the fictitious neighborhood with boilers, it can be observed that, compared to the pre-pandemic economic scenario, more subsidization strategies are found profitable for at least one combination of *EEMs*, such as:

- Cases 10 and 13 (i.e., differentiated incentives with immediate payment are provided for all *EEMs*, with the largest subsidized amount for wood fiber insulation).
- Cases from 16 to 19 (i.e., differentiated incentives with immediate payment provided only for the wood fiber).

These results highlight the potential of using energy policies to support the selection of *EEMs* with given features (in this case, for instance, pushing the selection of a more sustainable and environmentally friendly insulation material such as wood fiber over traditional *XPS*).

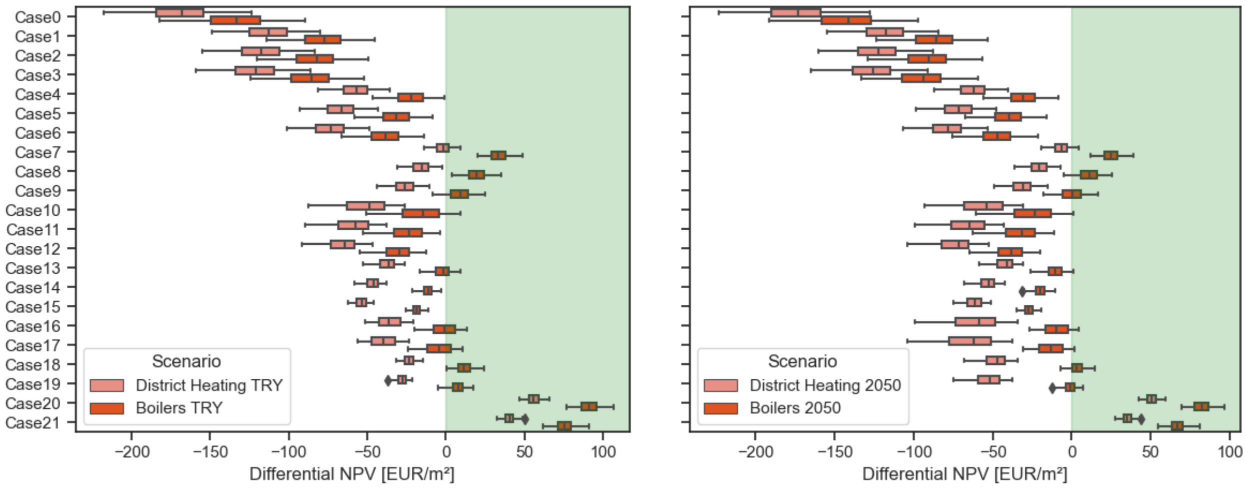

Figure 3. Post-pandemic 1 *NPV*s for the two climatic and district scenarios for each analyzed subsidization strategy (green area showing economic sustainability).

Figure 4 shows the results of the *NPV*s for the post-pandemic 2 scenario. The boxplots show that for the boiler districts even more subsidization strategies lead to economically viable investments. In fact, this is found true for all strategies except for those without public contribution (i.e., Case 0) and those with subsidizations with only 25% of all investments (i.e., Cases 1–3). As regards the neighborhood connected to the district heating network, economic sustainability is found only for the same cases observed in the two previous economic scenarios. It can be commented that, although, for this neighborhood, running energy costs proved to be more stable even in uncertain economic situations, with indubitable advantages limiting risks of energy poverty for the building users, larger incentives are necessary to allow energy retrofitting measures to be convenient. This provides the opportunity to consider dedicated subsidization strategies, accounting also for the type of installed HVAC system, and looking for a more global building performance, rather than just on the specific energy efficiency measure itself.

