

# Multi-Objective Optimization of Design nZEBs in Uzbekistan

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**Abstract:** The growth in energy demand from the residential sector in Uzbekistan points to the urgency to adopt nearly zero-energy building (nZEB) strategies that can be tailored to domestic climate and economic conditions. The present building stock, represented by weak thermal performance, results in excessive energy consumption for heating and cooling and excessive CO<sub>2</sub> emissions. To address this, the study examines multi-objective optimization methods for residential building retrofitting via integration of advanced insulation systems and renewable energy technology. The calculation uses heating and cooling degree days (HDD/CDD), which is in compliance with national standards ShNK 2.08.01-24 (Thermal Protection of Buildings) and KMK 2.01.04-18 (Building Climatology), to determine energy loads, taking techno-economic factors into consideration in terms of cost-effectiveness. Simulations were conducted for a typical three-room house, varying insulation thickness (0–50 mm), solar collectors, and photovoltaic panels. Results show that particular annual energy requirements decreased from 53.9 to 34.6 kWh/(m<sup>2</sup>·yr), and CO<sub>2</sub> emission decreased from 45.44 to 18.84 kg/(m<sup>2</sup>·yr) with improved insulation. Additionally, payback periods decreased from 8.94 to 8.45 years, confirming economic feasibility. The findings suggest that enhanced retrofitting coupled with solar technologies can greatly reduce operational energy usage and environmental impact, offering a sustainable solution for residential development in Uzbekistan.

## 1 INTRODUCTION

The demand for energy-efficient buildings in Uzbekistan is both environmentally and sustainably required by the climatic variation requirements of a country. An energy understanding of heating and cooling requirements is paramount to building design to the near-optimal energy use levels in Uzbekistan. Heating and cooling degree days throughout the present study are a tool to be analyzed for climatic conditions throughout the region, building insulation, and density to focus on energy efficiency in dwelling buildings. National and international standards, ShNK 2.08.01-24 and KMK 2.01.04-18, are calibrated within the study to offer accurate estimates of energy needs and information regarding energy efficiency and thermal performance that dwelling buildings in Uzbekistan can be designed to offer.

## 2 MATERIALS AND METHODS

### 2.1 Data Description

To compare how external temperature variability influences the cooling and heating energy requirements of buildings, this study employed the tried method of heating and cooling degree days (HDD and CDD) [1], [2].

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A degree day is the temperature difference (in °C) between the indoor comfort level and the mean daily outdoor air temperature whenever such a difference is larger than some specified base value. The latter depends on the quality of building insulation and on its thermal properties. As specified in the national standard ShNK 2.08.01-24 for Uzbekistan, the reference temperature of the indoor comfort is 20 °C [3].

Different base thresholds were used for buildings with different standards of insulation. Since this variable is quite different by building type, two heating thresholds—10 °C and 12 °C—were selected following the approach of Christenson et al. (2006) [4]. These thresholds were fixed based on each building's volume-weighted heat loss, as computed in accordance with ShNK 2.08.01-24 [3]. In older, non-retrofitted homes, thresholds of 10–12 °C were appropriate, while in newer buildings, there are lower thresholds. In buildings built after 1995, when national thermal protection standards were adopted, the usual heating base temperature of 10 °C was applied to HDD calculation.

The case study is based on a typical three-room residential building, as shown in Figure 1. The geometric characteristics of the building, including room dimensions and calculated areas and volumes, are presented in Table 1.

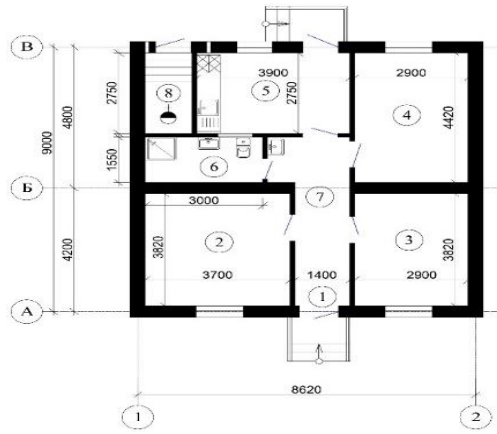


Figure 1: Three-room residential building used as the case study object.

