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Original
Assessment of cost optimal solutions for high performance multi-family buildings in Iran / Alvand, Mohammadhossein; Gholami, Zahra; Ferrara, Maria; Fabrizio, Enrico. - In: ENERGY PROCEDIA. - ISSN 1876-6102. - STAMPA. - 111:(2017), pp. 318-327. [10.1016/j.egypro.2017.03.102]

Publisher:
Elsevier Ltd

Published
DOI:10.1016/j.egypro.2017.03.102

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 111 (2017) 318 – 327

Energy Procedia

8th International Conference on Sustainability in Energy and Buildings, SEB-16, 11-13 September 2016, Turin, ITALY

Assessment of cost optimal solutions for high performance multi-family buildings in Iran

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Abstract

According to the international benchmarks proposed for the energy demand reduction, the Iranian government, for limiting domestic energy demand growth, has set some energy efficiency policies. In this regard, the present study proposes various solutions to investigate the feasibility of improving the performance of an existing typical multi-family building in Iranian context, to achieve a high performance one with proper cost-optimal levels of energy performance by using the global cost approach defined by EU legislation. Precisely 50 different packages of energy efficiency measures were analyzed in terms of economic and energy performance with consideration on the effects of different envelope thermal insulation, shading system, window types and highly efficient systems in addition to the solar renewable energy source. Then the impact of the selected measures on energy efficiency improvement and global cost were studied and revealed that obtaining high performance building simultaneously with the cost optimal levels can be fulfilled, just when the financial support from the government subsidies exist, otherwise there is still a long way from being economically feasible.

Peer-review under responsibility of KES International.

Keywords: high performance; buildings simulation; energy efficiency measures; cost optimal level; energy performance; multi-family building; Iran

1. Introduction

With regard to the international efforts to reduce the growing energy consumption, it is highly remarkable that the building sector has an important role due to its responsibility for more than 40 % of global energy used, and approximately one third of global greenhouse gas emissions, both in developed and developing countries [1].

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Peer-review under responsibility of KES International.
doi:10.1016/j.egypro.2017.03.102

In this context, it is noticeable that Iran was the world's ninth largest emitter of greenhouse gas (GHG) in 2012 [2], the average energy consumption in Iranian residential sector is 2.5 times higher than the European average [3], and the energy consumption in Iran is growing rapidly with an average annual rate of about 8% [4]. Since Iran is one of the biggest owners of oil and gas reserves, energy was not an issue of concern before the international agreement on climate change. However, after the adoption of the Kyoto Protocol on August 2005 by Iran, extensive theoretical and practical research has been carried out for guidelines and standards in this area. These includes efforts to curtail wasteful energy use and to limit domestic demand growth, by implementation of the energy efficiency policies and the energy value increment through the energy subsidy reform, through raising the prices of domestic petroleum, natural gas, and electricity. Khalili Araghi et al. [5] examined the effects of reducing energy subsides in Iran which reveals that a higher energy prices will decrease energy consumption by Iranian households. The first phase of the reform was adopted in 2010, and the second phase was conducted in 2014 [6], with the purpose of reducing the energy consumption in the Iranian construction sector by at least 30% [7]. Tahsildoost et al. [8] studied energy retrofit techniques in Iranian educational building, using two methods based on The International Performance Measurement and Verification Protocol (IPMVP) and ASHRAE Guideline 14. Bagheri et al. [9] started developing an energy performance label for office buildings in Iran, by defining the characteristics of Reference Buildings as the energy efficient buildings, and designing and authorizing the label appearance for implementation as a national standard, using and validating an indigenous software tool (Behsazan) for simulating energy consumption in buildings of Iran. Heravi et al. [10] examined the energy performance of buildings by evaluation of design and construction measures concerning building energy efficiency in Iran.

Sustainability in general, and energy efficiency in particular are key measures for improving building performance [11], therefore a large number of scientific works were conducted in order to determine strategies for energy efficient building by employing various methods considering the construction style and local climate. Since these are new topics for the Iranian context, existing guidelines for other countries, like the recast of the European Energy Performance of Building Directive (EPBD) [13], may be used as a basis for the development of this branch of science and technology in Iran. In particular, the EPBD introduced the concept of cost-optimal level, which is defined in European legislation as "the energy performance level which leads to the lowest cost during the estimated economic lifecycle" and established a comparative methodology framework for its calculation, based on the global cost method.

