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# Energy-optimized vs. cost optimized design of high-performing dwellings: the case of multi-family buildings

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## Abstract

Living in multi-family buildings is very common in Italy and it is important to optimize the design strategies to minimize the energy demand of these buildings and their related operational costs. This is particularly important for low-income tenants, and is pursued by many social housing developments where a good energy performance design is reached. In this work, a simulation-based optimization methodology that combines the use of TRNSYS® with GenOpt® is applied in order to minimize two objective functions - the annual primary energy demand and the operational energy cost - in different system technology scenarios, and verify the differences between energy-optimized design and cost-optimized design in a northern Italy climate. The study is performed on a typical floor of a real multi-family building for social housing. The envelope optimization demonstrates a potential reduction of the energy demand and cost for heating and cooling of more than 35%. The relationship between optimal solutions, system technology scenarios and optimization objectives is deeply analyzed. It is possible to find a set design solutions that are optimal in all the analyzed scenarios. This provides a set of design alternatives that are close to the environmental optimum and are able to reduce the low-income tenants vulnerability.

**Keywords:** simulation-based optimization; multi-family building; social housing; energy system technology scenarios, operational cost

## 28 **1. Introduction**

29 In Italy, according to the most recent census (ISTAT 2010), 54.9% of Italian families live in  
30 apartments in multi-family buildings. Furthermore, 78% of families that cannot afford buying a place  
31 live in rented apartments. Therefore, multi-family buildings represent a significant part of the building  
32 stocks and will be the major typology for new developments in cities, where 85.5% of people live in  
33 apartments.

34 Besides, since multi-family is the common building typology for social housing interventions,  
35 improving their energy performance also constitutes a challenge for contrasting the risk of energy  
36 poverty for low-income households (Faiella et al., 2014). A recent study (Copiello, 2016)  
37 demonstrates that energy efficiency may help the low-income tenants be neutral about the rent  
38 increase that may occur for new social housing interventions. Moreover, after the introduction of the  
39 Directive 2012/27/EU and the principles of heat accounting, many problems related to the cost  
40 repartition and the non-homogeneity between the different apartments in multi-family buildings have  
41 arisen (Ficco et al., 2016; Fabrizio et al., 2017)).

42 These are the reasons why increasing the energy efficiency and improving the design quality of  
43 new and existing multi-family buildings for social housing may significantly reduce the energy  
44 consumptions and the CO<sub>2</sub> emissions of the residential sector while keeping the energy operational  
45 costs for tenants under control.

### 46 *1.1. The optimization tools and objectives in the literature*

47 In the context of more and more ambitious performance requirement for buildings, fostered by  
48 European regulation, the building design has become a complex optimization problem. New tools  
49 and methods that combine building energy simulation with optimization techniques have been  
50 developed and studied, enabling designers to accurately calculate the actual energy consumption of  
51 buildings in different design configurations.

52 In the literature, such studies adopt either quasi steady-state energy assessment models compliant  
53 to EN ISO 13790 (Kapsalaki et al, 2012; Ferreira et al., 2016) or dynamic simulation models (Wang  
54 et al. 2011; Bayraktar et al, 2012) when the selection and comparison of design alternatives is either  
55 manual or automated. However, the development of building dynamic simulation and its combination  
56 with automated optimization has been recognized as a powerful tool for designers to evaluate  
57 thousands of different building design solutions (Xing et al., 2016). This allows the building design  
58 to be accurately optimized according to different objective functions, which entails the dynamic  
59 calculation of the building energy consumption as a starting point.

60 Depending on the aim of the study, the choice of the optimization objective can vary between  
61 primary energy minimization, global cost or life cycle cost minimization, thermal or visual comfort  
62 maximization, etc., but it is important to consider that this choice clearly affects the resulting building  
63 design. Also, the techno-economic scenario in which the building is optimized is affected by  
64 uncertainty and it is necessary to consider multiple scenarios in order to find robust solutions  
65 (Rysanek et al, 2013).

66 Many researchers are dealing with the problem of developing strategies for the economic  
67 feasibility of energy-optimal building design, as there is often a gap between the economic optimum  
68 and the zero (or positive) energy target (Ferrara et al., 2014; Pikas et al, 2015; Zacà et al, 2015).  
69 Energy and cost are indeed the two objectives that are most frequently addressed in the literature.  
70 34% of studies related to the building design optimization problems (Evins, 2013) deal with the  
71 energy objective, while cost objectives are addressed in around 30% of the studies. Among those  
72 addressing cost optimization, only 20% focus on operational costs. In fact, the majority of such  
73 studies add up investment, maintenance, replacement and operational costs occurring within the  
74 building lifecycle in the so-called global cost objective function. This is because the European  
75 Directive 2010/31/EU has introduced the cost-optimal methodology as a tool for defining the energy  
76 performance level leading to the lowest global cost within the building economic lifecycle.

77 The cost-optimal methodology is often adopted in a context where the building owner is also the  
78 building user. In this situation, the building owner can optimize his investments and operational costs  
79 in order to minimize the global cost over a defined time period. In this perspective, the operational  
80 cost may often be hidden within the value of the global cost. This is the case of most of the studies  
81 dealing with the cost-optimal methodology application (Kurnitski et al. 2011, Tronchin et al. 2012,  
82 Tronchin et al., 2014, Pikas et al., 2017).

83 When dealing with social housing, however, the building owner, who is also the investor, is  
84 different from the building user. In this context, different financial models may be applied and special  
85 attention has to be given to the operational costs, as the low-income tenants directly pay for them.

#### 86 *1.2. The optimization variables in the literature*

87 The design space in which the building has to be optimized depends on the considered design  
88 variables. These variables may be related to the building envelope, not only in terms of construction,  
89 but also in terms of geometry and facade design, or to the energy system, in terms of technology and  
90 design, or both. For example, some authors (Prando et. al., 2015; Brandao de Vasconcelosa et al.,  
91 2016) considered only variables related to the building envelope, such as window type, insulation  
92 thickness and shading type. Other authors (Ascione et al. 2016, Monetti et al. 2015) compared  
93 different technologies for heating and cooling energy supply.

94 Some of the building design optimization studies considered both envelope and energy systems,  
95 assuming that these two groups of design variables are strictly interrelated. This was proven for a  
96 single-family building (Ferrara et. al, 2016a), where it was demonstrated that the choice of the  
97 building system influences the optimal design of the building envelope variables. However, very few  
98 studies investigated this problem in relation to the more complex multi-family buildings design.

99 *1.3. Aim of the present work*

100 This work presents a replicable simulation-based optimization methodology to study in deep the  
101 multi-family building design optimization problem in the Italian context.

102 The envelope-related design variables affecting the building heating and cooling energy needs are  
103 identified and optimized in different heating and cooling systems scenarios, addressing separately the  
104 non-renewable primary energy demand and the operational cost minimization objectives. The study  
105 defines an economic objective function exclusively based on the operational cost for heating and  
106 cooling as relevant for the social housing model, where low-income tenants are more interested in  
107 low energy operational cost.

108 A theoretical framework for properly weighting the heating and cooling energy needs according  
109 to the different objectives and system scenarios is presented, aiming at exploring the dependence of  
110 the optimal design solution on such objectives and scenarios.

111 It is expected that reducing energy needs also reduces the operational costs, however, due to  
112 differences in the weighting terms related to the energy or cost objectives, the energy-optimized and  
113 the cost-optimized building design may not be the same. In fact, the resulted optimal solutions are  
114 investigated in order to understand how and to what extent the two optimal design configurations  
115 differ one from the other. The energy optimum, which minimizes the primary energy demand and  
116 CO<sub>2</sub> emissions of the multi-family building, is compared to the economic optimum that will be  
117 preferable in the tenants' perspective.

118 Further considerations about the influence of the energy supply system scenario in the  
119 determination of such optimal solutions will be provided together with a study on the resilience of  
120 the design variables to the variation of the optimization objectives and/or the system scenario.

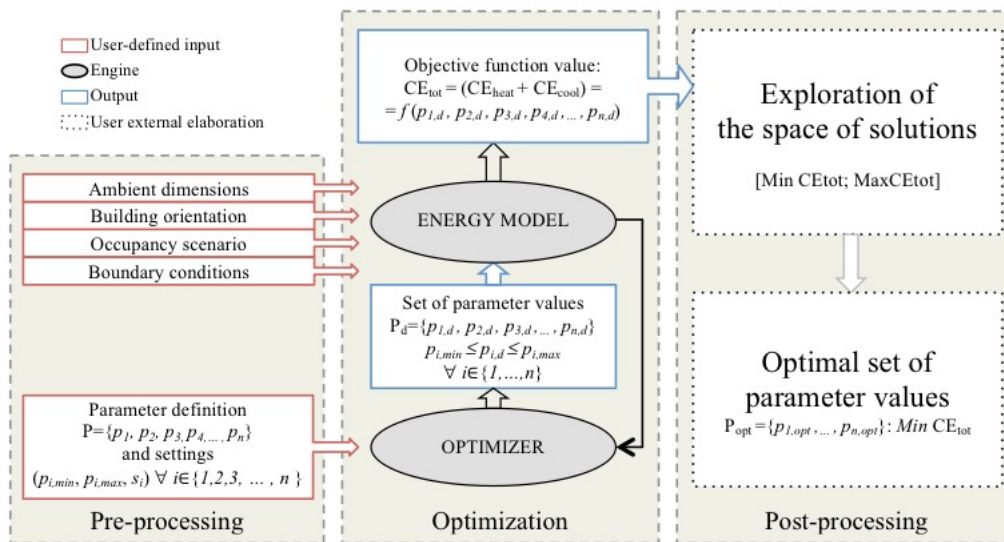
121 The analysis is based on a case-study that is representative of new construction for social housing  
122 in Italy and the findings of the study could inform the current design practice.

125 **2. Simulation-based methodology**

126 *2.1. The optimization process*

127 The methodology that is proposed involves the coupling between a dynamic energy simulator and an  
 128 optimizer in a simulation-based optimization process. Among the available tools for simulation-based  
 129 optimization, the presented methodology relies on TRNSYS® as simulation tool and GenOpt® as  
 130 optimization tool, as shown in Figure 1.

131



132

133 *Figure 1. Simulation-based optimization methodology for the present study*

134

135 In the pre-processing stage, the TRNSYS model is created including the building boundary  
 136 conditions, and the set of design parameters is defined.