As there is no unified European definition of cooling degree days, most research applies the American standard assuming comfort temperature to be 18.3 °C (65 °F) [5]; [4]. Since this value doesn't include in consideration indoor comfort conditions in Uzbekistan, where by default 20 °C was used, the present research utilized 22 °C as an upper limit of comfort for cooling based on previous works [6]. Accordingly, the indicators of degree-days were calculated as follows:

$$HDD = \sum_{i=1}^n (20^{\circ}\text{C} - \theta) \text{ for } n = \text{days per year and } \theta \leq 10^{\circ}\text{C, or } 12^{\circ}\text{C,}$$

and cooling degree days (CDD) by

$$CDD = \sum_{i=1}^n (\theta - 20^{\circ}\text{C}) \text{ for } n = \text{days per year and } \theta \geq 22^{\circ}\text{C.}$$

Because residential development across Uzbekistan is spatially heterogeneous, the HDD and CDD values

were weighted according to regional population distribution derived from CORINE Land Cover (CLC) data [7]. Thereby, population weighting was applied using Thiessen polygons (for STAR II data) and grid-cell population density (for the CCLM model) to ensure representative climate coverage.

Heating energy demand represents the total heat required to maintain indoor comfort and is affected by transmission and ventilation losses, both of which are temperature and degree-day-dependent. Simultaneously, it is reduced by solar and internal gains, such as heat emitted from electrical appliances and occupants [8]. When outdoor temperatures exceed indoor levels, these heat flows reverse direction, thereby defining the building's cooling energy demand [3].

The annual heating energy demand ( $Q_h$ ) for each residential building was determined according to the national regulation KMK 2.01.04-18 [9] [10], using:

$$Q_h = 24 \times 10^{-3} \cdot f \cdot HDD \cdot (H_T + H_V) - \eta \cdot (Q_S + Q_I) \text{ (kWh/a)}, \quad (1)$$

where  $f$  is the factor for inclusion of a night setback of the heating system temperature=0.95 (kh/d),  $H_T$  is the transmission heat losses,  $H_V$  is the heat ventilation losses,  $\eta$  is the factor for inclusion of the utilisation factor of internal and solar heat gains,  $Q_S$  is the usable solar heat gains (constant value),  $Q_I$  is the usable internal heat gains (constant value).

The wall surface specifications and their orientations used in the calculations are summarized in Table 2.

Transmission losses ( $H_T$ ) quantify conductive and convective heat flow through building elements and depend on the thermal quality (U-values) of envelope components. Lower U-values indicate improved insulation performance [11]. These losses are computed as:

$$H_T = \sum_{i=1}^4 (F_{xi} \cdot U_i \cdot A_i) + A \cdot \Delta U_{TB} \text{ (W/K)}, \quad (2)$$

where  $F_{xi}$  is the temperature correction factor (depending on the kind of building component),  $F_{xi}$  [wall, window, roof]=1,  $F_{xi}$  [basement]=0.6,  $U_i$  is the mean U-value of a building component (W/(m<sup>2</sup> K)),  $A_i$  is the surface area of each building component (m<sup>2</sup>),  $A$  is the heat transmitting surrounding area (m<sup>2</sup>),  $\Delta U_{TB}$  is the thermal bridge correction factor=0.05 (W/(m<sup>2</sup> K)).

Ventilation heat losses ( $H_V$ ) result from air exchange between the interior and exterior. Assuming uniform air tightness for all building types:

$$H_V = 0.19 \left( \frac{W}{\text{Km}^3} \right) \cdot V \text{ (m}^3\text{)}, \quad (3)$$

where  $V$  is the heated building volume (constant per building type).

The properties of windows and doors used for solar gain calculations are presented in Table 3.