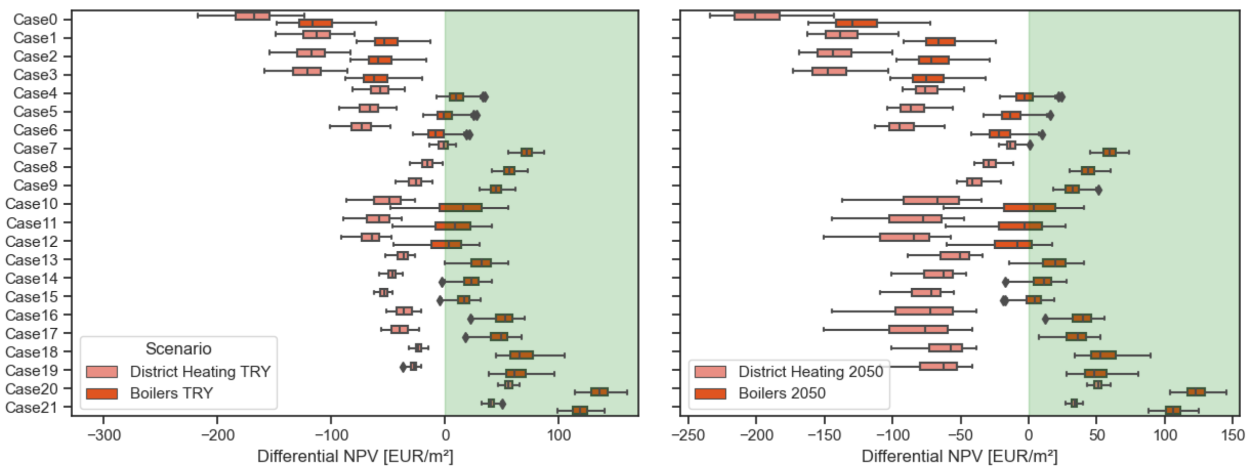

Figure 4. Post-pandemic 2 *NPV*s for the two climatic and district scenarios for each analyzed subsidization strategy (green area showing economic sustainability).

3.2. Analysis of the Energy Efficiency Measures

Besides the economic sustainability of the investments, it is also important to understand which are the *EEMs* that lead to optimal solutions according to the three objectives used. For this reason, the composition of the Pareto front was evaluated for all cases.

For the sake of brevity, only the Pareto fronts of the parametric optimization performed for the neighborhood with boilers with the current climatic conditions; i.e., the most profitable scenarios are outlined in detail in the following tables and figures, for both pre- and post-pandemic scenarios. Tables 6–8 report the number of optimal solutions for each strategy and the selected energy efficiency measures for each building archetype, expressing the percentage of points on the Pareto front with maximum insulation thickness, triple glazing windows, and *XPS* as insulation material. The comparison of the results in the three economic scenarios highlights that the number of solutions in the Pareto fronts decreases as the profitability of the investments increases. Considering that the results of the energy and sustainability objectives do not vary, the only aspect that affects which points are on the Pareto front, and thus the composition of the *EEMs* of the non-dominated solutions, is the variation in the *NPV*s.

In general, it can be seen that for the strategies with profitable combinations: (a) the percentage of solutions using the maximum insulation thickness is higher, (b) the share of points on the Pareto front recommending triple-glazed windows is equal to 100%, and (c) the choice between *XPS* and wood fiber insulation is balanced. The profitability of the investment affects not only the composition of the *EEMs*, but also the number of points on the Pareto front. In fact, as the investments become more profitable, the number of optimal solutions decreases, except for Cases 20 and 21, which have positive *NPV*s even in the pre-pandemic economic scenario. This trend underlines that the best *EEMs*, which optimize both energy and sustainability goals, can be clearly identified, if appropriate subsidization strategies capable of producing successful investments are proposed. The previous considerations are confirmed also by the results of the post-pandemic scenario 2 shown in Table 8.

A visual comparison of the variation of the *EEMs* on the Pareto surface is also depicted by means of boxplots in Figures 5–7. The first column of the plots reports the proportion of *EEMs* of the optimal solutions for all cases, while the second column shows the same metric only for the cases with positive *NPV*s. Regardless of the scenario, it is again possible to visually assess that the profitable cases tend to have the maximum insulation thickness, triple-glazed windows, and either *XPS* or wood fiber as insulation material. In addition, Figure 8 shows a quick comparison of the *EEMs* of the optimal solutions for all cases in the pre- and post-pandemic scenarios. From those charts, no particular differences can be depicted between the pre- and post-pandemic scenarios. This is due to the fact that non-profitable cases have more optima and, therefore, the change in *EEMs* of the profitable cases has less impact on the overall evaluation. For this reason, it is essential to focus only on subsidization strategies that lead to profitable cases, not only for the economic return of the investment, but also to consistently promote the strategies and *EEMs* that are more likely to result in positive economic performances, with equal energy and environmental outcomes.

To better understand why the number of optima decreases as investments become profitable, Figure 9 shows the Pareto points for subsidization strategy 10 in the neighborhood with boilers simulated with the current climate scenario for the three economic evaluations, i.e., pre-pandemic, post-pandemic 1, and post-pandemic 2. Strategy 10 was chosen because no profitable combination of inputs was found in the pre-pandemic scenario, at least one was found in the post-pandemic, and more than half of the combinations have positive *NPV*s in the post-pandemic scenario 2. The plots show that the more profitable the cases become, the more the scattering area decreases, promoting only a subset of points to be on the Pareto front. This indicates that effective incentive strategies can play an important role in narrowing down the focus on specific *EEMs*. By designing and implementing such strategies, it can be easier to identify the most beneficial *EEMs* to prioritize.

Table 6. Percentage of points on the Pareto having the maximum insulation thickness, triple glazing windows, and *XPS* as insulation for each archetype (pre-pandemic scenario). In green, those cases with positive *NPVs*.