137 In the optimization stage, the iterative process driven by a PSO optimization algorithm leads to  
 138 evaluate a great number of design solutions, each related to a different set of parameter values, until  
 139 the objective function is minimized. The PSO is chosen for its ability to deal with discrete variables  
 140 in building design problems (Ferrara, 2017a). The output of the optimization stage is a big dataset  
 141 containing, for each solution that was evaluated within the process, the objective function value, the  
 142 parameter values that are related to each objective function and other secondary functions related to



166 where  $Q_h$  is the annual energy demand for space heating and  $Q_c$  is the annual demand for space  
167 cooling, both evaluated by the dynamic simulation tool;  $T_{h,k}$  and  $T_{c,j}$  are related to the technical  
168 system that is used for supplying the heating and the cooling energy, respectively. The terms  $w_h$  and  
169  $w_c$  are the weighting terms of the heating and cooling energy demands that are used for computing  
170 the objective function *OF*.

### 171 2.3. Definition of the objective functions

172 For the purpose of this study, two different optimization processes have to be carried out separately,  
173 one optimizing the energy performance and the other optimizing the operational energy cost.  
174 Therefore, two objective functions have to be defined.

175 For the energy optimization, the objective function is the annual specific non-renewable primary  
176 energy demand for heating and cooling. In this case, the weighting terms in Eq. (1.2) are computed  
177 as follows

$$178 \quad w_{h,energy} = \frac{f_{T_{h,k}}}{\eta_{T_{h,k}}} \quad (2.1)$$

$$179 \quad w_{c,energy} = \frac{f_{T_{c,j}}}{\eta_{T_{c,j}}} \quad (2.2)$$

180 where  $\eta_{T_{h,k}}$  and  $\eta_{T_{c,j}}$  are the mean seasonal efficiencies of the energy systems  $T_{h,k}$  and  $T_{c,j}$  for heating  
181 and cooling supply, depending on the adopted energy conversion technology. The terms  $f_{T_{h,k}}$  and  
182  $f_{T_{c,j}}$  represent the primary energy conversion factors related to the energy carriers that are used by  
183 the selected energy systems. It has to be pointed out that such conversion factors usually differ from  
184 one European Member State to the others, depending on the characteristics of the national energy  
185 production and supply systems.

186 Therefore, the objective function for energy optimization is defined as follows

$$187 \quad OF_{Energy} = Q_h \cdot \frac{f_{T_{h,k}}}{\eta_{T_{h,k}}} + Q_c \cdot \frac{f_{T_{c,j}}}{\eta_{T_{c,j}}} \quad [\text{kWh}/(\text{m}^2 \text{ yr})] \quad (3)$$

188 Concerning the cost optimization, the objective function is the specific annual operational costs for  
189 space heating and cooling. The weighting terms of Eq. (1.2) are computed as follows

$$190 \quad w_{h,\text{cost}} = \frac{c_{T_{h,k}}}{\eta_{T_{h,k}}} \quad (4.1)$$

$$191 \quad w_{c,\text{cost}} = \frac{c_{T_{c,j}}}{\eta_{T_{c,j}}} \quad (4.2)$$

192 where  $c_{T_{h,k}}$  and  $c_{T_{c,j}}$  are the average annual prices of one kWh for space heating and cooling,  
193 depending on the energy carrier used in the technical systems, and  $\eta_{T_{h,k}}$  and  $\eta_{T_{c,j}}$  are the seasonal  
194 efficiencies of the technical systems  $T_{h,k}$  and  $T_{c,j}$  as in Eq. (2.1-2.2).

195 Therefore, the objective function for operational energy cost optimization is defined as follows

$$196 \quad \text{OF}_{\text{Cost}} = Q_h \cdot \frac{c_{T_{h,k}}}{\eta_{T_{h,k}}} + Q_c \cdot \frac{c_{T_{c,j}}}{\eta_{T_{c,j}}} \quad [\text{kWh}/(\text{m}^2 \text{ yr})] \quad (5)$$

197 Similarly to the primary energy conversion factors, also the average annual energy prices may vary  
198 throughout Europe according to the tariff adopted by the energy suppliers and the different national  
199 energy incentives policies.

200 Assuming that the present study is carried out in the Italian context, as shown above, the weighting  
201 terms may vary according to the energy system technologies and the related energy carriers.  
202 Therefore, in order to cover all the possible design solutions, the optimization process should be  
203 repeated for each combination of energy systems that may be installed in the building that has to be  
204 optimized.

205 After computing the weights for each of the selected systems for heating and cooling ( $w_h$  and  $w_c$   
206 respectively), the ratio  $w_c/w_h$  indicates the relative weight of the cooling terms to the heating term  
207 (for example, a ratio equal to 2 indicates that the cooling energy demand weights two times the  
208 heating demand and therefore the minimization of the objective function will be mostly cooling-  
209 driven). It has to be noted that some systems for heating supply may not be combined with others for  
210 cooling supply. In those cases, the scenario is defined as “not compatible”. The creation of a matrix

211 (Table 1) helps identify the feasible solutions and therefore the weights to be given to the objective  
 212 functions to perform the optimization in multiple energy system scenarios.

213 *Table 1. The matrix of weights for the computation of the objective functions.*

	$w_{h,1}$	$w_{h,\dots}$	$w_{h,l}$
$w_{c,1}$	$w_{c,1}/w_{h,1}$	not compatible	$w_{c,1}/w_{h,l}$
$w_{c,\dots}$	$w_{c,\dots}/w_{h,1}$	$w_{c,\dots}/w_{h,\dots}$	not compatible
$w_{c,m}$	$w_{c,m}/w_{h,1}$	$w_{c,m}/w_{h,\dots}$	$w_{c,m}/w_{h,l}$

214

#### 215 2.4. On the locus of optimal points

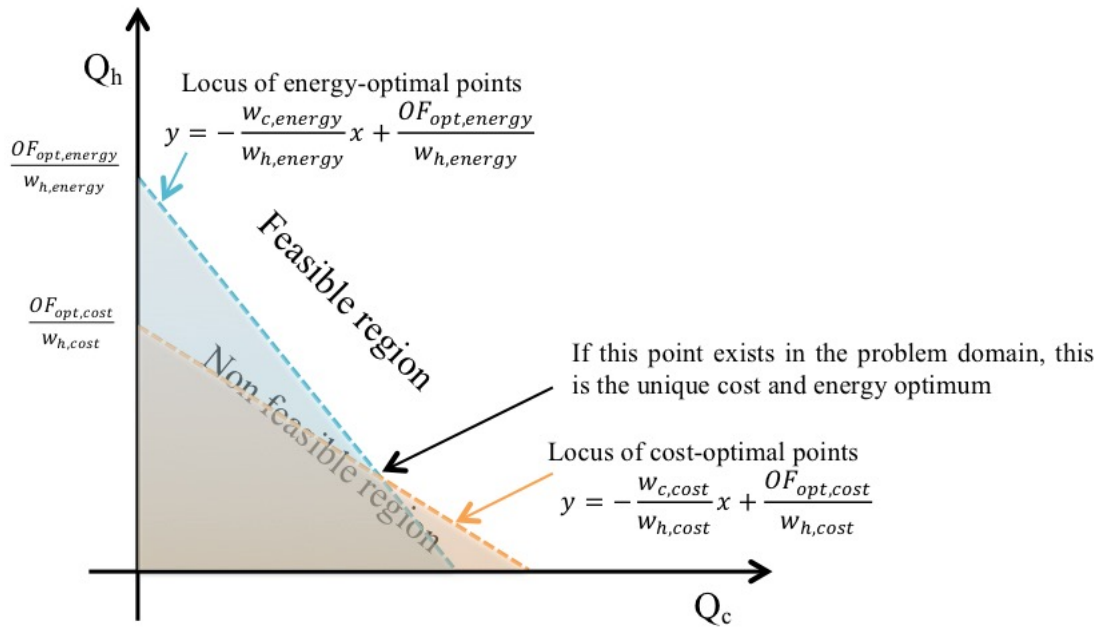
216 Based on previous considerations, the objective function of the above-presented problem is linear,  
 217 where  $Q_h$  and  $Q_c$  are the two independent variables, which depend, in turn, on the set of parameter  $\mathbf{P}$ .  
 218 Therefore, each objective function value is associated to a certain ratio  $Q_h$  and  $Q_c$  values or, better, to  
 219 a set of  $Q_h, Q_c$  couples, as there may be different  $Q_h, Q_c$  couples leading to the same objective function  
 220 value. For the given objective function value, the relationship between the values of  $Q_h$  and  $Q_c$  may  
 221 be expressed, based on Eq (1.2), as follows

$$222 \quad Q_h = -Q_c \cdot \frac{w_c}{w_h} + \frac{OF}{w_h} \quad (6)$$

223 where OF is the selected objective function value (either cost or energy) and  $w_h$  and  $w_c$  are the related  
 224 weights defined in (2.1-2) and (4.1-2). As a consequence, there may be a set of  $Q_h, Q_c$  couples leading  
 225 to the minimum objective function value ( $OF_{opt}$ ). On a bi-dimensional graph, as in Figure 2, where  
 226  $Q_c$  is on the x-axis and  $Q_h$  is on the y-axis, the locus of points related to  $OF_{opt}$  can be seen in the  
 227 following form

$$228 \quad y = -mx + q \quad (7)$$

229 where, based on (6), the slope  $m$  is expressed by the  $w_c/w_h$  ratio, and the intercept  $q$  is expressed by  
 230 the  $OF_{opt}/w_h$  ratio.



231

232 *Figure 2. Problem domain and locus of optimal points*

233

234 The domain of such function depends on the existence of the  $Q_h, Q_c$  couples, which depends on the  
 235 multi-dimensional space of points generated by the all possible sets of parameter  $\mathbf{P}$ . The slope of this  
 236 line will be different for each system scenario, depending on the matrix of weights in Table 1. The  
 237 example reported in Figure 2 represents the case in which the ratio  $\frac{w_{c,energy}}{w_{h,energy}}$  is greater than the ratio

238  $\frac{w_{c,cost}}{w_{h,cost}}$  but the opposite situation may occur.

239 For the same system scenario, the locus of cost-optimal points and the one of energy-optimal points  
 240 may have different slopes, according to their  $w_c/w_h$  ratios. In this case, the two lines will cross in a  
 241 unique point that is both the energy-optimal and cost-optimal solution, if that point is within the  
 242 problem domain (in other words, if the related  $Q_h, Q_c$  couple exists). Otherwise, this is only a  
 243 theoretical point and the energy-optimum and the cost-optimum will be in different positions on the  
 244 related lines (see Figure2).