Solar heat gains ( $Q_S$ ) arise primarily through glazing and depend on the total solar transmittance ( $g$ ), window area, and orientation-specific solar radiation intensity ( $I_i$ ). Assuming full solar exposure:

$$Q_S = \sum_{i=1}^4 0.567 \cdot I_i \cdot g_i \cdot A_i \text{ (kWh/a)}, \quad (4)$$

where  $I_i = 155$  (East), 270 (South), 55 (West), 100 (North) (kWh/(m<sup>2</sup> a)),  $g_i$  is the total energy transmittance of glazing type in case of vertical insolation [-],  $A_i$  is the area of windows (m<sup>2</sup>).

Internal gains ( $Q_I$ ) result from occupants and electrical equipment. Due to their variability, KMK 2.01.04-18 [9] recommends the following simplified expression:

$$Q_I = 22 \cdot \left(\frac{\text{kWh}}{\text{m}^3}\right) \cdot 0.32 \cdot V \text{ (m}^3\text{)}, \quad (5)$$

For comparability across building types, the simplified KMK approach was also used to estimate annual cooling energy demand ( $Q_C$ ) [kWh/a]:

$$Q_C = (1 - \eta_{HP}) \cdot (0.024 \cdot CDD \cdot (\sum_{i=1}^4 F_{xi} \cdot U_i \cdot A_i + 0.05 \cdot A + 0.19 \cdot V) + (\sum_{i=1}^4 0.567 \cdot I_i \cdot g_i \cdot A_i + 22 \cdot 0.32 \cdot V)). \quad (6)$$

## 2.2 Solar collectors

As it intends to cover the energy demand for water heating as much as possible using solar collectors, we introduce two types of solar collectors: glazed flat-plate and evacuated tubular solar collectors. Both types of solar collectors were analyzed for their potential integration into domestic hot water (DHW) installations and combined space heating and DHW configurations (commonly referred to as *combi-systems*). Therefore, we use the annual solar collectors' energy outputs (kWh/year) using the method proposed by the IEA-SHC<sup>1</sup>:

$$Q_{gcDHW} = 0.44 H_0 A_{sc}^{DHW}, \quad (7)$$

$$Q_{gccombi} = 0.33 H_0 A_{sc}^{combi}, \quad (8)$$

where,  $H_0$  is the annual global horizontal solar irradiation (kWh/m<sup>2</sup>),  $A_{sc}^{DHW}$  and  $A_{sc}^{combi}$  are solar collector aperture area (m<sup>2</sup>) for DHW system and combi-system, respectively.

Table 1: Room dimensions and calculated areas and volumes.

Name	Width	Length	Height
Hall	1,4	3,82	3
Living room	3,7	3,82	3
Bedroom	2,9	3,82	3
Bedroom	2,9	4,42	3
Kitchen	3,9	2,75	3
W/c	1,55	3	3
Corridor	1,4	5,15	3
Furnace	1,2	2,75	3

Table 2: Wall surface specifications and orientation.

Name	W.r	L(m)	h(m)	Aw (m2)	Ad (m2)	As (m2)
Wall1	West	9,4	3	0	0	28,2
Wall2	South	9	3	3,6	2,5	20,9
Wall3	East	9,4	3	0	0	28,2
Wall4	North	9	3	3,15	4,5	19,35

Table 3: Window and door properties for Solar gain.

Name	W.r	L (m)	Width (m)	Area (Ai)	gi	Ii
Window1	South	1,5	1,2	1,8	0,75	700
Window2	South	1,5	1,2	1,8	0,75	700
Window3	North	1,5	1,2	1,8	0,75	250
Window4	North	1,5	0,9	1,35	0,75	250
Door1	South	2,5	1	2,5		
Door2	North	2,5	0,9	2,25		
Door3	North	2,5	0,9	2,25		

Since the share of air-conditioned dwellings is significantly lower than that of heated ones, the computed cooling demand was multiplied by the proportion of households equipped with cooling units to obtain the actual cooling energy requirement. Equal distribution of air-conditioning systems across building types was assumed.