	Maximum Insulation Thickness (%)			Window TH (%)			XPS as Insulation (%)			Number of Optima (-)
	Archetype1 A1	Archetype2 A2	Archetype3 A3	Archetype1 A1	Archetype2 A2	Archetype3 A3	Archetype1 A1	Archetype2 A2	Archetype3 A3	
Case0	57.1	44.9	63.3	100.0	100.0	100.0	57.1	49.0	49.0	49
Case1	57.1	44.9	63.3	100.0	100.0	100.0	57.1	49.0	49.0	49
Case2	57.1	44.9	63.3	100.0	100.0	100.0	57.1	49.0	49.0	49
Case3	57.1	44.9	63.3	100.0	100.0	100.0	57.1	49.0	49.0	49
Case4	56.5	47.8	67.4	100.0	100.0	100.0	56.5	52.2	52.2	46
Case5	56.5	47.8	67.4	100.0	100.0	100.0	56.5	52.2	52.2	46
Case6	56.5	47.8	67.4	100.0	100.0	100.0	56.5	52.2	52.2	46
Case7	71.0	51.6	80.7	100.0	100.0	100.0	61.3	48.4	51.6	31
Case8	61.9	45.2	66.7	100.0	100.0	100.0	59.5	54.8	52.4	42
Case9	59.1	45.5	65.9	100.0	100.0	100.0	59.1	54.6	52.3	44
Case10	76.9	69.2	84.6	100.0	100.0	100.0	30.8	30.8	30.8	13
Case11	68.8	75.0	75.0	100.0	100.0	100.0	25.0	31.3	25.0	16
Case12	64.7	76.5	76.5	100.0	100.0	100.0	23.5	29.4	29.4	17
Case13	65.4	46.2	88.5	100.0	100.0	100.0	30.8	42.3	46.2	26
Case14	66.7	45.5	72.7	100.0	100.0	100.0	33.3	54.6	36.4	33
Case15	56.8	43.2	65.9	100.0	100.0	100.0	43.2	54.6	47.7	44
Case16	50.0	45.8	91.7	75.0	66.7	70.8	16.7	16.7	16.7	24
Case17	50.0	45.8	91.7	75.0	66.7	70.8	16.7	16.7	16.7	24
Case18	50.0	45.8	91.7	75.0	66.7	70.8	16.7	16.7	16.7	24
Case19	50.0	45.8	91.7	75.0	66.7	70.8	16.7	16.7	16.7	24
Case20	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8
Case21	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8

Table 7. Percentage of points on the Pareto having the maximum insulation thickness, triple glazing windows, and *XPS* as insulation for each archetype (post-pandemic scenario 1). In green, those cases with positive *NPVs*.

	Maximum Insulation Thickness (%)			Window TH (%)			XPS as Insulation (%)			Number of Optima (-)
	Archetype1 A1	Archetype2 A2	Archetype3 A3	Archetype1 A1	Archetype2 A2	Archetype3 A3	Archetype1 A1	Archetype2 A2	Archetype3 A3	
Case0	55.8	48.1	57.7	100.0	100.0	100.0	55.8	53.9	48.1	52
Case1	55.8	48.1	57.7	100.0	100.0	100.0	55.8	53.9	48.1	52
Case2	55.8	48.1	57.7	100.0	100.0	100.0	55.8	53.9	48.1	52
Case3	55.8	48.1	57.7	100.0	100.0	100.0	55.8	53.9	48.1	52
Case4	56.3	52.1	62.5	100.0	100.0	100.0	56.3	58.3	52.1	48
Case5	56.3	52.1	62.5	100.0	100.0	100.0	56.3	58.3	52.1	48
Case6	56.3	52.1	62.5	100.0	100.0	100.0	56.3	58.3	52.1	48
Case7	63.9	50.0	69.4	100.0	100.0	100.0	63.9	52.8	63.9	36
Case8	61.0	48.8	65.9	100.0	100.0	100.0	60.9	58.5	58.5	41
Case9	59.5	47.6	66.7	100.0	100.0	100.0	59.5	57.1	57.1	42
Case10	81.8	81.8	100.0	100.0	100.0	100.0	36.4	36.4	36.4	11
Case11	76.9	69.2	84.6	100.0	100.0	100.0	30.8	30.8	30.8	13
Case12	73.3	73.3	73.3	100.0	100.0	100.0	26.7	26.7	26.7	15
Case13	76.9	69.2	100.0	100.0	100.0	100.0	30.8	46.2	30.8	13
Case14	66.7	55.6	77.8	100.0	100.0	100.0	22.2	50.0	22.2	18
Case15	57.6	39.4	81.8	100.0	100.0	100.0	39.4	57.6	42.4	33
Case16	90.0	80.0	100.0	100.0	100.0	100.0	40.0	40.0	40.0	10
Case17	90.0	80.0	100.0	100.0	100.0	100.0	40.0	40.0	40.0	10
Case18	100.0	66.7	100.0	100.0	100.0	100.0	50.0	33.3	50.0	12
Case19	80.0	60.0	100.0	100.0	100.0	100.0	40.0	33.3	53.3	15
Case20	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8
Case21	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8

Table 8. Percentage of points on the Pareto having the maximum insulation thickness, triple glazing windows, and *XPS* as insulation for each archetype (post-pandemic scenario 2). In green, those cases with positive *NPVs*.

