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Assessment of cost-optimal energy performance requirements for the Italian residential building stock

Vincenzo Corrado[a,]*, Ilaria Ballarini[a], Simona Paduos[a]

[a]*Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino, Italy*

Abstract

Directive 2010/31/EU establishes that Member States must ensure that minimum energy performance requirements for buildings are set with a view to achieve cost-optimal levels. The paper presents a methodology for identifying the cost-optimal levels for the Italian residential building stock, following the Guidelines accompanying the Commission Delegated Regulation No. 244/2012. The methodology is applied to a reference building of the *IEE-TABULA* project and considering different energy efficiency measures. The energy performance and the global cost calculations are performed according to UNI/TS 11300 and UNI EN 15459, respectively. A new cost optimisation procedure based on a sequential search-optimisation technique considering discrete options is applied.

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Keywords: cost-optimal methodology; energy performance assessment; simplified energy model; reference building

1. Introduction

European Directive 2010/31/EU (EPBD recast) [1] on the energy performance (EP) of buildings requires Member States (MS) to introduce a comparative methodology framework at national level in order to define cost-optimal levels of minimum EP requirements for buildings and building elements (EPBD recast, art. 4.1 and 14), and compare them with the national requirements set in building codes.

* Corresponding author. Tel.: +39-011-090-4456; fax: +39-011-090-4499.
E-mail address: vincenzo.corrado@polito.it

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A cost-optimal level is the EP level which leads to the lowest cost during the estimated economic life-cycle, determined taking into account energy-related investment costs, maintenance and operating costs (including energy costs and savings, the category of building concerned, earnings from energy produced), and disposal costs, where applicable. The estimated economic life-cycle is determined by each MS; it refers to the remaining estimated economic life-cycle of a building as a whole or of a building elements, depending on the considered EP requirements. The cost-optimal level shall lie within the range of performance levels where the cost-benefit analysis calculated over the estimated economic life-cycle is positive.

The EPBD recast requires MSs to report on the comparison of the minimum EP requirements and those calculated on the basis of the cost optimal levels. The European Commission has to provide MSs with a comparative methodology framework (EPBD recast, article 5 and Annex III).

The present article provides a methodology for identifying the cost-optimal levels of the energy performance requirements for the Italian residential building stock. The proposed comparative methodology framework is in accordance with the current legislation. The methodology is applied to a reference building selected within the European research project *IEE-TABULA*.

Nomenclature

A	area	[m^2]
C	cost	[€]
COP	coefficient of performance	[-]
EER	energy efficiency ratio	[-]
g	total solar energy transmittance	[-]
P	power	[W]
R	rate	[-]
t	time	[h]
U	thermal transmittance	[$Wm^{-2}K^{-1}$]
V	volume	[m^3]
Val	value	[€]
η	efficiency	[-]
τ	solar transmittance	[-]

Subscripts

a	annual	H	heating
C	cooling	I	initial
coll	solar collector	lw	lower
d	distribution (subsystem)	min	minimum
disc	discount (rate)	n	normal, net
e	emission (subsystem)	opt	optimum
env	envelope	P	primary
f	floor	sh	solar shading
F	final	tot	total
fl	slab	up	upper
g	global, gross	W	hot water
gl	glass	w	window
gn	generation (subsystem)	wl	wall

2. Comparative methodological framework

On March 21st, 2012 the Commission Delegated Regulation (EU) No. 244/2012 [2] supplementing the Directive 2010/31/EU was published, establishing a comparative methodology framework for calculating cost-optimal levels of minimum requirements for the energy performance of buildings and building elements. On April 19th, 2012 followed the publication of the Guidelines that accompany the Regulation [3]. The Guidelines include information to help MSs to apply the comparative methodology at the national level and enable them to:

- define reference buildings (both residential and tertiary sectors, both existing and new), representative of the building stock in terms of function and climatic conditions,
- define the energy efficiency measures (EEMs) to be assessed for the reference buildings, extended to the whole building or to building elements,
- evaluate the final and primary energy need for the reference buildings before and after the realization of EEMs,
- calculate the costs of EEMs applied to the reference buildings in the expected economic life-cycle.