Many studies performed in other countries demonstrated the effectiveness of the cost optimal methodology in studying cost-effective energy efficiency measures able to reach the nearly Zero Energy objective. Ferrara et al. [14] used a simulation-based optimization method to study cost optimal solutions for a real low-consumption house in France, with a view of obtaining nearly zero energy buildings. Becchio et al. [15] assessed cost optimal levels of a single-family house by presenting guidelines for designing reference building envelope and technical systems solution for nZEB. Ganiç et al. [16] investigated the possibilities of adapting of the cost optimal methodology to the Turkish context and tested the validity of the process under different market conditions. At the Iranian level, some studies were developed on the design of typical zero-energy homes [17], on traditional passive techniques [18] and on the simulation-based optimization of buildings based on genetic algorithms [19].

1.1. Scope and objectives

The present study aims to investigate energy performance and cost optimal solutions for a multi-family building in Iranian context by following the European cost-optimal approach, and at the same time taking into account Iranian legislation [20]. This is done by following different steps, each representing one sub-objective. These are [21]:

- Definition of energy efficiency measures (EEMs) that can be applied to a reference case study building concerning the building envelope, the energy systems and the exploitation of renewable energy sources.
- Assessment of the energy performance of several packages of EEMs and evaluation of the impact of these measures on the energy performance of the reference building;
- Calculation of the global cost of each package of EEMs and definition of the cost optimal level.

Furthermore, the study aims to test the applicability of a European methodology to a context that differs from Europe from both technical and economic points of view.

2. Methodology

2.1. The case study

The selected case study, which from now on will be called Real-Case (RC), is a new construction located in Shiraz, in the in southwest of Iran (latitude 29° 37′ 0″ N, longitude 52° 32′ 0″ E and altitude: 1484 m - 4869 ft.).

Each Iranian city, according to specific service needs and population, is divided into defined urban areas. The height and types of buildings in any of these areas are determined into a urban master plan [22]. The RC is located in district 6 of Shiraz city, in which area more than half of the buildings are high-rise buildings, or in other words, the number of their floors are more than seven.

In details, the RC is an eleven-story multi-family building composed by 220 residential units. The total gross floor area is 5292.11 m², the net conditioned area is 4166.85 m² and the building height is 36.3 m.

The basement and the ground floor are unconditioned, with the exception of a suit of 92.86 m² of net conditioned area 3.30 m height at the ground floor.

All the other floors have the same plan with 459 m² of gross area and 3.30 m height, divided in four residential units (net conditioned areas: A1=107.42 m², A2= 92.86 m², A3= 99.63 m², A4=104.36 m²).

The building orientation is WN-ES, its S/V ratio is equal to 0.25 m^{-1} and the rate of transparent surfaces to the opaque envelope is 19 %. Architectural plans and an isometric view are presented in Fig. 1.

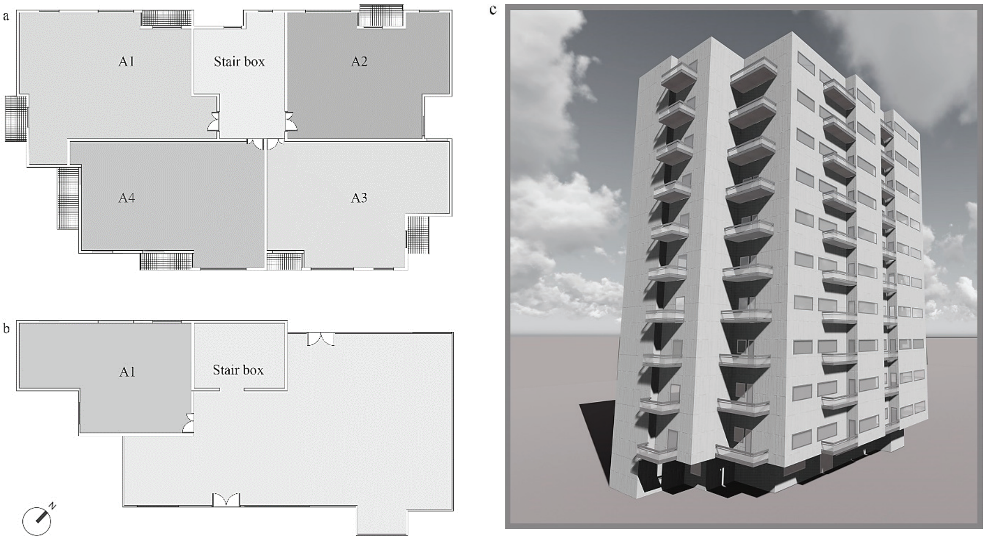


Fig. 1. Architectural plans of RC with defined thermal zones and an isometric view. (a) Typical floor; (b) ground floor; (c) isometric view.