	Maximum Insulation Thickness (%)			Window TH (%)			XPS as Insulation (%)			Number of Optima (-)
	Archetype1 A1	Archetype2 A2	Archetype3 A3	Archetype1 A1	Archetype2 A2	Archetype3 A3	Archetype1 A1	Archetype2 A2	Archetype3 A3	
Case0	55.6	48.9	66.7	100.0	100.0	100.0	55.6	55.6	55.6	45
Case1	55.6	48.9	66.7	100.0	100.0	100.0	55.6	55.6	55.6	45
Case2	55.6	48.9	66.7	100.0	100.0	100.0	55.6	55.6	55.6	45
Case3	55.6	48.9	66.7	100.0	100.0	100.0	55.6	55.6	55.6	45
Case4	61.1	41.7	72.2	100.0	100.0	100.0	61.1	63.9	50.0	36
Case5	60.0	47.5	67.5	100.0	100.0	100.0	60.0	60.0	55.0	40
Case6	60.0	47.5	67.5	100.0	100.0	100.0	60.0	60.0	55.0	40
Case7	66.7	57.1	85.7	100.0	100.0	100.0	66.7	71.4	57.1	21
Case8	64.3	42.9	89.3	100.0	100.0	100.0	64.3	57.1	53.6	28
Case9	64.3	42.9	89.3	100.0	100.0	100.0	64.3	57.1	53.6	28
Case10	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8
Case11	81.8	81.8	100.0	100.0	100.0	100.0	36.4	36.4	36.4	11
Case12	81.8	81.8	100.0	100.0	100.0	100.0	36.4	36.4	36.4	11
Case13	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8
Case14	90.9	72.7	100.0	100.0	100.0	100.0	36.4	54.6	36.4	11
Case15	83.3	66.7	100.0	100.0	100.0	100.0	33.3	50.0	33.3	12
Case16	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8
Case17	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8
Case18	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8
Case19	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8
Case20	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8
Case21	100.0	100.0	100.0	100.0	100.0	100.0	50.0	50.0	50.0	8