### 245 3. Application to a reference case-study

#### 246 3.1. Case-study description: initial scenario

247 The case study is a real multi-family building that is representative of new construction for social  
248 housing in Northern Italy (degree days between 2100 and 3000). The whole 6-floors building is  
249 composed of 35 apartments of different sizes, for a total net floor area of 2330 m<sup>2</sup>.

250 External walls are made of a layer of bricks (30 cm) with external thermal insulation (10 cm), for a  
251 wall thermal transmittance U equal to 0.26 W/(m<sup>2</sup>K). The mean thermal transmittance of the  
252 transparent surfaces is equal to 1.45 W/(m<sup>2</sup>K), which is related to double low-e glass windows with  
253 metal frame. The solar factor is 0.59. As shown in Figure3, there are fixed shadings on the facades,  
254 including balconies and loggias, which are typical features of Italian construction. Additional details  
255 on the case study building features are in (Ferrara et al. 2016b).

256 For the purpose of this work, one typical floor of the case study building was selected for carrying  
257 out optimization studies. As reported in Figure 3, the floor is composed of 7 apartments, having  
258 different floor areas and surface-to-volume ratios (Table 2), for a total conditioned floor area of  
259 466 m<sup>2</sup>.



260

261 *Figure 3. Case study building. South façade view, vertical section and plan of the typical 7-*  
262 *apartments floor.*

263 Table 2 reports the specific primary energy consumption and the operational costs related to each  
 264 apartment and to the entire floor. These values refer to the building actual configuration, which is the  
 265 so-called “initial scenario” for the optimization.

266 *Table 2. Initial scenario. Annual primary energy consumption and annual energy costs for each*  
 267 *apartment and floor values.*

		<b>A</b>	<b>B</b>	<b>C</b>	<b>D</b>	<b>E</b>	<b>F</b>	<b>G</b>	<b>Floor</b>
Floor area	(m <sup>2</sup> )	86.0	48.7	77.5	77.5	47.4	47.6	81.1	465.8
S/V	(m <sup>-1</sup> )	0.74	0.66	0.26	0.26	0.32	0.27	0.45	0.46
Heating	EP <sub>H</sub> (kWh/(m <sup>2</sup> yr))	26.5	17.7	19.2	18.9	15.5	13.6	26.9	20.7
	C <sub>H</sub> (€/m <sup>2</sup> )	4.27	2.85	3.10	3.04	2.50	2.20	4.34	3.34
Cooling	EP <sub>C</sub> (kWh/(m <sup>2</sup> yr))	15.3	18.3	10.0	9.7	20.7	20.2	14.4	14.7
	C <sub>C</sub> (€/m <sup>2</sup> )	1.26	1.52	0.82	0.80	1.72	1.68	1.18	1.22
DHW	EP <sub>W</sub> (kWh/(m <sup>2</sup> yr))	21.9	25.0	22.4	22.4	25.2	25.1	22.2	23.1
	C <sub>W</sub> (€/m <sup>2</sup> )	1.58	1.80	1.62	1.62	1.82	1.82	1.60	1.66
Vent	EP <sub>V</sub> (kWh/(m <sup>2</sup> yr))	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
	C <sub>V</sub> (€/m <sup>2</sup> )	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24
Tot	EP <sub>gl</sub> (kWh/(m <sup>2</sup> yr))	78.8	76.1	66.7	66.0	76.5	74.2	78.6	73.6
	C <sub>gl</sub> (€/m <sup>2</sup> )	8.35	7.41	6.78	6.70	7.28	6.94	8.36	7.46
Energy rating		A1	A1	A1	A1	A1	A1	A1	A1

268  
 269 The primary energy and the costs in such scenario were calculated considering a district heating  
 270 system for heating supply ( $T_{h,ini}$ ) and electric chillers for cooling supply ( $T_{c,ini}$ ). Therefore the  
 271 efficiencies, the primary energy factors and the energy costs are defined as follows

- 272 •  $\eta_{T_{h,ini}}=0.88$ , based on the building Energy Performance Certificate;
- 273 •  $f_{h,ini}=0.62$ , as declared by the district heating supplier (the district heating system in that  
 274 area combines heat generation from waste, from a co-generation plant and from a biomass  
 275 source);
- 276 •  $\eta_{T_{c,ini}}=2.05$ , Italian reference efficiency for electric chillers (DM 26/06/2015);
- 277 •  $f_{c,ini}=1.95$ , Italian non-renewable primary energy conversion factor for electricity  
 278 (DM 26/06/2015);

279 •  $c_{h,ini}=0.09$  €/kWh<sub>th</sub> (Linea Reti e Impianti, 2016);

280 •  $c_{c,ini}=0.20$  €/kWh<sub>el</sub> (Eurostat, 2016).

281 An electric mechanical ventilation system with a heat exchanger is also used, where the mean  
282 seasonal efficiency of the sensible heat recovery is 0.5.

283 The energy simulations for calculating  $Q_h$  and  $Q_c$  were carried out with the IWEC weather data for  
284 Piacenza (weather station 160840, which is the closest to the actual building location).

285 The primary energy demands for DHW and ventilation were not included in the optimization, as they  
286 are not affected by the building envelope design. However, they were calculated with simplified  
287 methods in order to estimate the weight of heating and cooling on the total energy demand. The  
288 primary energy and cost for DHW were calculated according to the Italian Standard UNI/TS 11300-  
289 2 and considering a gas condensing boiler ( $\eta_{DHW}=0.85$ ,  $f_{DHW}=1.05$ ,  $c_{DHW}=0.08$  €/kWh<sub>th</sub>). The  
290 primary energy and cost for ventilation (respectively  $EP_v$  and  $C_v$ ) represent the electrical energy use  
291 and the related cost for handling of the ventilation air. They are derived considering a 0.5Wh/m<sup>3</sup>  
292 specific installed power factor, as indicated for the Italian reference building in DM 26/06/2015, and  
293 0.20 €/kWh<sub>el</sub> as electricity cost.

294 As shown in Table 2 the energy rating, according to the current Italian energy performance  
295 certification regulation (DM 26/06/2015), is A1 for each apartment and for the entire floor.

### 296 3.2. Definition of the optimization parameters and the objective functions

297 As described in the statement of the optimization problem, the set of design variables and their range  
298 and step of variation delineate the design space to be explored within the optimization process. In this  
299 study, this process aims at investigating possible performance improvements of a reference multi-  
300 family building without changing its layout. Therefore, the optimization parameters were selected  
301 among the design variables of the building envelope that may affect the energy needs, while the  
302 building geometry and the apartments layout are fixed to their actual configuration.

303 As shown in Table 3, the selected design variables are related to the thermal resistance of the  
 304 insulation panels and to the solar absorption coefficient of the external walls, to the type and size of  
 305 the windows, to the horizontal overhang and fins dimensions of South-oriented windows, to the depth  
 306 of the loggias facing North and South. The range and the step of their variation were set according to  
 307 regulation requirements, technical feasibility and market criteria. In the Nomenclature, all the defined  
 308 parameters are reported.

309 *Table 3. Project parameters description*

Parameter Name	Description	unit	min	max	step	Initial value
sISOLN	North walls - thermal resistance insulation	m <sup>2</sup> K/W	1.12	5.40	0.53	1.65
sISOLEW	East/West walls - thermal resistance insulation	m <sup>2</sup> K/W	1.12	5.40	0.53	1.65
sISOLS	South walls - thermal resistance of insulation	m <sup>2</sup> K/W	1.12	5.40	0.53	1.65
abs-back	North walls' absorption factor	-	0.2	0.8	0.3	0.2
abs-backS	South walls' absorption factor	-	0.2	0.8	0.3	0.2
abs-backEW	East/West walls' absorption factor	-	0.2	0.8	0.3	0.2
S_overhproj (m)	Overhang projection length for South windows	m	0.0	1.2	0.2	0.0
Ploggia_S (m)	Overhang projection length for South loggia	m	1.2	3.0	0.3	1.8
Ploggia_N (m)	Overhang projection length for North loggia	m	1.2	3.0	0.3	1.8
WT	North window type	-		1,2,3,4,5,6		1
WTS	South window type	-		1,2,3,4,5,6		1
WTW	West window type	-		1,2,3,4,5,6		1
WTLN	North Loggia window type	-		1,2,3,4,5,6		1
WTLS	South Loggia window type	-		1,2,3,4,5,6		1
WW_A_Loggia (m)	Window width apt. A Loggia	m	1.1	2.9	0.2	1.3
WW_A_South(m)	Window width apt. A South facade	m	2.1	2.9	0.2	2.5
WW_A_West (m)	Window width apt. A West facade	m	1.1	2.5	0.2	1.7
WW_B_South (m)	Window width apt. B South facade	m	1.5	2.5	0.2	1.9
WW_B_Loggia (m)	Window width apt. B Loggia South	m	1.2	2.6	0.2	1.2
WW_C_South (m)	Window width apt. C South facade	m	1.5	3.3	0.2	1.9
WW_C_North (m)	Window width apt. C North facade	m	1.9	4.3	0.2	2.3
WW_D_South (m)	Window width apt. D South facade	m	1.5	3.3	0.2	1.9
WW_D_North (m)	Window width apt. D North facade	m	1.9	4.3	0.2	2.3
WW_E_South (m)	Window width apt. E South facade	m	1.5	2.5	0.2	1.9
WW_E_Loggia (m)	Window width apt. E Loggia South	m	1.2	2.6	0.2	1.2
WW_F_Loggia (m)	Window width apt. F Loggia South	m	1.4	2.4	0.2	1.8
WW_F_South (m)	Window width apt. F South facade	m	1.3	2.3	0.2	1.3
WW_G_Loggia(m)	Window width apt. G Loggia North	m	2.1	4.9	0.2	3.1
WW_G_North(m)	Window width apt. G North	m	1.2	3.0	0.2	1.2
WW_G_South (m)	Window width apt. G South facade	m	0.9	3.5	0.2	1.1

310  
 311 Table 4 reports the selected options for variation of window type parameters, which are related to  
 312 different combinations of glass thermal transmittance, solar factor and visible transmittance. The set

313 of parameters, with their dimension and constraints, defines the space of solutions of the problem, in  
 314 which the search of the optimal design solutions may be conducted with different objectives.