Walls are made of low-insulated concrete blocks while the roof and floor have concrete structure without insulation. Windows are double-glazed with aluminum frame.

Space heating is provided by an hydronic heating system with radiator. Heating energy is supplied by a gas boiler (BIS 0). Space cooling is provided by a multi-split system equipped with DX coils in each room. Radiators and indoor DX unit are the terminals for heating and cooling, respectively.

2.2. Energy efficiency measures

In order to study the feasibility of improving the building performance, a collection of 50 EEMs related to the building envelope and the energy system were selected and their impact on the reduction of energy demand for heating, cooling, domestic hot water, lighting and equipment was investigated.

The EEMs for building envelope consist of five different levels of thermal insulation (EI 1, EI 2, EI 3, EI 4 and EI 5 in Table 1). A parametric simulation study was performed covering a range between 4 and 40 cm of insulation thickness and it was shown that variations in energy performance with respect to the RC are tangible in the range of 4 - 18 cm, while in the range between 20 and 40 cm the improvement in energy performance is minimal. Therefore, it was decided to survey the insulation with thickness of 6, 10, 14, 18, and 30 cm (it is noteworthy that the 6 cm insulation corresponds to the Iran national legislation, code 19).

Two EEMs were set for window types, as described in Table 2, and two shading system option (SO1 is a between glass blind and SO2 is an external blind).

Two different EEMs for building energy systems were considered as EEMs. As shown in Table 3, BIS 1 includes a gas condensing boiler with water radiator terminal for heating system, and a split cooling system with indoor DX unit with higher performance than that of BIS 0. BIS 2 includes an air-to-air heat pump (VRF) as heating and cooling system, with indoor DX unit as terminals. In both BIS 1 and BIS 2, the domestic hot water is provided by solar water heater with auxiliary gas condensing boiler.

Three EEMs based on solar renewable energy were selected (Table 4). The first is the installation of solar panels, which covers about 60% of required DHW, while the others refer to two different configurations of PV system. The measure named PV 12.7 kW_p consists in the maximum number of PV panels that can be placed on the building roof (49 panels with a total area of 82 m^2) and PV 52.4 kW_p includes PV covering all the roof and also the building façade corresponding to the three highest floors (202 panels with a total area of 338.3 m^2).

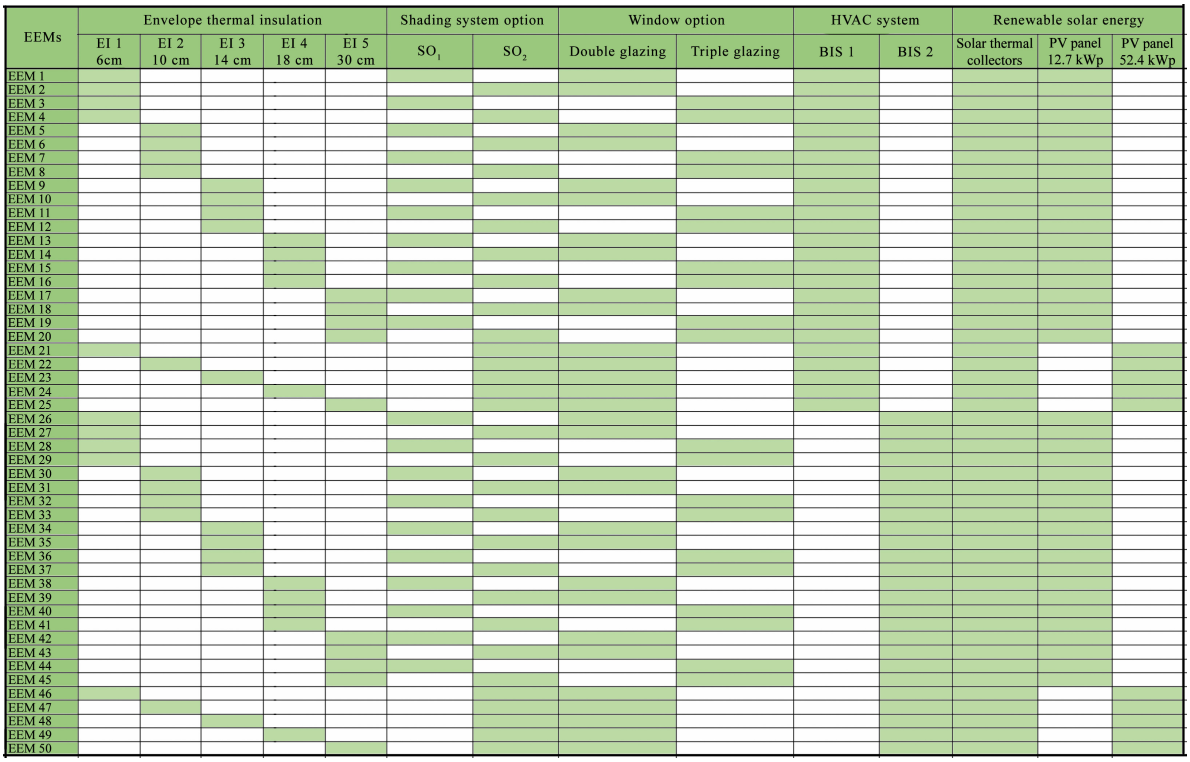
Fig.2 shows how the 50 package of EEMs were formed by combining the described single measures. Colored box show the components of each EEM package.