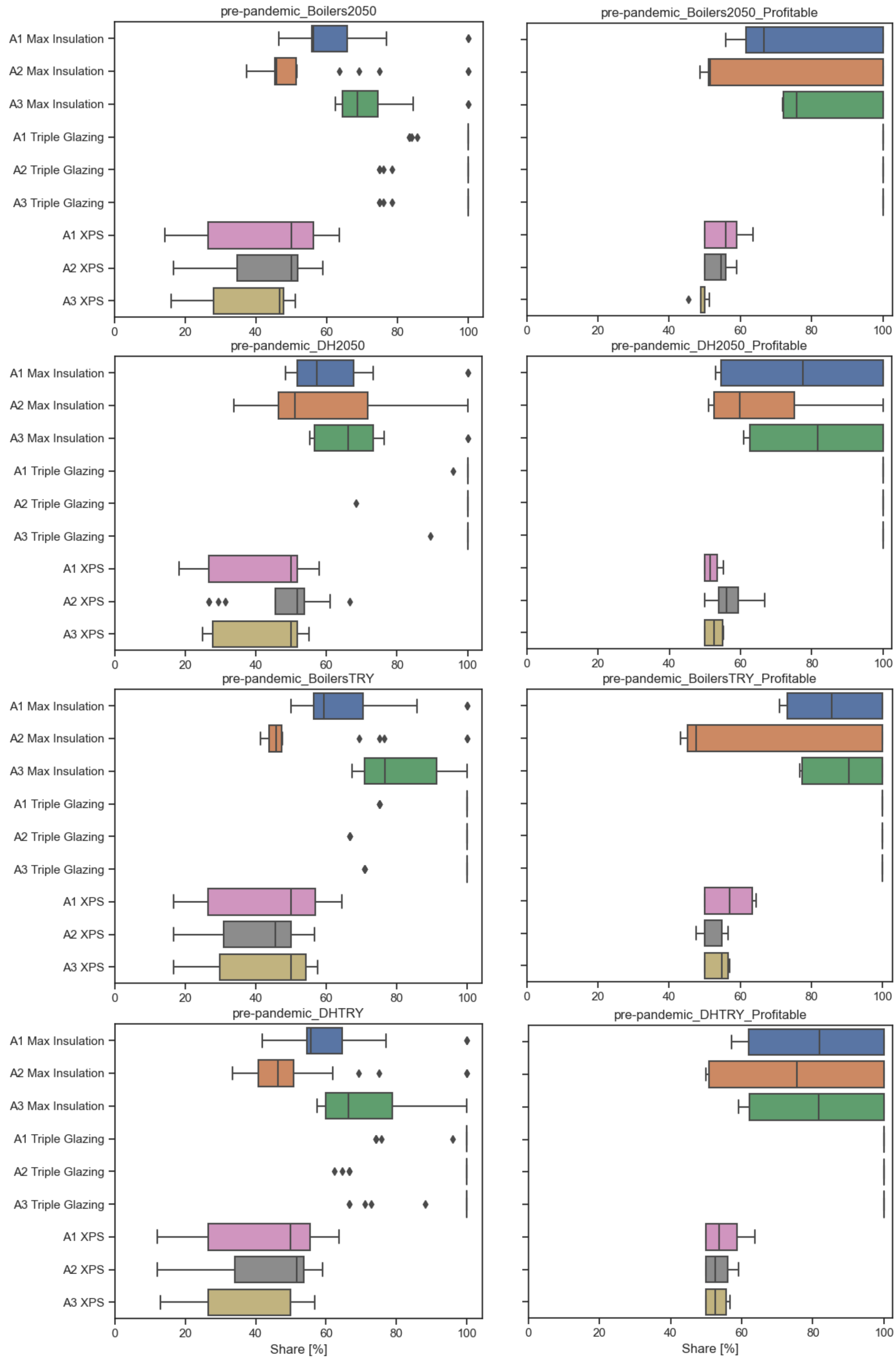

Figure 5. Variation of the *EEMs* on the Pareto surface for all cases and only profitable cases with outliers shown as black diamonds (pre-pandemic).

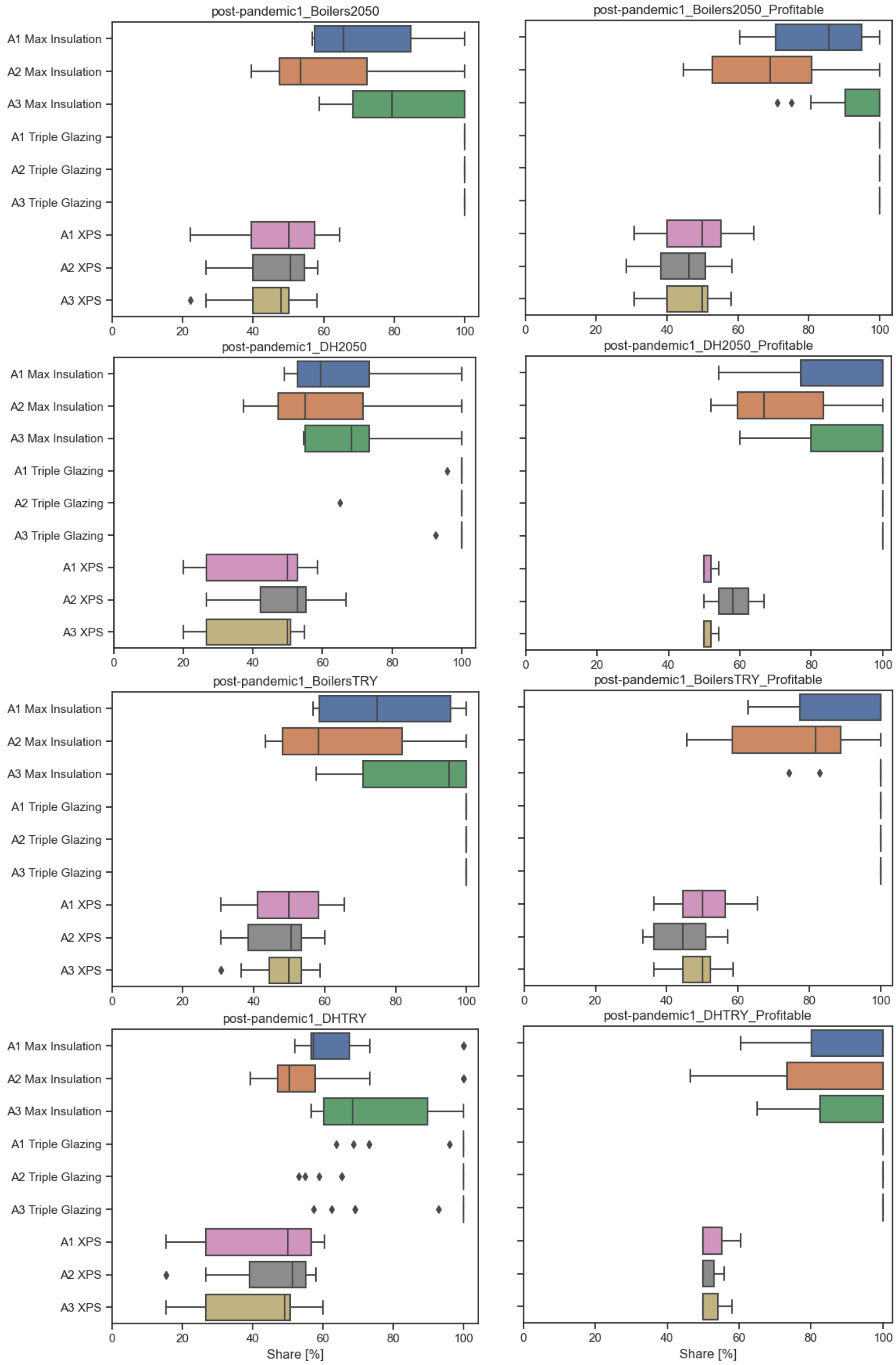

Figure 6. Variation of the *EEMs* on the Pareto surface for all cases and only profitable cases with outliers shown as black diamonds (post-pandemic 1).