Using this common methodology, the MSs identify the optimal cost levels for the minimum EP requirements for new or existing buildings, or parts of it, and compare the results of these calculations with the minimum EP requirements in force. If the result of the comparative analysis carried out shows that the minimum EP requirements in force are much less efficient than those arising from the analysis of the cost optimal levels (deviation greater than 15%), the MS must give reasons for this difference or develop a plan outlining the appropriate measures to be introduced in order to reduce significantly the energy gap [4].

The evaluation of the input data (e.g. climatic conditions, investment costs, etc.) and the calculations are carried out at national level by each MS. Market data of real buildings and of parts of them, in combination with existing databases of costs, should be the basis for calculation of the global cost [5].

3. Energy performance and global cost

3.1. Energy performance assessment

The aim of the calculation procedure is to determine the total annual primary energy demand to fulfill the user's needs, including heating, cooling, ventilation, domestic hot water and lighting. To calculate the EP, MSs are recommended to use the CEN standards.

EN 15603:2008 [6] provides a general procedure for evaluating the primary energy demand by aggregating the energy demands per final use and energy carrier (electricity, fuel), also considering energy generated on-site from renewable sources. According to EN 15603:2008, each calculation term is specified in a precise standard, such as:

- EN ISO 13790:2008 [7] on the thermal energy calculation for space heating and cooling,
- the EN 15316 [8] group of standards on the energy performance of heating and DHW systems, including cogeneration, district heating and renewable energy systems,
- EN 15243:2007 [9] on the energy performance of air conditioning systems,
- EN 15193:2007 [10] to calculate the energy demand for lighting.

The proposed methodology also refers to the Italian technical specifications UNI/TS 11300 (four parts) [11], which specify national application procedure of the above listed European technical standards.

3.2. Global cost evaluation

The Commission Delegated Regulation [2] requires the evaluation of the cost-optimal level both at a macro-economic and at a financial level. Concerning the macroeconomic level, the global cost is defined by considering the costs corresponding to the CO_2 emissions too, as the monetary value of the environmental damages caused by the emissions related to the building energy consumption. Concerning the financial level calculation, the methodology is based on the overall costs, considering the initial investment, the sum of the annual costs for each year (energy, maintenance, operation and any additional costs), the extraordinary replacement of systems and components, the final value, and the costs of disposal, as appropriate. All costs are actualized to the starting year.

The financing framework methodology is based on the net present value (global costs) calculation, carried out according to Standard EN 15459:2007 [12], which provides a method for considering the economic aspects related to the application of heating systems and other technical systems that affect the energy consumption of the building. According to this Standard, the calculation of the global cost $C_g(t)$ referred to the starting year t_0 may be performed by a component or system approach, by considering the initial investment C_I, and for every component or system j, the annual costs C_a and the discount rate $R_{disc(i)}$ for every year i (referred to the starting year), the final value Val_F. The global cost is directly linked to the duration of the calculation period t, as shown in Eq.(1).

$$C_g(t) = C_I + \sum_j \left[\sum_{i=1}^{t} \left(C_{a,i}(j) \cdot R_{disc}(i) \right) - Val_{F,t}(j) \right] \tag{1}$$

4. Definition of reference buildings

According to the comparative methodology framework, the calculation of cost-optimal levels should be performed on "reference buildings". In order to obtain results as general as possible, the "reference buildings". should be typical buildings able to represent the building stock.

The Commission Guidelines [3] recommend to establish reference buildings in one of the two following ways:

- Selection of a real example representing the most typical building in a specific category (type of use with reference occupancy pattern, geometrical features, thermo-physical characteristics of the building envelope, technical services systems, etc.).
- Creation of a "virtual building" including, for each relevant parameter, the most common materials and systems.

The choice between these two options should depend on expert enquiries, statistical data availability, etc. As an example of methodology for identifying reference buildings, the Guidelines mention some projects carried out under the *Intelligent Energy Europe* programme, like *TABULA*.

TABULA (*Typology Approach for Building stock Energy Assessment*) was a three-year project (June 2009-May 2012) involving thirteen European countries, among which Italy [13]. The objective of the project was to create a harmonised structure for "European Building Typologies" in order to estimate the energy demand of residential building stocks at national level and, consequently, to predict the potential impact of energy efficiency measures and to select effective strategies for upgrading existing buildings.