Table 1. Thermal features of the RC and the building envelope energy efficiency measures, (EI).

Envelope thermal insulation (EI)	EI 1	EI 2	EI 3	EI 4	EI 5
Insulation thickness (cm)	6	10	14	18	30
	U-value (W/m²K)	U-value (W/m²K)	U-value (W/m²K)	U-value (W/m²K)	U-value (W/m²K)
External wall	0.272	0.207	0.168	0.142	0.096
Floor	0.461	0.307	0.231	0.185	0.116
Roof	0.466	0.310	0.232	0.186	0.116

Table 2. Window types

Type	Description	U-value (W/m²K)
1	4_15_4 , Double glazing, Low emissivity - argon - low emissivity	1.431
2	4_15_4_15_4, Triple glazing, Low emissivity - argon -simple glaze - argon - Low emissivity	0.945



EEMs	Envelope thermal insulation					Shading system option		Window option		HVAC system		Renewable solar energy		
	EI 1 6cm	EI 2 10 cm	EI 3 14 cm	EI 4 18 cm	EI 5 30 cm	SO_1	SO_2	Double glazing	Triple glazing	BIS 1	BIS 2	Solar thermal collectors	PV panel 12.7 kWp	PV panel 52.4 kWp
EEM 1	🟩					🟩		🟩		🟩		🟩	🟩	
EEM 2	🟩						🟩	🟩		🟩		🟩	🟩	
EEM 3	🟩					🟩			🟩	🟩		🟩	🟩	
EEM 4	🟩						🟩		🟩	🟩		🟩	🟩	
EEM 5		🟩				🟩		🟩		🟩		🟩	🟩	
EEM 6		🟩					🟩	🟩		🟩		🟩	🟩	
EEM 7		🟩				🟩			🟩	🟩		🟩	🟩	
EEM 8		🟩					🟩		🟩	🟩		🟩	🟩	
EEM 9			🟩			🟩		🟩		🟩		🟩	🟩	
EEM 10			🟩				🟩	🟩		🟩		🟩	🟩	
EEM 11			🟩			🟩			🟩	🟩		🟩	🟩	
EEM 12			🟩				🟩		🟩	🟩		🟩	🟩	
EEM 13				🟩		🟩		🟩		🟩		🟩	🟩	
EEM 14				🟩			🟩	🟩		🟩		🟩	🟩	
EEM 15				🟩		🟩			🟩	🟩		🟩	🟩	
EEM 16				🟩			🟩		🟩	🟩		🟩	🟩	
EEM 17					🟩	🟩		🟩		🟩		🟩	🟩	
EEM 18					🟩		🟩	🟩		🟩		🟩	🟩	
EEM 19					🟩	🟩			🟩	🟩		🟩	🟩	
EEM 20					🟩		🟩		🟩	🟩		🟩	🟩	
EEM 21	🟩						🟩	🟩		🟩		🟩		🟩
EEM 22		🟩					🟩	🟩		🟩		🟩		🟩
EEM 23			🟩				🟩	🟩		🟩		🟩		🟩
EEM 24				🟩			🟩	🟩		🟩		🟩		🟩
EEM 25					🟩		🟩	🟩		🟩		🟩		🟩
EEM 26	🟩					🟩		🟩			🟩	🟩	🟩	
EEM 27	🟩						🟩	🟩			🟩	🟩	🟩	
EEM 28	🟩					🟩			🟩		🟩	🟩	🟩	
EEM 29	🟩						🟩		🟩		🟩	🟩	🟩	
EEM 30		🟩				🟩		🟩			🟩	🟩	🟩	
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EEM 46	🟩						🟩	🟩			🟩	🟩		🟩
EEM 47		🟩					🟩	🟩			🟩	🟩		🟩
EEM 48			🟩				🟩	🟩			🟩	🟩		🟩
EEM 49				🟩			🟩	🟩			🟩	🟩		🟩
EEM 50					🟩		🟩	🟩			🟩	🟩		🟩

Fig. 2. Packages of Energy Efficiency Measures configuration.