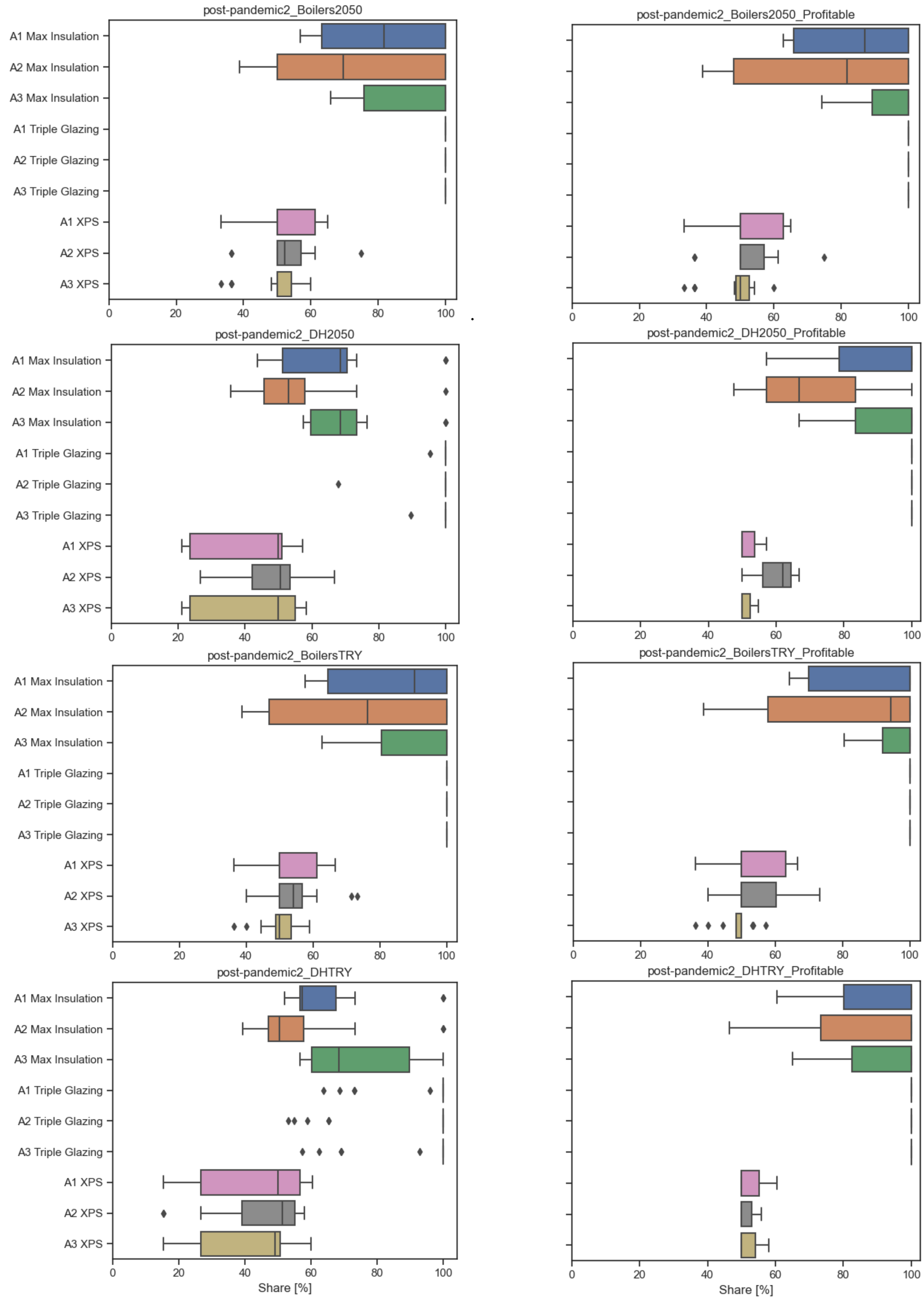

Figure 7. Variation of the *EEMs* on the Pareto surface for all cases and only profitable cases with outliers shown as black diamonds (post-pandemic 2).