Each participating country developed a "National Building Typology", which is a set of model residential buildings ("building types"), each representing a building age class (i.e. a construction period) and a building size class (e.g. single-family house, multi-family building, apartment block, etc.). Each building type is characterised by specific energy related properties, which reflect typical technical systems, construction features and geometric characteristic of the represented construction period.

The Italian "National Building Typology" was developed for the climatic zone with a number heating degree days between 2100 and 3000, which include more than 50% of the national municipalities. The Italian building types were defined in the geometrical features (e.g. conditioned volume, conditioned floor area, compactness factor, etc.) both as real example buildings (multi-family buildings and apartment blocks) and as virtual or "archetypes" buildings (single-family houses and terraced houses). Typical construction elements and technical systems were associated to each building type according to the experience and to the technical literature [14].

5. Proposal of a optimization procedure

A new energy cost optimization procedure based on a sequential search-optimization technique was developed and applied to each reference building, to calculate of the cost-optimal energy performance. The procedure refers to the model developed in US [15], The method considers, for each energy efficiency measure, a discrete number of options (e.g. different levels of thermal insulation), described by relevant parameters (e.g. thermal transmittance). Different packages of energy efficiency measures are applied and compared: each package is a set of energy efficiency options, one for each measure.

A reference package of energy efficiency options is assumed as the starting point of the optimization calculation; the cost associated with each package of energy efficiency options is defined by comparison with the reference set.

Subsequently, the procedure allows to identify a sequence of configurations (packages of energy efficiency measures) that constitute the "partial optimums". To switch from a partial optimum to the next one, all the parameters that characterize the levels of each energy efficiency measure are modified one at a time. Among all the tested configurations, the next partial optimum is that which allows the highest reduction in terms of global cost.

The flow-chart of the calculation path and of the optimization procedure are shown in Figs. 1 and 2, respectively.

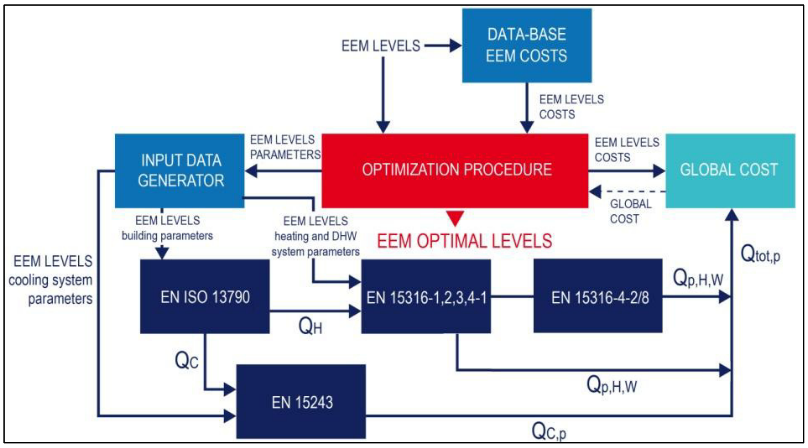

Fig.1. Flow chart of the calculation path.