315 *Table 4. Options for window type parameters*

<b>ID</b>	<b>Glazing</b>	<b><math>U_g</math> (<math>W/m^2K</math>)</b>	<b><math>g</math> (-)</b>	<b><math>\tau_1</math> (-)</b>
1	4/16/4	1.27	0.59	0.71
2	4/15/4	1.10	0.61	0.78
3	6/12/4/12/4	0.70	0.29	0.58
4	6/16/6	1.10	0.33	0.63
5	6/16/6	1.29	0.33	0.66
6	4/16/4/16/4	0.70	0.50	0.64

316  
 317 As mentioned above, different energy system technologies for heating and cooling have been  
 318 considered in the study, leading to different formulation of the objective functions, based on  
 319 Equations (3) and (5). Table 5 lists them and shows the main data assumed in the study, as follows:

- 320 •  $\eta_{gen}$  represents the reference seasonal energy efficiency for each generation system (DM  
 321 26/06/2015);
- 322 •  $\eta_{T_{h,k}}$  and  $\eta_{T_{c,k}}$  represent the seasonal global energy efficiency for the heating and cooling  
 323 energy systems as the generation efficiency multiplied by a 0.82 standard utilization factor  
 324 that takes into account the efficiency of the distribution, the emission and the regulation  
 325 systems;
- 326 •  $f_{T_{h,k}}$  and  $f_{T_{c,k}}$  represent the Italian non-renewable primary energy conversion factors of the  
 327 specific energy carrier for heating and cooling supply;
- 328 •  $w_{energy}$  is the energy weight factor as defined in Eq. (2.1) and (2.2);
- 329 •  $c_{T_{h,k}}$  and  $c_{T_{c,k}}$  are the specific costs of the kWh related to the energy carriers of the heating  
 330 and cooling energy systems;
- 331 •  $w_{cost}$  is the cost weight factor as defined in Eq. (4.1) and (4.2).

332

333

334 *Table 5. Efficiencies and weights related to the technical systems for heating and cooling supply*  
 335 *considered in the study.*

	$\eta_{gen}$	$\eta_{T_{h,k}}$	$f_{T_{h,k}}$	$w_{energy}$	$c_{T_{h,k}}$	$w_{cost}$
Heating technology	[-]	[-]	[-]	[-]	[€/kWh]	[-]
District Heating (DH)	-	0.88	0.62	0.70	0.09	0.102
Gas Condensing Boiler (GCB)	0.95	0.78	1.05	1.35	0.10	0.128
Gas Heat Pump (GHP)	1.20	0.98	1.05	1.07	0.10	0.102
Electric Heat Pump (EHP)	3	2.46	1.95	0.79	0.20	0.081
Cooling technology	$\eta_{gen}$	$\eta_{T_{c,k}}$	$f_{T_{c,k}}$	$w_{energy}$	$c_{T_{c,k}}$	$w_{cost}$
	[-]	[-]	[-]	[-]	[€/kWh]	[-]
Electric chiller (EC)	2.5	2.025	1.95	0.96	0.20	0.098
Gas Absorption chiller (GAC)	0.6	0.49	1.05	2.13	0.10	0.203

336

337 The combination of different energy system technologies for heating and cooling generates the four  
 338 main scenarios considered in the study, each of them characterized by specific weighting factors to  
 339 compute the objective functions for the optimization.

340

### 341 3.3. Optimization runs

342 For each energy system scenario, the optimization process was run both for minimizing and for  
 343 maximizing the objective functions, so that at the final stage, as post-processing, the space of solution  
 344 could be explored from its minimum to its maximum.

345 The GenOpt binary version of the PSO algorithm (Wetter, 2011), based on the performance study  
 346 reported in (Ferrara, 2017), was run with the following settings: 20 particles, social acceleration set  
 347 to 2.5, cognitive acceleration set to 1.5, maximum velocity equal to 4. The random seed was set to 1

348 and the Von Neumann neighborhood topology was used with a size of 5. Each optimization was run  
 349 until 150 generations are reached.

350 The four energy system scenarios are defined as follows:

- 351 • Scenario 1 corresponds to the initial scenario characterized by a District Heating system for  
 352 heating supply and an Electric Chiller for cooling supply;
- 353 • Scenario 2 is characterized by the combination of a Gas Condensing Boiler for heating  
 354 supply and an Electric Chiller for cooling supply;
- 355 • Scenario 3 is characterized by the combination of a Gas Heat Pump for heating supply and a  
 356 Gas Absorption Chiller for cooling supply;
- 357 • Scenario 4 is characterized by the combination of a Electric Heat Pump for heating supply  
 358 and an Electric Chiller for cooling supply;

359 The resulting weights  $w_c$ ,  $w_h$  and the ratio  $w_c/w_h$  (in colors) for each scenario are reported, based on  
 360 the structure of Table 1, for both the energy objective function (Table 6) and the cost objective  
 361 function (Table 7).

362

363

364 *Table 6. The matrix of the total energy weight  $w_c/w_h$  of each the design scenario for the*  
 365 *computation of the objective functions.*

	Heating sys	DH	GCB	GHP	EHP
Cooling sys	$w_{energy}$	0.70	1.35	1.07	0.79
EC	0.96	1.37	0.71	not feasible	1.22
GAC	2.13	not feasible	not feasible	2.00	not feasible

366

367

368

369

370

371 *Table 7. The matrix of the total cost weight  $w_c/w_h$  of each the design scenario for the computation*  
 372 *of the objective functions.*

	Heating sys	DH	GCB	GHP	EHP
Cooling sys	$w_{cost}$	0.102	0.128	0.102	0.081
EC	0.098	0.95	0.76	not feasible	1.22
GAC	0.203	not feasible	not feasible	2.00	not feasible

373

374 Where, for a specific scenario, the  $w_{c,energy}/w_{h,energy}$  ratio equals the  $w_{c,cost}/w_{h,cost}$  ratio, the two  
 375 optimization processes run for minimizing primary energy and cost are expected to lead to equal  
 376 results. In fact, each optimal solution is characterized by an optimal  $Q_c/Q_h$  ratio related to the  
 377 minimum objective function value. Each different  $w_c/w_h$  ratios will lead to different optimal  $Q_c/Q_h$   
 378 ratios. The difference between the energy and cost optimization for a same system scenario can be  
 379 explained by the difference between the related energy and cost  $w_c/w_h$  ratios. Therefore, it is  
 380 expected that the greater the difference between  $w_c/w_h$  ratios, the biggest differences between the  
 381 energy-optimized design and the cost-optimized design will be appraised.

382

#### 383 4. Results and discussion

384 Results are presented into three types of diagrams. The first type (e.g. Figure 4) reports on the  
 385 horizontal axis the energy objective function (3), representing the specific annual non-renewable  
 386 primary energy need of the case-study floor. The cost objective function (5), representing the specific  
 387 annual energy cost in euros per square meter of conditioned floor area, is reported on the vertical axis.  
 388 The second type (e.g. Figure 5) reports the specific energy need for space cooling ( $Q_c$ ) on the

389 horizontal axis and the specific energy need for space heating ( $Q_h$ ) on the vertical axis. In these  
390 graphs, each point represents one building design configuration associated to one combination of  
391 parameter values. The points that were found within the same optimization process, for the same  
392 system scenario and objective function, are clustered in clouds where points have the same color (e.g.  
393 Figure 8), according to the colors used in Table 6 and Table 7.

394 The third type of graph (e.g. Figure 10) reports on the vertical axes the range of variation of the  
395 parameter values and on the horizontal axis the frequency distribution of those values within the  
396 solution in the optimum neighborhoods.

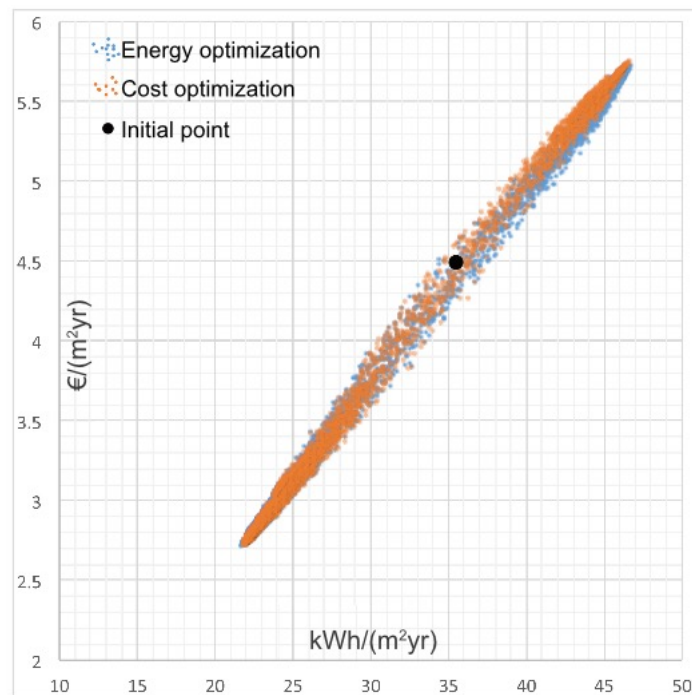
397 A detailed results analysis is reported for the Scenario 1, then results related to the other scenarios  
398 are summarized and compared.

399

#### 400 *4.1. Scenario 1: detailed analysis of results*

401 Figure 4 reports all points evaluated within the optimization processes in Scenario 1 (DH+EC) with  
402 the two objectives. The points of the design space that were evaluated within the energy optimization  
403 process are reported in blue, while orange points are referred to the cost optimization process. As  
404 shown, these points are part of the same design space, which was searched through in different ways  
405 according to the optimization objective. Since the optimization process was run for both minimizing  
406 and maximizing the objective functions, the graph shows that the range of possible solutions led to  
407 primary energy values within the range 21.6-46.7 kWh/(m<sup>2</sup>yr) and to operational energy cost values  
408 in the range between 2.7 and 5.8 €/m<sup>2</sup>yr).

409 The black dot indicates the position of the initial building design in the initial scenario. It is shown  
410 that both the primary energy demand for space heating and cooling and the operational energy costs  
411 can be reduced by around 40%.



412

413 *Figure 4. Primary energy (x-axis) and cost (y-axis) values of the points of the design space that were*  
414 *evaluated within the energy optimization (blue) and the cost-optimization (orange) in scenario 1.*

415

416 It is interesting to note that the two objective functions lead to similar ranges of possible solutions in  
417 both dimensions and thus to optimal points that are very close to each other in the graph.