Table 3. Energy efficiency measures for building installation systems (BIS).

Title	BIS 0	BIS 1	BIS 2
Heating	- Gas boiler Terminal: water radiator	-Gas condensing boiler Terminal: water radiator	-Air to air heat pump (VRF) Terminal: Indoor DX unit
Cooling	-Split system Terminal: indoor DX unit	-Split system Terminal: indoor DX unit	-Air to air heat pump (VRF) Terminal: Indoor DX unit
Domestic hot water (DHW)	- Gas boiler	-Solar water heater with auxiliary gas condensing boiler	-Solar water heater with auxiliary gas condensing boiler
Ventilation	- Natural ventilation	-Natural ventilation	-Natural ventilation

Table 4. EEMs for energy production based on solar source.

Title	SC DHW 60%	PV 12.7 kW_p	PV 52.4 kW_p
Property	26 solar collectors (SC) covers about 60% of required DHW.	49 polycrystalline PV panels with 15.51 module efficiency.	202 polycrystalline PV panels with 15.51 module efficiency.

2.3. Energy evaluation

In order to calculate the precise amount of energy required for heating and cooling related to each package of EEM, energy evaluation was performed through the dynamic simulation software EnergyPlus (version 8.4) [23]. The modeling process was performed in two steps. First, the RC geometry was modeled with DesignBuilder simulation software (version 3.4.0.041), that provides advanced modelling tools in a user friendly environment [24].

Then, the model in .idf format was exported to EnergyPlus software in order to perform all the systems modeling and run the calculations. In EnergyPlus, the building thermal zone calculation method is a heat balance model, which means that the air inside the room is modeled with uniform temperature. Moreover, the temperature, the long and short wave irradiation for room surfaces are assumed as uniform, the surfaces have diffuse radiation and the heat conduction is one dimensional [23].

Each building floor was divided into 5 thermal zones, of which 4 are conditioned (each apartment, one zone) and one unconditioned (stair box).The ground floor has 3 thermal zones, one conditioned studio, an unconditioned hall and the stair box. The basement is an unconditioned thermal zone. In total, the building model consists of 54 thermal zones (41 of them are conditioned).

The weather file of Shiraz is taken from EnergyPlus weather data sources, and refers to ITMY (Iran Typical Meteorological Year) Data, based on periods of record from 30 to 43 years [25].

The following operational parameters, were set based on residential building typology. People were fixed to 0.04 pers/m², power densities were defined 5.2 W/m² for lighting and 4.5 W/m² for equipment [26]. Occupancy were set using standard schedules for a family of four people, during week days and weekend. The total ventilation and infiltration rate were set to 0.8 air changes per hour (ACH). Shading systems are active during the cooling season and when necessary according to the defined set points, which were set to 21 °C from 7 a.m. to 8 p.m. (and 19 °C during the remaining hours) for heating, and to 26 °C from 7 a.m. to 5 p.m. (and 28 °C during the remaining hours) for cooling.

Boilers were modeled by using the normalized boiler efficiency curve, which represents the changes in the boiler's nominal thermal efficiency due to changes in loading and operating temperature. The nominal thermal efficiency of the gas boiler for BIS0 was set to 0.8, while this value was set to 0.95 for the gas condensing boiler (BIS1). Performance curves [27] were used to define the air to air heat pump (VRF) operation for BIS2, which has a rated heating COP equal to 4.96 and rated cooling COP equal to 5.03. The split air-conditioner that was modeled as cooling system for BIS0 has a nominal EER equal to 2.80, while the one in BIS1 has a nominal EER equal to 3.98.

The domestic hot water demand was calculated through the method defined in Technical Account and Installation Handbook [28-29], and estimated as 2394.57 m^3/year. The DHW system for BES0 was modeled as a gas boiler with 290 kW power, while for BES 1-2 it was modeled as solar water heater with auxiliary gas condensing boiler with 232 kW power.