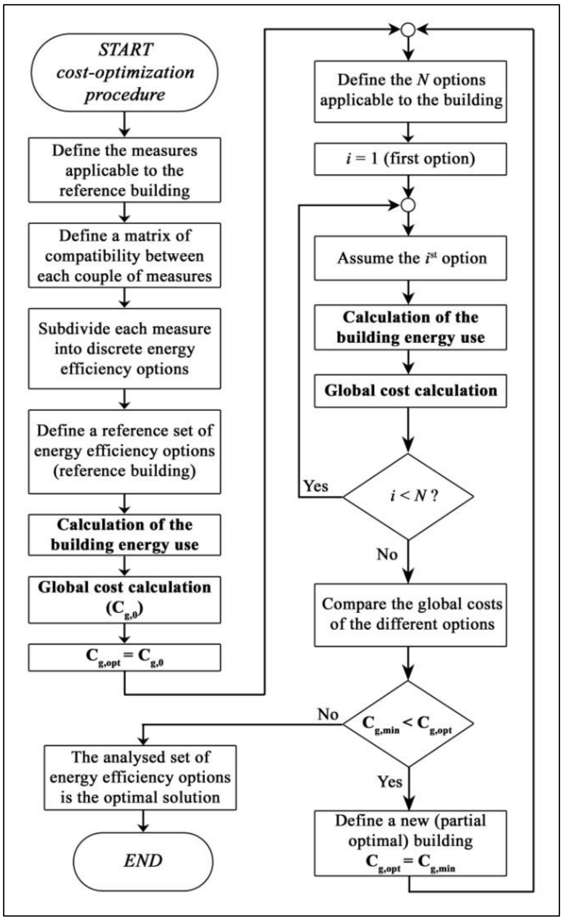

Fig. 2. Flow chart of the cost optimization procedure.

6. Application to a case study

6.1. Description of the case study

The cost-optimal comparative methodology has been applied to a building included in the Italian “National Building Typology” of *TABULA*. The selected reference building is an apartment block built in the period from 1946 to 1960. The picture and the main data of the building type are shown in Table 1.

Table 1. Main data of the case study.

Picture	Geometrical data			Building construction data			System data (mean seasonal values)		
	V_g	[m^3]	5949	U_{wl}	[Wm^{-2}K^{-1}]	1.15	Radiators	$\eta_{H,e}$	0.925
	$A_{f,n}$	[m^2]	1552	U_w	[Wm^{-2}K^{-1}]	4.90	Central distribution (vertical pipes)	$\eta_{H,d}$	0.901
	A_{env}/V_g	[m^{-1}]	0.46	$g_{gl,n}$	[-]	0.85	Non-condensing boiler	$\eta_{H,gn}$	0.85
	A_w	[m^2]	217	$U_{fl,up}$	[Wm^{-2}K^{-1}]	1.65	Electric water heater	$\eta_{W,gn}$	0.75
	no. units		24	$U_{fl,lw}$	[Wm^{-2}K^{-1}]	1.30			

6.2. Energy efficiency measures

The energy efficiency measures (EEMs) applied to the reference building are listed in Table 2 for the building envelope, in Table 3 for the technologies using renewable energy sources and in Table 4 for the technical systems.

An appropriate parameter has been associated to each measure; e.g. the *U*-value for the thermal insulation of the building envelope; the heat generator efficiency (either η or *COP* or *EER*) for the technical systems replacement; the collectors area (A_{coll}) for the thermal solar system installation; the peak power (*P*) for the PV systems.

For each measure, up to five energy efficiency options or levels (EEOs) have been defined. The first level usually represents an inefficient solution used as a test value; the second level represents the requirement fixed by in force legislation [16]; the levels from three to five (if applicable) are more efficient solutions.

Table 2. Energy efficiency measures (EEMs) and related options (EEOs) referred to the building envelope of the case study.

EEM			EEO				
			1	2	3	4	5
Wall insulation (on external surface)	U_{wl}	[Wm^{-2}K^{-1}]	0.45	0.34	0.29	0.25	0.20
	cost	[€]	41 719	49 484	55 001	61 003	71 883
or Wall insulation (on cavity)	U_{wl}	[Wm^{-2}K^{-1}]	0.45	0.34	-	-	-
	cost	[€]	34 338	41 326	-	-	-
Upper floor insulation	$U_{fl,up}$	[Wm^{-2}K^{-1}]	0.40	0.30	0.27	0.23	0.20
	cost	[€]	8 489	11 427	12 732	15 003	17 303
Lower floor insulation	$U_{fl,lw}$	[Wm^{-2}K^{-1}]	0.45	0.33	0.29	0.24	0.20
	cost	[€]	15 386	18 585	20 240	23 084	26 383
Windows	U_w	[Wm^{-2}K^{-1}]	5.00	2.20	1.90	1.60	1.30
	cost	[€]	51 320	68 984	72 803	86 887	90 945
Associated technology			single glass	double glass	double low-e glass	triple low-e glass	triple low-e glass
Solar shading devices	τ_{sh}	[-]	0.20	0.20	-	-	-
	cost	[€]	9 548	25 063	-	-	-
Associated technology			fixed louvres	mobile louvres	-	-	-

Table 3. Energy efficiency measures (EEMs) and related options (EEOs) referred to the technologies using renewable energy sources.