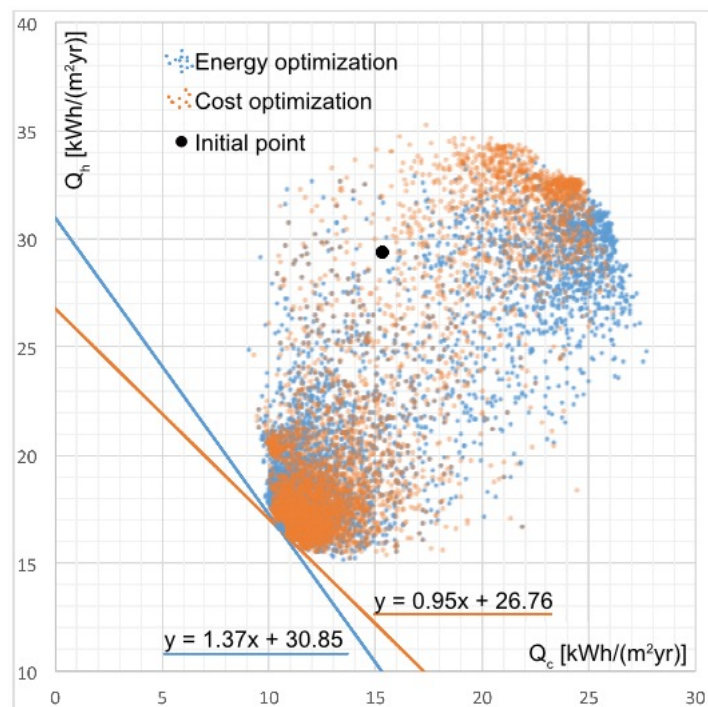
418 However, looking at Figure 5, it appears that similar objective function values can be reached with  
419 many different  $Q_c/Q_h$  couples, therefore related to different building design configurations.

420 In fact, Figure 5 reports the energy needs for space heating and cooling related to the same points  
421 represented in Figure 4. The two *loci* of optimal points are also reported, together with their equations.

422 Based on the theory explained in Section 2.4, a set of points laying on a line that is parallel to the blue  
423 or orange line is related to the same primary energy or cost value, respectively. The shape of the

424 clouds reported in Figure 5 demonstrates that there are a great number of design alternatives for each  
425 objective function value. In the presented case, this number is higher for energy or cost values in the

426 middle of the solution range, close to the initial configuration (black dot), and becomes smaller when  
427 approaching to the *loci* of optimal points.



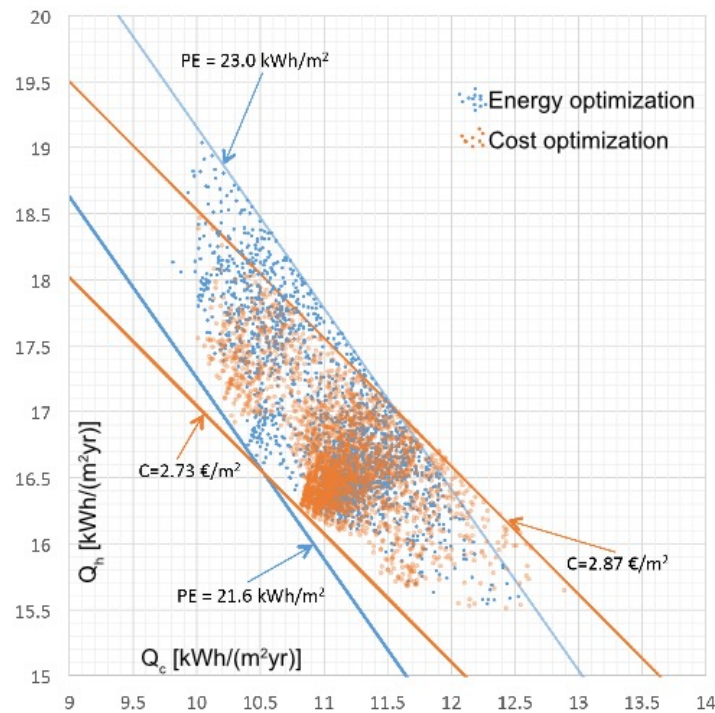
428

429 *Figure 5.  $Q_c$  (x-axis) and  $Q_h$  (y-axis) values of the points of the design space that were evaluated*  
430 *within the energy optimization (blue) and the cost-optimization (orange) in Scenario 1.*

431

432 However, in the neighborhood of optimum, there is still a significant set of design alternatives leading  
433 to similar objective function values, as shown in Figure 6, where a zoom on the optimal region of  
434 Figure 5 is reported. The objective function value to be considered as the upper bound of the optimum  
435 neighborhood was set to the minimum objective function value increased by 5% of the difference  
436 between the minimum and the maximum objective function values (max-min range).

437 As shown in Figure 6, the optimal points for the two objective functions (the points laying on the  
438 respective *loci* of optimal points) are quite close to the crossing point of the two lines, but they do not  
439 exactly correspond to that point. This means that there are two different  $Q_c/Q_h$  couples that are related  
440 to the two optimal points, each corresponding to a different optimal design configuration.



441

442 *Figure 6. Neighborhood of the optimal points in Scenario 1.*

443

444 In Table 8, the parameter values related to the energy optimum (the point laying on the blue line in  
445 Figure 6; PE=21.6 kWh/m<sup>2</sup>) and to the cost optimum (the point laying on the orange line in Figure 6;  
446 C=2.73 €/m<sup>2</sup>) are reported with the values related to the initial building design configuration.

447 It is shown that the values of parameters related to external wall insulation in all orientations  
448 (sISOLN, sISOLEW, sISOLS) are significantly increased in both optimal scenarios.

449 The grey color highlights the parameter values where differences occur between the initial solution  
450 and the optimal solutions. These differences are related to the external wall solar absorption  
451 coefficients, the depth of the loggias and of the external shadings, to the width of some windows and  
452 to the window type.

453 Based on these results, the cost-optimization seems to be heating-driven, coherently with the higher  
454 weight related to the heating term. In fact, the higher values of solar absorption coefficients and the  
455 smaller depth of loggias increase heating gains in winter. Following the same principle, the window  
456 type 6, which is selected for south windows in the cost-optimized scenario, has the same thermal  
457 transmittance of the window type 3, but a higher solar factor.

458 *Table 8. Objective function and parameter values in the initial scenario and in the two optimal*  
 459 *solutions (energy and cost). The grey color indicates the parameters of which the optimal value*  
 460 *changes according to the objective function.*

Parameter name	Initial value (INI)	Energy-optimal value (Eopt)	Cost-optimal value (Copt)	Parameter name	Initial value	Energy-optimal value (Eopt)	Cost-optimal value (Copt)
inWN (m <sup>2</sup> K/W)	1.73	5.40	5.40	WW_A_Loggia (m)	1.3	1.1	1.1
inWS (m <sup>2</sup> K/W)	1.73	5.40	5.40	WW_A_South(m)	2.5	2.7	2.1
inWE (m <sup>2</sup> K/W)	1.73	5.40	5.40	WW_A_West (m)	1.8	1.1	1.1
abs-back (-)	0.2	0.2	0.2	WW_B_South (m)	1.8	1.7	1.5
abs-backS (-)	0.2	0.2	0.5	WW_B_Loggia (m)	1.2	1.6	1.6
abs-backEW (-)	0.2	0.2	0.5	WW_C_South (m)	1.8	1.9	1.7
WT (-)	1	3	3	WW_C_North (m)	2.4	1.9	1.9
WTS (-)	1	3	6	WW_D_South (m)	1.8	1.7	1.7
WTW (-)	1	3	3	WW_D_North (m)	2.4	1.9	1.9
WTLS (-)	1	3	6	WW_E_South (m)	1.8	1.7	1.5
WTLN (-)	1	3	3	WW_E_Loggia (m)	1.2	1.6	1.6
S_overhproj (m)	0	1.2	1.2	WW_F_Loggia (m)	1.8	1.6	1.6
Ploggia_S (m)	1.8	1.8	1.4	WW_F_South (m)	1.2	1.3	1.1
Ploggia_N (m)	1.8	2.1	1.2	WW_G_Loggia(m)	3.1	2.1	2.1
				WW_G_North(m)	1.2	1.1	0.9
				WW_G_South (m)	1.1	1.6	1.6

Point	Qc/Qh ratio	PE kWh/m <sup>2</sup>	C €/m <sup>2</sup>
INI	0.51	35.4	4.56
Eopt	0.62	21.6	2.74
Copt	0.67	21.8	2.73

461

462 In the last rows of Table 8, the Qc/Qh ratio referred to the initial point (INI), the energy optimum

463 (Eopt) and the cost optimum (Copt) points are reported.

464 Beyond the resulted absolute objective function values, which may be affected by uncertain modeling

465 assumptions, the most interesting result is related to the wide range of possible building design

466 configuration leading to objective function values in the optimum neighborhood. Within this

467 neighborhood, the variety of design solutions, and thus of different combinations of parameter values,

468 is demonstrated by the range of Qc/Qh ratios. For the system Scenario 1, the Qc/Qh ratio of the points

469 in the optimum neighborhood ranges from 0.53 to 0.8 for the energy optimization and from 0.54 to

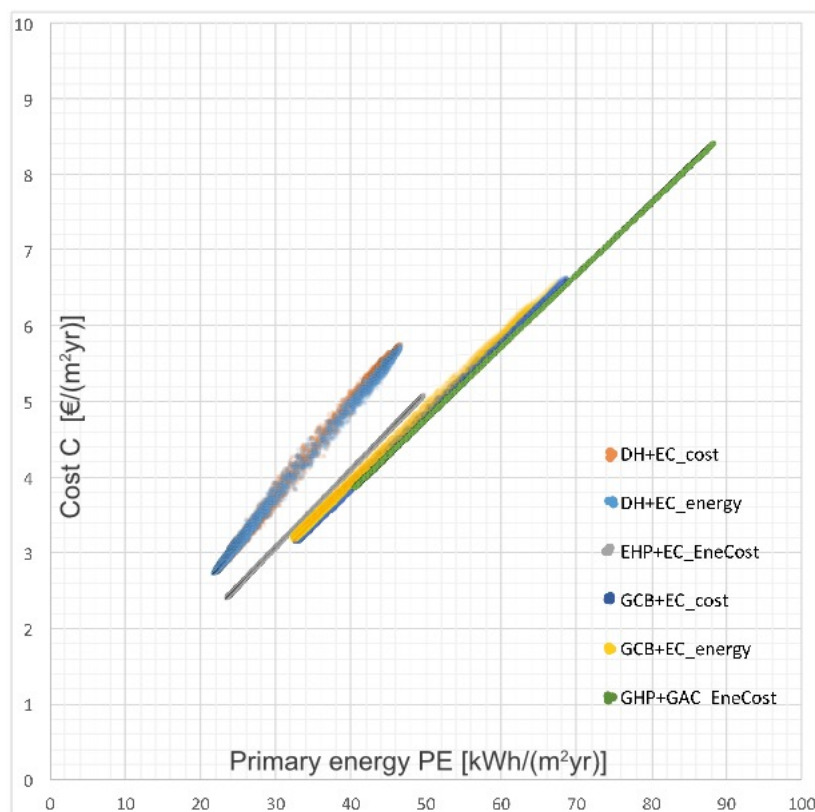
470 0.73 for the cost optimization. These ranges are reported below in Figure 9, together with those related

471 to the other system scenarios.