26 thermal collector were modeled integrated with water heater, supplying nearly 60% of required DHW. PV panels were modeled by using equivalent one-diode option and are connected to a simple ideal inverter having efficiency equal to 0.95. As described before, the type of PV panels is the same in both system configurations, but the number of panels differs from 49 to 202.

2.4. Economic evaluation

The global cost of each EEMs was calculated according to the method described in European Standard EN 15459:2007 [27]. Global cost calculation can be written by the following equation

$$C_G(\tau) = \mathrm{C_I} + \sum_{\mathrm{j}} \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j).R_d(i) \right) - V_{f,\tau}(j) \right] \tag{1}$$

where C_G (τ) represent global cost referred to starting year τ_0, C_I is the initial investment costs, $C_{a,i}$ (j) annual cost year i for component j (containing running costs and periodic or replacement costs), $R_d\ (i)$ is the discount rate for year i, $V_{f,\tau}$ (j) is the final value of component j at the end of the calculation period referred to the starting year τ_0.

In this study, the calculation period was set to 30 years. The inflation and market interest rates were set to 19.16% and 18.93%, respectively. These values are derived from the average values from last 10 years (2006 - 2015), retrieved from the central bank of Islamic republic of Iran. These gives a real interest rate of -0.19 % that can be explained by the actual economic situation of Iran.

The investment cost of EEMs were calculated on the basis of Iran market prices. Because of the absence of a detailed price list, Authors retrieved all the costs for each EEM from the Iranian current market in Rial unit, but, as in this study the economic evaluation is performing based on the European legislation, these values are converted into the Euro unit (1 Euro is equal to 34,016 Rial) [31].

Concerning replacement costs of the building envelope, 20 years were considered as lifespan for windows and 25 years for shading systems (25 year lifespan), while other components were considered with a lifespan equal to that of the building (50 years). The replacement cost of the building energy system were considered with regard to the component lifespan as defined in Annex A, EN 15459:2007, in which also yearly maintenance costs were determined as a percentage of the initial investment cost for building installation systems. Energy cost for space heating, DHW (natural gas and electricity), and for space cooling, interior lighting, interior equipment, fans, pumps (electricity) were considered. Iranian current prices were applied for calculations, as follows:

- Natural gas: 0.022 €/m³ [32]
- Electricity: 0.062 €/kWh [33]
- Feeding energy from PV into the grid [33]: 0.287 €/kWh if $P_{e,\,PV} \leq 20\ kW_p$
  0.256 €/kWh if $P_{e,\,PV} \leq 100\ kW_p$

3. Results

3.1. Primary energy consumption and PV on-site energy production

The total annual energy consumption was evaluated in terms of primary energy for heating, cooling, domestic hot water, lighting and equipment energy uses. These values were calculated based on Iranian primary energy factor (2.7 for electricity and 1.05 for natural gas).

Fig. 3 shows the total annual energy consumption for each package of EEMs. It has to be noted that the solar panels contribution for DHW is constant in all EEMs (10.04 kWh/m² year), due to the equal number of solar collectors available in each EEMs. No energy efficiency measures were considered for lighting and equipment, so the value related to them are constant in all EEMs.

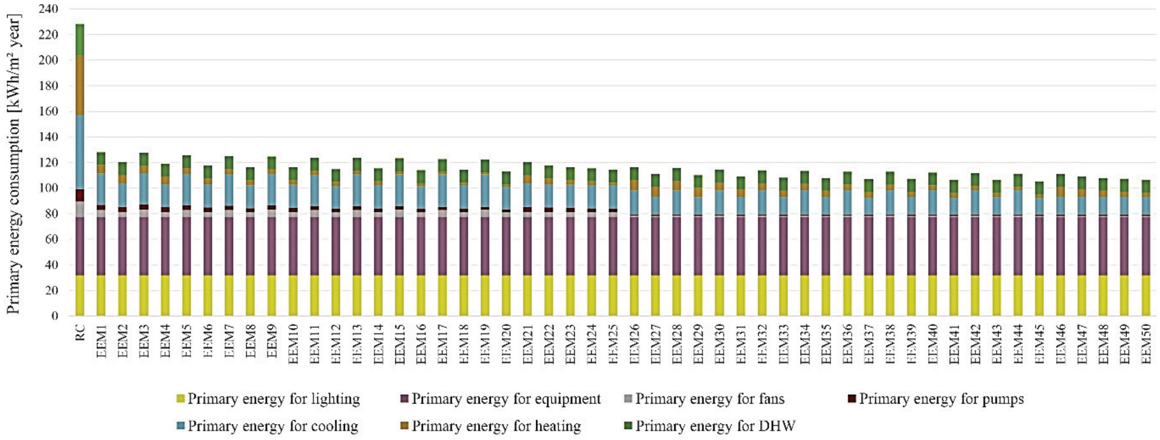

Fig. 3. Annual primary energy consumptions.