EEM		EEO 1	2	3	4	5
Thermal solar system	A_{coll} [m^2]	29	48	67	-	-
	cost [€]	51 840	86 400	121 000	-	-
Photovoltaic system	P [kW$_p$]	3	6	8	11	-
	cost [€]	12 000	27 000	39 000	51 000	-

Table 4. Energy efficiency measures (EEMs) and related options (EEOs) referred to the thermal systems of the case study.

EEM		EEO 1	2	3	4	5
Heat generator for space heating	$\eta_{H,gn}$ [-]	0.88	0.98	1.00		
	COP [-]				3.70	4.13
	cost [€]	83 150	85 450	126 200	153 800	158 400
Associated technology		standard boiler	standard boiler	condensing boiler	heat pump	heat pump
		radiators	radiators	fancoils	fancoils	fancoils
		central control	zone control	room control	room control	room control
Heat generator for domestic hot water	$\eta_{W,gn}$ [-]	0.88	0.98	1.00	-	-
	cost [€]	19 200	24 000	38 400	-	-
Associated technology		standard boiler	standard boiler	condensing boiler	-	-
Chiller	EER [-]	3.20	3.86	4.20	-	-
	cost [€]	100 800	113 400	126 000	-	-
Associated technology		air-to-air chiller	air-to-air chiller	air-to-air chiller	-	-
or						
Combined heat generator for space heating and domestic hot water	$\eta_{H,W,gn}$ [-]	0.88	0.98	1.00	-	-
	cost [€]	99 480	105 000	147 360	-	-
Associated technology		standard boiler	standard boiler	condensing boiler	-	-
		radiators	radiators	fancoils	-	-
		central control	zone control	room control	-	-
Chiller	EER [-]	3.20	3.86	4.20	-	-
	cost [€]	100 800	113 400	126 000	-	-
Associated technology		air-to-air chiller	air-to-air chiller	air-to-air chiller	-	-
or						
Combined generator for heating, cooling and domestic hot water	COP [-]	2.50	2.90	3.30	-	-
	EER [-]	2.40	2.80	3.20	-	-
	cost [€]	149 200	153 800	158 400	-	-
Associated technology		heat pump	heat pump	heat pump	-	-
		fancoils	fancoils	fancoils	-	-
		room control	room control	room control	-	-

Not all the energy efficiency measures are applicable together, because some of them are inconsistent with the others (e.g. separate heat generators for space heating and DHW and combined heat generators, see Table 4).

The initial investment cost value associated to each EEO is shown too. This value takes into account all costs incurred up to the point when the building or the building element is delivered to the customer, ready to use. These costs include design, purchase of building elements, connection to suppliers, installation and commissioning processes. The costs were got both by extensive market surveys and by analysing official databases [17].

6.3. Calculation options and boundary conditions

The energy performance of the case study considering the different energy efficiency measures was calculated according to the Italian technical specification UNI/TS 11300 [11]. The global cost analysis was performed applying the EN 15459. According to the calculation model, the following assumptions and simplifications were applied:

- climatic data of Milan (from the national technical standard UNI 10349 [18]),
- ventilation rate fixed at 0.3 h^{-1},
- simplified approach to calculation internal heat gains, building internal heat capacity, temperature of unconditioned spaces, and thermal bridge effects (percentage increase of the transmission heat transfer),
- value of shading reduction factor for external obstacles fixed at 0.8,
- simplified calculation of the mean monthly values of the technical subsystem efficiencies,
- conversion coefficient to primary energy fixed at 2.17 for electricity, and at 1 for fossil fuels,
- real interest rate fixed at 4%, costs of electricity and natural gas derived from the National Authority for Electricity and Natural Gas (AEEG), 2.8% annual increase in gas price and 2% in electricity price,
- annual maintenance costs variable from 1% to 4% of the investment cost depending on the technology,
- technical lifespan of building elements fixed at 30 years, of systems variable from 15 to 35 years.

6.4. Results

Figure 3 shows the sets of partial optimum points related to different applications of the optimization procedure to the same case study, starting from different sets of EEOs. Two different optimization paths, resulting from the application of the worst and best combination of EEOs in terms of EP level as starting point, are highlighted in Fig. 3 with their related partial optimum points. Regardless the chosen starting point, the procedure leads to the same optimum level, which corresponds to the minimum global cost, as reported in Table 5.