472 4.2. All scenarios: results summary and resilience of the optimum

473 Figure 7 and Figure 8 report the two representations of the results in all scenarios.

474 The variations of the max-min ranges of objective function values related to the system scenarios are  
475 shown in Figure 7. It is clear that the scenario EHP+EC can lead to the minimum operational cost,  
476 while the scenario DH+EC can lead to the minimum primary energy consumption. The GHP+GAC  
477 scenario is the one that may lead to the highest energy and cost objective function values with the  
478 defined set of parameters.



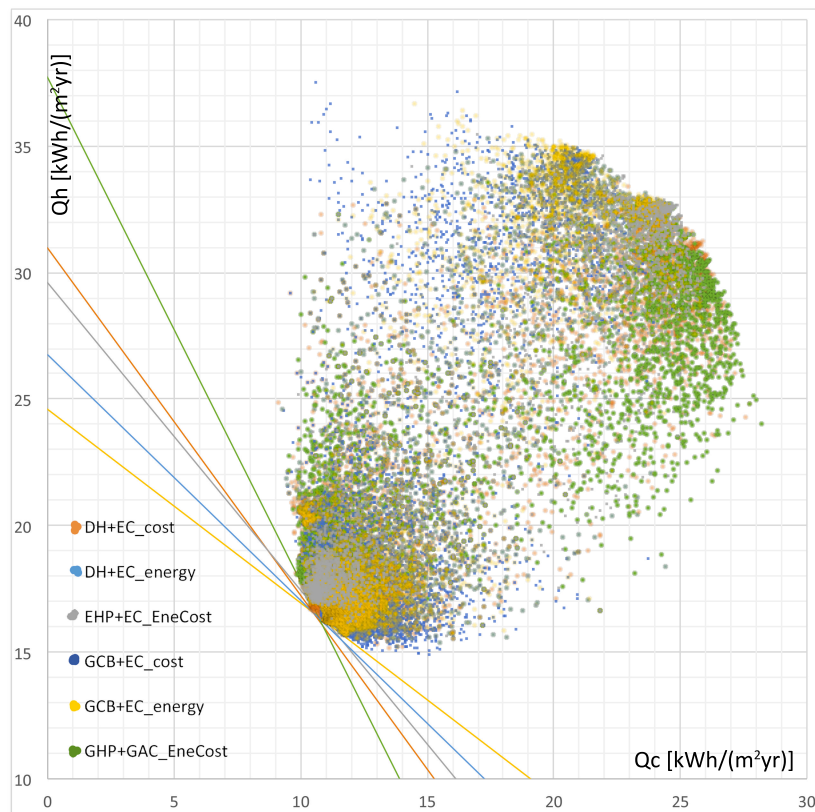
479

480 *Figure 7. Primary energy (x-axis) and cost (y-axis) values of the points of the design space that were*  
481 *evaluated within optimization processes in all scenarios.*

482

483 The results representation in Figure 8 shows the position of the clouds of points with respect to the  
484 different *loci* of optimal points resulting from the different scenarios. The  $Q_c/Q_h$  ratios and the  
485 objective function values for each of the optimal points for each scenario are reported in Table 9.

486



487

488 *Figure 8.  $Q_c$  (x-axis) and  $Q_h$  (y-axis) values of the points of the design space that were evaluated*  
 489 *within the optimization in all scenarios.*

490

491 *Table 9. Objective function values and  $Q_c/Q_h$  ratio of optimal solutions (energy and cost) in all*  
 492 *scenarios.*

493

Scenario	Point	$Q_c/Q_h$ ratio	PE kWh/m <sup>2</sup>	C €/m <sup>2</sup>	PE range (max-min) kWh/m <sup>2</sup>	C range (max-min) €/m <sup>2</sup>
DH+EC_Energy	INI	0.51	35.4	4.56		
	Eopt	0.62	21.6	2.74	21.8	
	Copt	0.67	21.8	2.73		3.02
GCB+EC	Eopt	0.74	32.4	3.17	36.8	
	Copt	0.67	32.5	3.15		3.48
GHP+GAC	ECopt	0.56	40.3	3.84	47.8	4.61
EHP+EC	ECopt	0.60	23.3	2.39	26.6	2.69

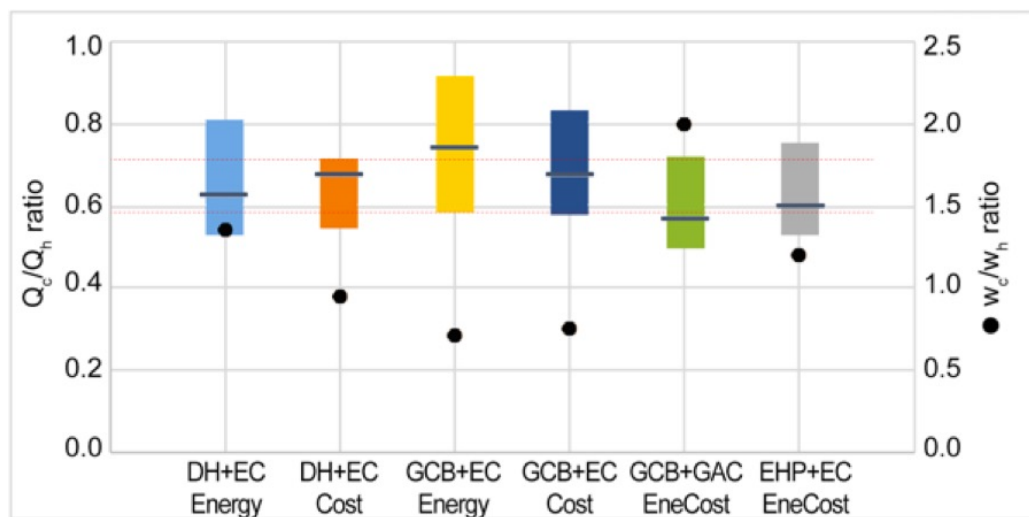
499

500 As mentioned above, Figure 9 reports the ranges of  $Q_c/Q_h$  ratios related to the building design  
 501 configurations within the optimum neighborhoods for the different scenarios and objectives. The  
 502 black lines represent the absolute optimum points in their neighborhood and the black dots report the

503 value of the  $w_c/w_h$  ratios of each corresponding scenario. As expected, there is an inverse correlation  
504 between the  $w_c/w_h$  ratio and the  $Q_c/Q_h$  ratio of the optimal solutions, as the higher the first, the lower  
505 the second and vice-versa.

506 Comparing the different scenarios, it appears that there is a smaller range of  $Q_c/Q_h$  ratios falling within  
507 the optimum neighborhood of all scenarios (it is between the two red lines in Figure 9). This means  
508 that there is a set of building design configurations that are optimal or nearly-optimal, regardless of  
509 the system scenario or the optimization objective.

510



511

512 *Figure 9. Range of  $Q_c/Q_h$  ratio related to the optimum neighborhood in relation to the  $w_c/w_h$  ratio of*  
513 *each system scenario.*

514

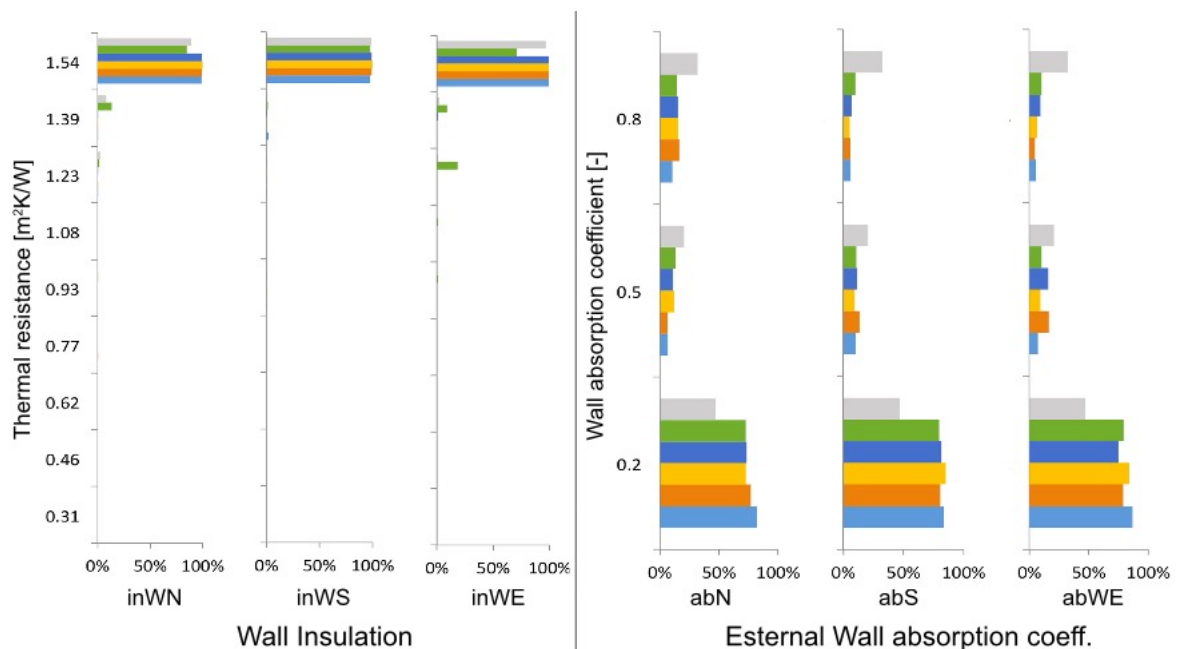
515 In order to analyze the parameter values associated to the points in the optimum neighborhoods  
516 leading to the above-presented ranges of  $Q_c/Q_h$ , the distribution of frequency of the values assumed  
517 by each parameter in the optimum neighborhood has been studied in Figures 10, 11, 12. These figures  
518 report, on the vertical axes, all the values within the range of variation of each design parameter; on  
519 the horizontal axis, the frequency of occurrence of each value within the set of solutions composing  
520 the optimum neighborhood. The different colors refer to the different scenarios as in previous Figures.