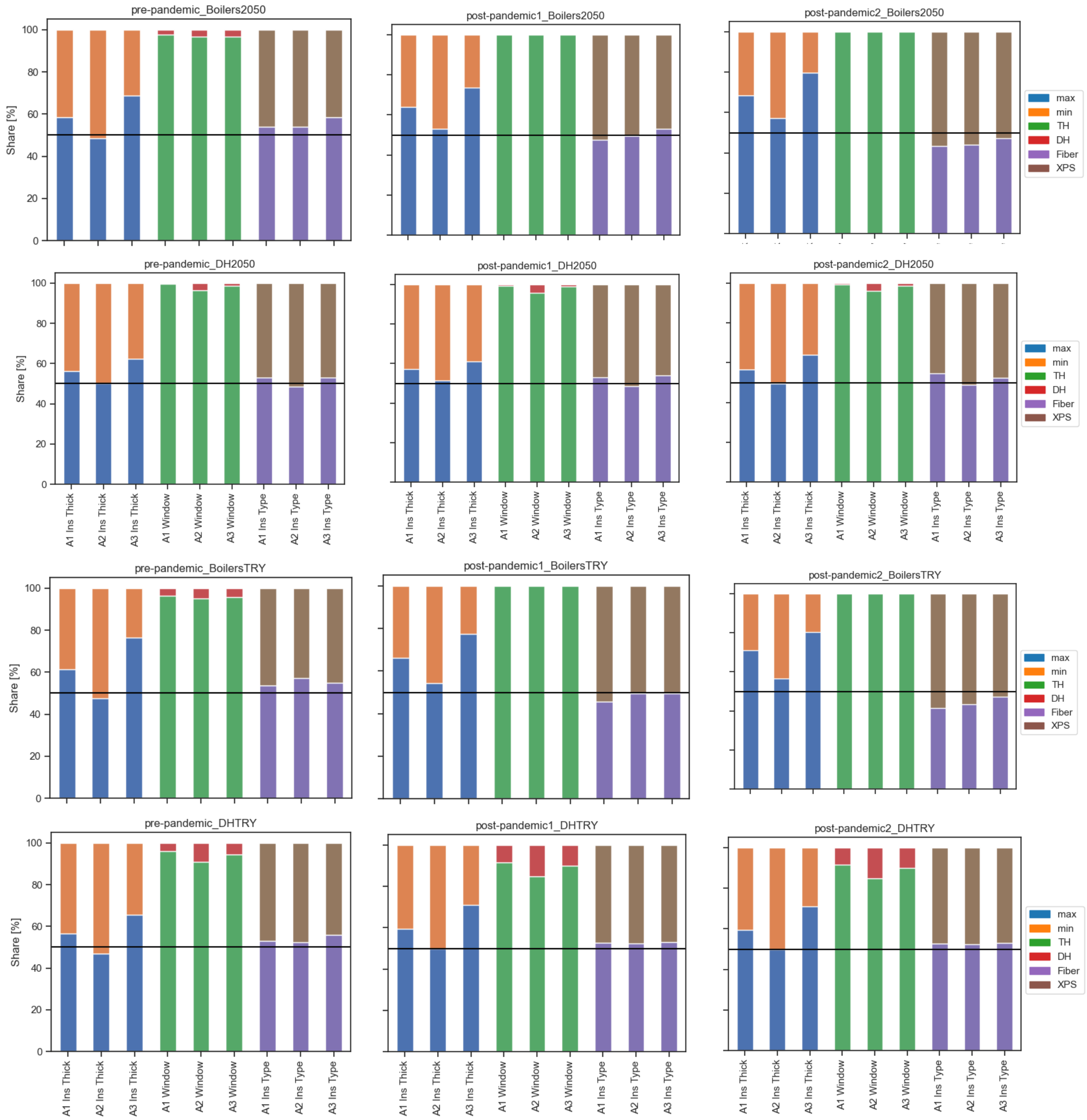

Figure 8. *EEMs* share comparisons for all cases considering pre- and post-pandemic scenarios.