In Fig. 3, the optimal range of the ratio between global cost and energy performance is also shown, in qualitative terms, according to the Guidelines of the European Commission [3].

Figure 4 shows the initial investment cost, the energy cost and the operational cost, for each partial optimum point of an optimization path of Fig. 3. The optimal level gets an annual primary energy use for heating, cooling and domestic hot water of 115 kWh·m^{-2} corresponding to an actualized global cost of 676 €·m^{-2}.

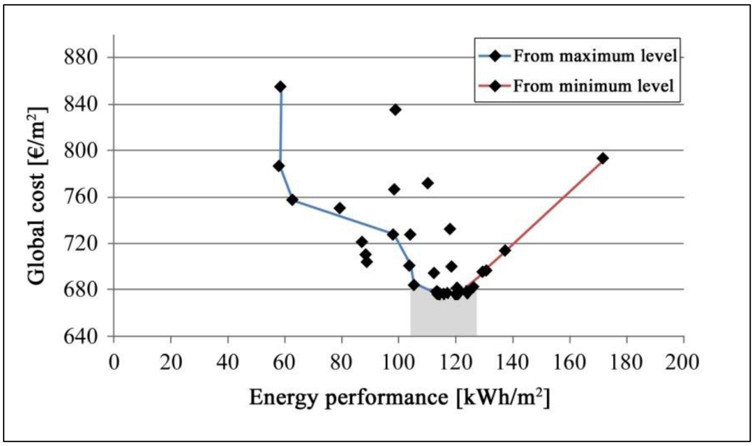

Fig. 3. Optimization paths and cost optimal range.

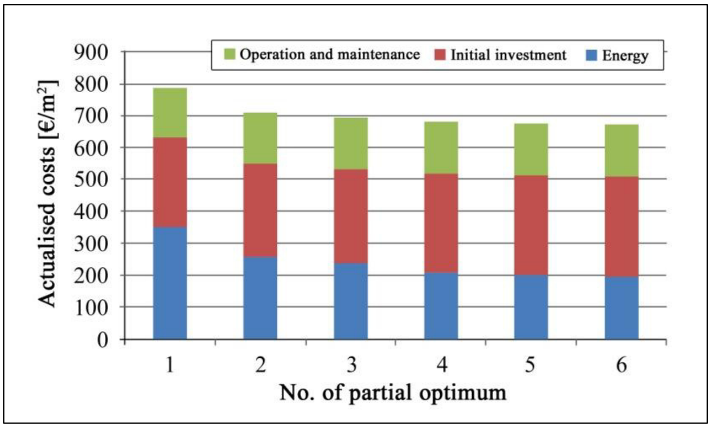

Fig. 4. Actualised costs in an optimization path.

Table 5. Optimal values of the design parameters.

Energy Efficiency Measure (EEM)	Symbol	Value	No. of EEO
Wall insulation (on cavity)	U_{wl} [Wm^{-2}K^{-1}]	0.34	2
Upper floor thermal insulation	$U_{fl,up}$ [Wm^{-2}K^{-1}]	0.20	5
Lower floor thermal insulation	$U_{fl,lw}$ [Wm^{-2}K^{-1}]	0.29	3
Windows	U_{w} [Wm^{-2}K^{-1}]	1.90	3
Solar shading device (fixed louvres)	τ_{sh} [-]	0.20	1
Chiller	EER [-]	3.20	1
Heat generator for space heating	$\eta_{H,gn}$ [-]	0.98	2
Heat generator for domestic hot water	$\eta_{W,gn}$ [-]	0.88	1
Thermal solar system	A_{coll} [m^2]	29	1
Photovoltaic system	P [kW$_p$]	3	1

7. Conclusions

In accordance with the EPBD recast dispositions, the article presents a new procedure for the optimization of the global cost optimal levels corresponding to the minimum levels of energy performance requirements. The procedure is based on a sequential search technique that considers a number of discrete options.

The results demonstrate the effectiveness of the proposed methodology, which allows to simultaneously take into account different technological solutions with a high number of energy efficiency options. For this reason, the proposed procedure is being adopted for the EPBD recast implementation at national level.

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