521 This allows the resilience of the optimal building design configuration (the set of optimal parameter  
522 values) to the variation of the system scenario and objective to be analyzed. On the other side, the  
523 fact that more than one parameter value is possible for reaching similar objective function values  
524 opens more possibilities to the designer who can select one or the other design configuration  
525 according to other constraints.

526 As shown in Figure 10, the parameters related to wall insulation appear to be the most resilient, as  
527 almost 100% of points within the optimum neighborhoods in all scenarios have the same values for  
528 wall insulation parameters. Also, the parameters related to the external wall solar absorption  
529 coefficients and the window types have a most frequent value, but there are a significant number of  
530 points with different values.

531 The design parameters related to the dimensions of windows and shadings are the less resilient, as  
532 their values can be combined in different ways within the optimum neighborhoods.

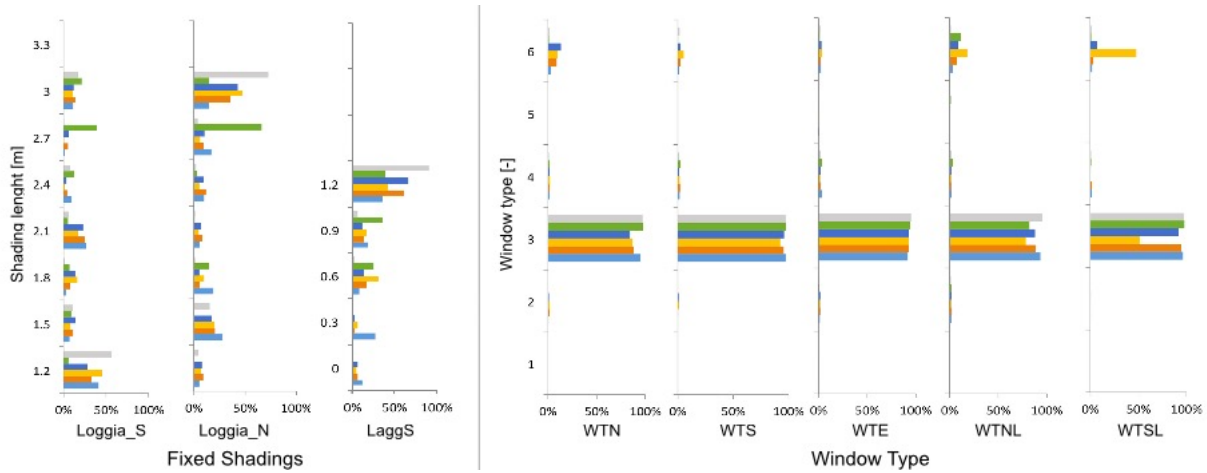
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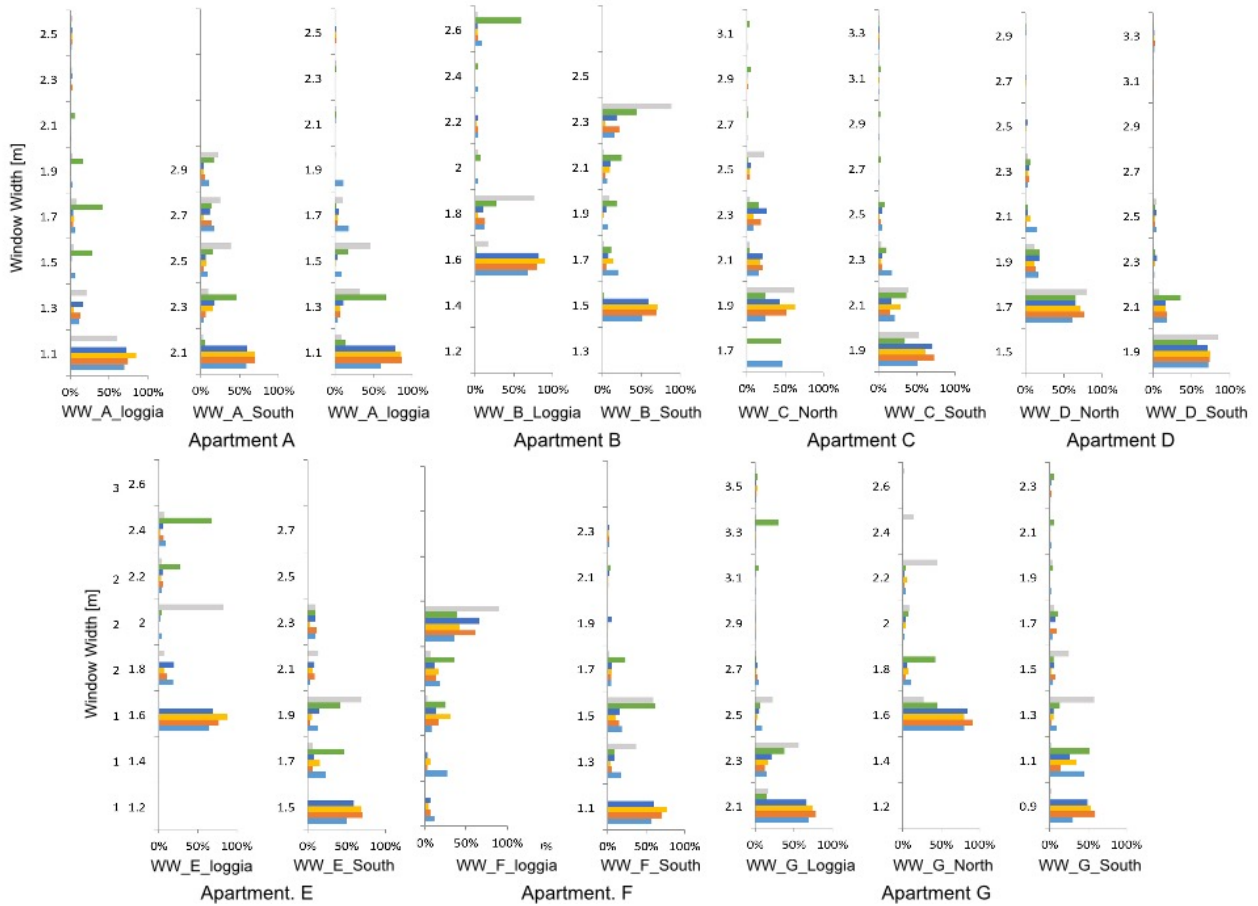
535 *Figure 10. Distribution of parameter values within the optimum neighborhoods/I*

536



537  
538  
539

Figure 11. Distribution of parameter values within the optimum neighborhoods/2



540  
541  
542

Figure 12. Distribution of parameter values within the optimum neighborhoods/3

## 543 **5. Conclusions**

544 This study deals with the envelope design optimization (passive energy efficiency measures) of a  
545 recent multi-family building for social housing in Italy according to different objectives (non-  
546 renewable primary energy consumption and operational costs) and different energy system scenarios.  
547 With the defined design parameters, based on the current design of the building, both the energy  
548 optimization and the cost optimization can decrease the sum of heating and cooling primary energy  
549 consumptions by more than 35% and the energy costs for heating and cooling by around 35%. This  
550 demonstrates that there is still a large potential for performance improvement with respect to the  
551 current construction practice of multi-family buildings in Italy.

552 This has a significant impact on the design, since performance improvements derive from increasing  
553 the wall insulation, from selecting window types with an optimal combination of thermal  
554 transmittance and solar factor according to the orientation, from modifying the depth of loggias, with  
555 obvious implications on the flat layout, and from adding fixed shadings elements of a specific depth,  
556 with implications on the façade design.

557 It was demonstrated that the extent to which the cost-optimized design differs from the energy-  
558 optimized design depends on the adopted system scenario. In fact, depending on such scenarios,  
559 different weights are assigned to the heating and cooling needs in the two objective functions (energy  
560 and cost). When the system scenario implies the use of more than one energy carrier, it is expected  
561 that the energy-optimized design is different from the cost-optimized design, because the ratio  
562 between the weights in the energy objective function differs from the cost weight ratio. In these cases,  
563 it was found that the performance improvements achieved in both the energy-optimized and the cost-  
564 optimized scenarios are very close to each other, but the optimal design solutions result in a different  
565 ratio between cooling and heating energy demands. This means that a different optimization objective  
566 may transform a cooling-driven optimization process into a heating-driven process or vice versa. On  
567 the other side, in the scenarios using only one energy carrier, the energy-optimized design is also

568 cost-optimized and the optimal solution depends only on the adopted system scenario. It has to be  
569 pointed out that, in this study, the non-renewable primary energy conversion factor was used to  
570 compute the energy weights. The differences between energy and cost optimization would change if  
571 total primary energy or delivered energy were used, because they would lead to different weighting  
572 ratios. However, because this study only considers energy supply from the grid and not from in-situ  
573 renewable energy production systems, only small differences would be appraised, as shown in a  
574 preliminary study (Ferrara, 2017b).

575 Moreover, it was demonstrated that the optimum neighborhood contains many different design  
576 solutions that lead to energy and cost values very close to the optimum. A great number of design  
577 alternatives that are almost equivalent in terms of performance can better support the design process  
578 in dealing with other constraints that are not specifically related to the energy design of the building.  
579 Furthermore, it was found that there is a set of design solutions that are included in the optimum  
580 neighborhood of all the analyzed scenarios. This provides a set of design alternatives that are very  
581 close to the energy optimum and, at the same time, are able to reduce the vulnerability of low-income  
582 tenants living in multi-family buildings while being resilient to the possible future variation of the  
583 energy system scenario.

584 Within this set of solutions in the optimum neighborhood, the optimal values of parameters related to  
585 the wall insulation and the window type appear to be the most robust in all scenarios.

586 It has to be noted that these results were achieved by optimizing the floor as a whole. Better results  
587 could be probably achieved by optimizing the performance of each apartment, but investigations on  
588 how to deal with the possible increase of construction costs due to a greater differentiation of  
589 construction components should be done.

590 Further work should complete the study and investigate the problem from the building owner  
591 perspective, including also the investment and maintenance costs in the cost objective function. Other  
592 developments will expand the design space considering design variables related to the building

593 envelope, to the energy systems and to on-site renewable energy sources at the same time. Future  
594 developments of the work will investigate the problem in different weather conditions and in different  
595 energy tariff scenarios.