Evidently, significant reduction in annual primary energy were obtained in heating (from 46.5 kWh/m² of RC to 1.60 kWh/m² in EEM 45) and cooling demand (from 57.8 kWh/m² of RC to 13.6 kWh/m² in EEM 20), that reveals the important role of energy efficiency measures such as insulation and shading systems.

The package resulting in the lowest primary energy consumption (105 kWh/m²) is EEM45, which is composed by 30 cm of insulation thickness, external blinds for shading, triple glazing windows and the air-to-air heat pump for heating and cooling (BIS2). This package is able to reduce the primary energy demand of RC (228 kWh/m²) by 117%.

The amount of solar radiation on horizontal surface for Shiraz city is about 2219 kWh/m² year, while for surfaces at an angle of 28 degrees, that is the optimal tilt for PV panels in Shiraz city, it is equal to 2449 kWh/m² year and for 90 degrees, that is the tilt of the panels placed of the building façade, it is equal to 1368 kWh/m² year [34].
As mentioned earlier, two photovoltaic systems are available as EEMs, one with 12.7 kW_p of peak power and the other with 52.4 kW_p of peak power. The related energy productions are respectively 20877.80 kWh and 46771.12 kWh. Since appropriate incentive tariffs exist for feeding energy in to grid (e.g. 1 kWh electricity going to utility is equal to about 4 kWh electricity coming from utility), in this study is assumed to sale all PV production to the grid.

For example, PV 12.7 kW_p with 20877.80 kWh of production can supply 12% of the electricity demand of EEMs1, but if all the PV production is sold to the grid, 50% of the EEMs1 required energy can be provided by the obtained amount of money.

3.2. Cost optimal levels of energy consumption

The results of various energy efficiency measures in terms of primary energy consumption and global cost can be seen in Fig. 4. A vertical line, which represents the maximum energy consumption, indicates the position of the RC. Energy efficiency measures leads energy consumption to be reduced to between 100 to 123 kWh/m² year (primary energy) in absolute terms and by about 44 to 54% in terms of percentage. Global cost varies from 170.78 €/m² in EEM46 (consisting the minimum level of thermal insulation with double glazing window and external shading system, with 202 PV panel on building's roof and façade) to 234.43 €/m² in EEM19 (medium level of thermal insulation with triple glazing window and intermediate shading system, with 49 PV panel on building's roof).

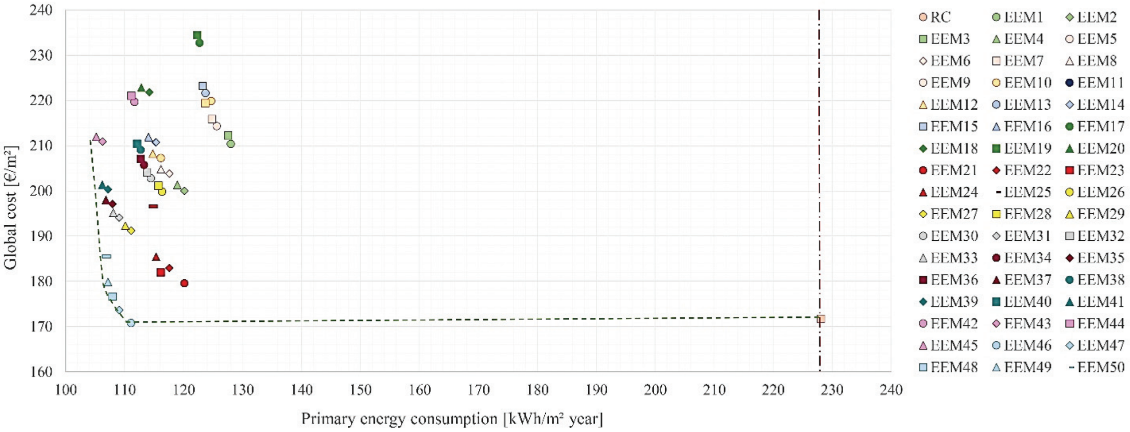

Fig. 4. Global cost versus primary net energy consumption of RC and of the other Energy Efficiency Measures.