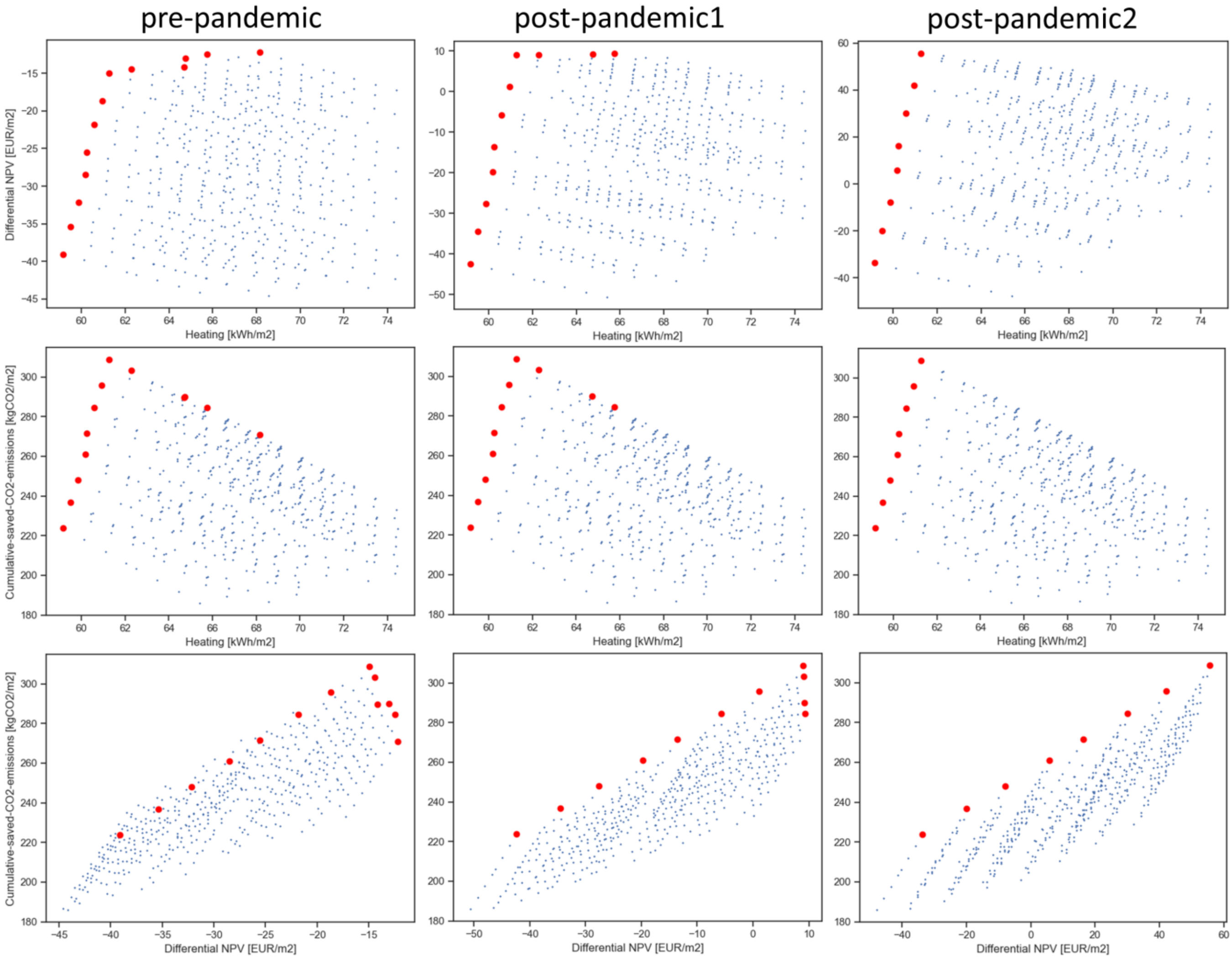

Figure 9. Case 10 optimal solution comparison in the three price scenarios (dominated solutions in blue and non-dominated solutions in red).

4. Conclusions

The renovation of existing building stock is crucial for achieving the carbon neutrality targets set by the EU. However, traditional building energy retrofit analyses often focus on individual buildings and pay limited attention to the influence of variables such as climate change and variation in the economic context. Additionally, incorporating multi-objective optimization and subsidy strategies is essential for informed decision making and policy development.

In this study, a parametric multi-objective optimization retrofit analysis of a district in Bolzano, Northern Italy, was conducted considering climate change, inflation due to the COVID-19 pandemic, different energy supply scenarios, and simplified subsidy strategies. The objective was to propose a methodology that supports policymakers in defining incentive programs, accounting for all factors that impact the energy needs of buildings, and understanding the role of incentives in multi-objective optimization. Various scenarios were evaluated, including two climate scenarios (typical reference year and 2050 future climate), two district energy supply scenarios (district heating vs. gas boilers), three economic scenarios (accounting for pandemic-related cost increase for energy efficiency measures and energy vectors), and 21 simplified subsidy strategies with different public contributions and payment periods.

The results indicate that climate change has a limited impact on the considered case study, as the city of Bolzano is primarily heating-dominated and the study focused on heating demand, which decreases slightly but not significantly. However, public contributions, energy supply, and costs strongly influence the economic feasibility found for the case study. Inflation had a notable impact on the district with gas boilers, while the stable energy prices of the district heating system can mitigate its effect. For the fictional district with gas boilers, the number of subsidization strategies leading to at least one profitable case increased from 5 out of 21 in the pre-pandemic case to 12 and 18 out of 21 in the post-pandemic 1 and post-pandemic 2 scenarios, respectively. The composition of the energy efficiency measures found on the Pareto surface revealed that positive Net Present Values prioritize the most energy-efficient retrofit solutions. The study allowed us also to observe that subsidization strategies, in addition to their composition, impact the number of points on the Pareto surface.

In conclusion, this study has integrated all the pertinent aspects required for proposing robust long-term retrofit schemes based on Building Performance Simulation. Although the findings are specific to the case study, the adopted methodology represents an example that could be replicated for other districts and cities, promoting the identification of more general measures and correlations between energy efficiency measures and ambient and economic context, supporting in such a way policymakers' decisions regarding the subsidization and definition of energy renovation strategies.

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Conflicts of Interest: The authors declare no conflict of interest.

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