596

## 597 **Nomenclature**

### 598 *Acronyms*

599	DH	District Heating
600	EC	Electric Chiller
601	EHP	Electric Heat Pump
602	GAC	Gas Absorption Chiller
603	GCB	Gas Condensing Boiler
604	GHP	Gas Heat Pump
605	INI	Initial building configuration
606	OPT	Optimal building configuration
607	PSO	Particle Swarm Optimization algorithm

608

### 609 *Latin letters*

610	abN	solar absorption coefficient of external wall – North façade
611	abS	solar absorption coefficient of external wall – South facade
612	abWE	solar absorption coefficient of external wall – West, East facades
613	Blr	Width of the window at the ground floor on the south façade (m)
614	Bm	Width of the window at the first floor on the south façade (m)
615	$C$	Operational cost (€)
616	$c$	specific energy cost (€/kWh)
617	$f_{pe}$	primary energy conversion factor
618	inWN	Thermal resistance of wall insulation – North façade (m <sup>2</sup> K/W)
619	inWS	Thermal resistance of wall insulation – South façade (m <sup>2</sup> K/W)
620	inWE	Thermal resistance of wall insulation – West, East facades (m <sup>2</sup> K/W)
621	Loggia_N	Depth of North loggia (m)
622	Loggia_S	Depth of South loggia (m)
623	Lagg_S	Depth of fixed shadings on the South façade windows (m)
624	$OF$	Objective function

625	<i>PE</i>	Primary Energy (kWh)
626	<i>p</i>	Parameter
627	<i>s</i>	Parameter variation step
628	<i>Q</i>	Energy need (kWh)
629	<i>w</i>	weight
630	WTE	Window Type of East, West facades (-)
631	WTN	Window Type of North facade (-)
632	WTNL	Window Type of North loggia facade (-)
633	WTS	Window type of South facade (-)
634	WTSL	Window Type of South loggia facade (-)
635	WW	Window width (m)
636		
637	Subscripts	
638	<i>c</i>	cooling
639	<i>h</i>	heating

640

## 641 **References**

- 642 Ascione F., N. Bianco, R.F. De Masi, C. De Stasio, G. M. Mauro, G. P. Vanoli. 2016. "Multi-objective optimization  
643 of the renewable energy mix for a building". *Applied Thermal Engineering* 101:612-621,  
644 doi: 10.1016/j.applthermaleng.2015.12.073.
- 645 Bayraktar M., E. Fabrizio, M. Perino. 2012. "The «extended building energy hub»: a new method for the simultaneous  
646 optimization of energy demand and energy supply in buildings". *HVAC&R Research* 18: 67-87. doi:  
647 10.1080/10789669.2011.588300
- 648 Brandão de Vasconcelos A., M. Duarte Pinheiro, A. Manso, A. Cabaço. 2016. "EPBD cost-optimal methodology:  
649 Application to the thermal rehabilitation of the building envelope of a Portuguese residential reference building".  
650 *Energy and Buildings* 111:12-25, doi: 10.1016/j.enbuild.2015.11.006.
- 651 Copiello, S. 2016. "Leveraging Energy Efficiency to Finance Public-Private Social Housing Projects". *Energy Policy*  
652 96: 217-230. doi:10.1016/j.enpol.2016.06.003.
- 653 Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency,  
654 amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.
- 655 CEN (European committee for standardization) Standard EN ISO 13790. 2008 - "Energy performance of buildings –  
656 Calculation of energy use for space heating and cooling".
- 657 DM (Decreto interministeriale) 26/06/2015 - Adeguamento linee guida nazionali per la certificazione energetica degli  
658 edifici.
- 659 European Union. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy  
660 efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and  
661 2006/32/EC.
- 662 European Union. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy  
663 performance of buildings (recast).
- 664 Eurostat. Energy Price Statistics, data extracted in 2016. <http://ec.europa.eu/eurostat/statistics->

- 665 explained/index.php/Energy\_price\_statistics
- 666 Evins, R. 2013. "A review of computational optimisation methods applied to sustainable building design", *Renewable*
- 667 *and Sustainable Energy Reviews*, 22: 230-245, doi:10.1016/j.rser.2013.02.004.
- 668 Fabrizio, E., M. Ferrara, V. Monetti. 2017. Smart heating systems for cost-effective retrofitting, in F. Pacheco-Torgal,
- 669 C. Granqvist, B. Jelle, G. Vanoli, N. Bianco, J. Kurnitski (Eds.), "Cost-effective energy efficient building
- 670 retrofitting. Materials, technologies, optimization and case studies", Elsevier - Woodhead Publishing, pp. 277-302
- 671 (ISBN 978-0-08-101128-7). Doi: 10.1016/B978-0-08-101128-7.00010-1.
- 672 Faiella I, Lavecchia L. 2014. "Energy Poverty in Italy". Occasional Paper 240, Bank of Italy.
- 673 Ferrara M., E. Fabrizio, J. Virgone, M. Filippi. 2014. "A simulation-based optimization method for cost-optimal
- 674 analysis of nearly Zero energy Buildings". *Energy and Buildings* 84:442-457. doi: 10.1016/j.enbuild.2014.08.031
- 675 Ferrara M., E. Fabrizio, J. Virgone, M. Filippi. 2016a. "Energy systems in cost-optimized design of nearly zero-energy
- 676 buildings", *Automation in Construction* 70: 109-127.
- 677 doi: 10.1016/j.autcon.2016.06.007.
- 678 Ferrara M., E. Sirombo, A. Monti, M. Filippi, E. Fabrizio. 2016b. "Influence of Envelope Design in the Optimization
- 679 of the Operational Energy Costs of a Multi-family Building". *Energy Procedia* 101: 216-223.
- 680 doi: 10.1016/j.egypro.2016.11.028.
- 681 Ferrara, M., Dabbene, F., Fabrizio, E. 2017a. "Optimization Algorithms Supporting the Cost Optimal Analysis: The
- 682 Behaviour of PSO". *Proceedings of the 15th IBPSA Conference - Building Simulation 2017*.
- 683 Ferrara M., E. Sirombo, E. Fabrizio. 2017b. "Comparison between energy-optimized and cost-optimized design of
- 684 multi-family buildings through automated optimization". *BSA 2017 Proceeding Book*, under press.
- 685 Ferreira, M., M. Almeida, A. Rodrigues. 2016. "Cost-optimal energy efficiency levels are the first step in achieving
- 686 cost effective renovation in residential buildings with a nearly-zero energy target", In *Energy and Buildings*
- 687 133:724-737. doi:10.1016/j.enbuild.2016.10.017.
- 688 Ficco, G., L. Celenza, M. Dell'Isola, P. Vigo. 2016. "Experimental comparison of residential heat accounting systems
- 689 at critical conditions". *Energy and Buildings* 130:477-487. doi: 10.1016/j.enbuild.2016.08.068.
- 690 ISTAT (Italian National Institute of Statistics). 2010. L'abitazione delle famiglie residenti in Italia. Statistiche in breve.
- 691 <http://www.istat.it/>
- 692 Kapsalaki M., V. Leal, M. Santamouris. 2012. A methodology for economic efficient design of Net Zero Energy
- 693 Buildings, *Energy and Buildings* 55: 765-778. doi: 10.1016/j.enbuild.2012.10.022.
- 694 Kurnitski J., Saari A., Kalamees T., Vuolle M., Niemelä J., Tark T.. 2011. "Cost optimal and nearly zero (nZEB)
- 695 energy performance calculations for residential buildings with REHVA definition for nZEB national
- 696 implementation." *Energy and Buildings* 43(11):3279-3288. Doi: 10.1016/j.enbuild.2011.08.033.
- 697 Linea Reti e Impianti. Data related to II trimestre 2016..[http://www.linea\\_ri.it/teleriscaldamento/servizi-cliente/tariffe-cremona](http://www.linea_ri.it/teleriscaldamento/servizi-cliente/tariffe-cremona)
- 698
- 699 Pikas, E., Thalfeldt, M., Kurnitski, J., Liias, R. 2015. "Extra cost analyses of two apartment buildings for achieving
- 700 nearly zero and low energy buildings". *Energy* 84:623-633. doi: 10.1016/j.energy.2015.03.026
- 701 Pikas, E., Kurnitski, J., Thalfeldt, M., Koskela, L., 2017. "Cost-benefit analysis of nZEB energy efficiency strategies with
- 702 on-site photovoltaic generation", *Energy*, 128: 291-301. Doi: 10.1016/j.energy.2017.03.158.
- 703 Prando D., A. Prada, F. Ochs, A. Gasparella, M. Baratieri. 2016. "Analysis of the energy and economic impact of cost-
- 704 optimal buildings refurbishment on district heating systems". *Science and Technology for the Built Environment*
- 705 21:876-891.
- 706 Rysanek A.M., R. Choudhary. 2013. "Optimum building energy retrofits under technical and economic uncertainty".
- 707 *Energy and Buildings* 57:324-337. Doi: 10.1016/j.enbuild.2012.10.027.
- 708 Tronchin L, Fabbri K, 2012. "Energy Performance Certificate of building and confidence interval in assessment: An
- 709 Italian case study", *Energy Policy*, 48:176-184. Doi: 10.1016/j.enpol.2012.05.011.
- 710 Tronchin L., Tommasino M.C., Fabbri, K. 2014. "On the cost-optimal levels of energy-performance requirements for
- 711 buildings: A case study with economic evaluation in Italy". *International Journal of Sustainable Energy Planning*
- 712 *and Management* 3:49-62. doi: 10.5278/ijsepm.2014.3.5.
- 713 UNI/TS 11300-2:2014 "Prestazioni energetiche degli edifici - Parte 2: Determinazione del fabbisogno di energia

- 714        primaria e dei rendimenti per la climatizzazione invernale, per la produzione di acqua calda sanitaria, per la  
715        ventilazione e per l'illuminazione in edifici non residenziali”.
- 716        Wang W., J. Zhang , W. Jiang, B. Liu. 2011. “Energy performance comparison of heating and air-conditioning systems  
717        for multi-family residential buildings”. *HVAC&R Research* 17: 309-322
- 718        Wetter M and Simulation Research Group, 2011. GenOpt – Generic Optimization Program, User manual, V.3.1.0.
- 719        Xing S., Z. Tian, W. Chen, B. Si, X. Jin. 2016. A review on building energy efficient design optimization from the  
720        perspective of architects. *Renewable and Sustainable Energy Reviews* 65:872-884, doi:10.1016/j.rser.2016.07.050.
- 721        Zacà I, D. D’Agostino, P. M. Congedo, C. Baglivo,. 2015. “Assessment of cost-optimality and technical solutions in  
722        high performance multi-residential buildings in the Mediterranean area”. *Energy and Buildings* 102:250-265.  
723        doi:10.1016/j.enbuild.2015.04.038.
- 724