The package of EEMs with minimum saving energy are EEM1 and EEM3 with about 128 and 127 kWh/m² year of net primary energy consumption with global cost values of 210.36 and 212.23 €/m². These measures consist in minimum thermal insulation with double glazing window and differ only in the shading system. Contrary, the maximum energy saving belongs to EEM 45, with 105 kWh/m² year primary energy consumption and with 211.96 €/m² global cost.

Fig. 5. Reports the impact of various system solutions on a larger scale regarding global cost and primary energy consumption. The weakest EEMs, in terms of primary energy consumption and global cost, are gathered in group A_1, while A_2 is in the second place. Actually the difference between them is on their shading systems, package A_2 consist exterior shading system so is more efficient and has a lower global cost, both A_1 and A_2 have the same building energy system (BIS1) as gas condensing boiler and split system, which represent the highest investment cost. Groups B_1 and B_2 are more efficient, while the difference between them is the same as previous ones and they both have air to air heat pump VRF (BIS 2) as an installation system, that has lower initial investment, replacement,

maintenance and energy cost. As can be seen groups C_2 and C_1 respectively have the lowest global cost, the difference among them and other groups is the number of PV installed.

The cost optimal level is reached with EEM13 and corresponds to around 171 €/m^2. The related cost optimal energy performance is 101.5 kWh/m^2. This can be achieved with a low level of thermal insulation EI1 (equal to the Iran national code 19, requirements), double glazing window, external shading system SO2, in combination with building installation system BIS2 (air to air heat pump, VRF with indoor unit direct expansion D.X), solar water heater with auxiliary gas condensing boiler and approximately 200 PV panels (338.3 m²).

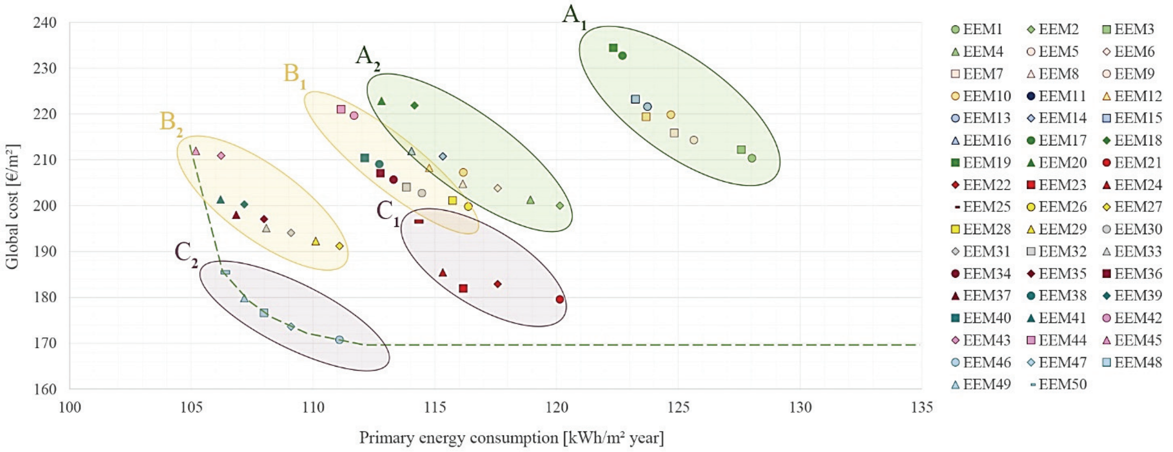

Fig. 5. Impact of various system solutions on a larger scale.

4. Discussion

The present study is one of the first studies of this type in Iranian context that simultaneously takes into consideration energy efficiency and cost optimality, using the comparative methodology framework defined for the European context.

Results reveal that high performance multi-family buildings in Iran-Shiraz and in all similar climatic conditions can be reached with advanced energy systems, an average level of thermal insulation, solar thermal collectors and with a large number of PV panels (on-site energy production from renewable source is the most effective measure), although the cost optimal level directly depends on suitable financial subsidies and government policies on renewable electricity price.

Further work should be done to optimize the methodology and adapt to the Iranian market. Similar studies can be developed for other building types and may lead to defined proper guidelines and standards for energy efficiency in the Iranian construction sector.

5. Conclusions

Cost optimal levels for a multi-family building in Iran, Shiraz city with semi-arid cold climate (Köppen climate classification BSk), were investigated by studying various energy efficiency measures. The path based on comparative methodology framework provided by the EU commission, was followed in order to define solutions that are technically and economically feasible. Special attention was paid to both building envelope and energy systems to reduce the RC required energy. The resulted cost optimal level is also related to significant improvements to the energy performance of the case study building.

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