### 2.3 Comprehensive Energy Balance Analysis of a Retrofitted Single-Family House

As discussed earlier, the retrofitting measures encompass the addition of thermal insulation to the external walls, ceiling, floor, and roof, along with the installation of a rooftop solar photovoltaic (PV) system and solar thermal collectors to enhance the building's overall energy performance. Therefore, the total annual energy consumption ( $Q_t^*$ , kWh/year) in the building after retrofitting can be defined as follows:

$$Q_t^* = \frac{1}{\eta_{wh}} \left[ \frac{Q_{heat}^* - Q_{gc}^{combi}}{\eta_{hs}} + Q_{water} - Q_{gc}^{DHW} \right] + (E_{el} - E_{PV}), \quad (9)$$

where  $Q_{heat}^*$  is the space heating demand (kWh/year) in the building after respective retrofitting envelopes of the building.

#### 2.2.1 Reduction of CO<sub>2</sub>-Emission Through the Refurbishment Measures

The emission of carbon dioxide (CO<sub>2</sub>) to the environment caused by utilizing energy from the primary energy sources that are obtained by combustion of fossil fuels. The annual CO<sub>2</sub> emission ( $M_{CO_2}$ , kg/year) can be defined by the following formula:

$$M_{CO_2} = \mu_f(Q_t - E_{el}) + \mu_{el} E_{el}, \quad (10)$$

where  $\mu_f$  and  $\mu_{el}$  are the specific CO<sub>2</sub> emission (kg/kWh) due to utilization of fuel (in our case natural gas) and electricity from the local network (obtained by utilizing fossil fuel). Accordingly, after retrofitting, CO<sub>2</sub>-emission can be written as follows:

$$M_{CO_2}^* = \mu_f(Q_t^* - E_{el} + E_{PV}) + \mu_{el} (E_{el} - E_{PV}) \begin{cases} E_{el} - E_{PV} \geq 0 \\ Q_t^* - E_{el} + E_{PV} \geq 0 \end{cases} \quad (11)$$

#### 2.2.2 The Retrofit Measure

During the simultaneous optimization, retrofitting windows, external wall insulation materials, ceiling, floor, and roof insulation materials and installation of

PV panels and solar water heating systems were considered. As items for retrofitting external walls insulation materials, windows, ceiling, floor, and roof insulation materials, the following variables are introduced:

$$U_{win}^* = \frac{U_{win}}{1 + U_{win} x_{ins}^{win}}, \quad (12)$$

$$U_r^* = \frac{U_r k_r}{k_r + U_r x_{ins}^r}, \quad (13)$$

$$U_{ew}^* = \frac{U_{ew} k_w}{k_w + U_{ew} x_{ins}^w}, \quad (14)$$

$$U_f^* = \frac{U_f k_f}{k_f + U_f x_{ins}^f}. \quad (15)$$

which will be used instead of U-values mentioned in (2) for envelopes of the building:  $x_{ins}^{win}$  is the R-value of windows;  $k_r$ ,  $k_w$  and  $k_f$  are the thermal conductivities (W/m·°C) of insulation materials embedded in the roof-floor external walls, and the floor of the buildings, respectively;  $x_{ins}^r$ ,  $x_{ins}^w$ , and  $x_{ins}^f$  are the thicknesses (m) of the same accorded insulation materials.

In the same way,  $x_{sc}^{DHW}$ ,  $x_{sc}^{combi}$ , and  $x_s^{PV}$  are variables (m<sup>2</sup>) introduced instead of surfaces areas of solar collectors for DHW system and “combi-system”, and solar PV panels, which will be designed for the building. Solar collectors and PV panels are installed on the south-oriented roof area. Therefore, it is necessary to optimize solar collectors and PV panels with constrains:

$$x_{sc}^{DHW} + x_{sc}^{combi} + x_s^{PV} \leq \frac{A_r}{2}. \quad (16)$$

#### 2.2.3 Economic Analysis for the Optimal Design

It is obvious that when retrofitting envelopes of buildings and installing solar collectors and PV panels, the initial investment cost of materials increases while reduction of the heating and cooling loads, the electricity consumption from the local network and consequently the energy cost is expected [10]. The optimal design of retrofitting and installation of solar collectors and PV panels is that design, at which the total cost reaches the minima. The total cost is the sum of the cost of all used material and the present value factor (PVF) of the cost of energy consumption over the lifetime of materials that is given by:

$$C_t = (C_{ther} + C_{ae})PVF + C_m, \quad (17)$$

where  $C_{ther}$  is the annual energy cost (US \$) for supplying the thermal energy is calculated as follows:

$$C_{ther} = \frac{C_{fuel}}{\eta_{hs}} \left[ \frac{Q_{heat} - Q_{gc_{combi}}}{\eta_{hs}} + Q_{water} - Q_{gc_{DHW}} \right], \quad (18)$$

where  $C_{fuel}$  is the specific fuel cost (US \$/kWh). The cost of annual electricity consumption ( $C_{ae}$ , US \$) with the specific cost of electricity ( $C_{el}$ , US \$/kWh) is:

$$C_{ae} = (E_{el} - E_{PV})C_{el}. \quad (19)$$

The material cost ( $C_m$ ) is considered as the initial investment cost that consists of:

$$C_m = C_{wall}x_{ins}^w + C_{win}x_{ins}^{win} + C_r x_{ins}^r + C_f x_{ins}^f + C_{DHW}x_{sc}^{DHW} + C_{combi}x_{sc}^{combi} + C_{PV}x_s^{PV}, \quad (20)$$

where  $C_{wall}$ ,  $C_f$ , and  $C_r$  are the specific costs (US \$/m) of insulation materials for the external walls, floor, and roof, respectively;  $C_{win}$  is the specific cost ( $\frac{US\$}{m^2 \cdot ^\circ C}$ ) for windows refurbishment;  $C_{DHW}$ ,  $C_{combi}$ , and

$C_{PV}$  are the specific costs (US \$/m<sup>2</sup>) of solar collectors for DHW and combi-system, and PV panels.

The PVF depends on the inflation rate  $g$ , and the rate of interest  $i$ . The PVF can be defined as follows:

$$PVF = \frac{(1+r)^{N-1}}{r(1+r)^N} \begin{cases} r = \frac{i-g}{1+g} & i > g \\ r = \frac{g-i}{1+i} & g > i \end{cases}, \quad (21)$$

$$PVF = \frac{N}{1+i}, \quad i = g, \quad (22)$$

Taking into account time value of investment, the discounted payback periods (in year) of retrofit measure can be defined by:

$$\tau_D = \frac{\ln \left| \frac{1 - rC_m}{C_t - C_{t0}} \right|}{\ln |1+r|}, \quad (23)$$

where  $C_{t0}$  is the annual cost of total energy before retrofitting (US \$).

### 2.3 Optimization Problem and Solution Technique

For simultaneous optimizing envelopes of buildings and integration of various energy generators powered by the renewable energy sources, the optimal designs were considered for three scenarios. As optimization parameters of envelopes, the insulation level of windows, roof, floor, and external walls was considered while as optimization parameters, integrating the solar collectors for the DHW and combined space and water heating, and PV panels on rooftop of buildings were considered. In the first scenario, the life-cycle cost (LCC) is minimized so that the optimal values of parameters are obtained for

buildings designed with various levels of thermal insulation. In the second scenario, it is aimed at maximizing the primary energy consumption saving for space heating while minimizing the investment costs. In the final scenario, to create nearly zero carbon communities, the total primary energy consumption is minimized for buildings whereas the investment cost is minimized. The formulated optimization problem was implemented in Python and solved using the package of GEKKO.

Thermal properties and economic parameters of retrofit measure are given in Table 4.

Table 4: Techno-economic parameters of retrofit measure.

Parameter	Unit	Value
Fuel cost	US \$/kWh	0.004
Electricity cost	US \$/kWh	0.029
Insulation cost for roof		26.0
Insulation cost for walls	US \$/m <sup>3</sup>	26.0
Insulation cost for floor		26.0
Cost of solar collector (DHW)		300
Cost of solar collector (combi)	USD \$/m <sup>2</sup>	200
Cost of solar PV		340
Thermal conductivity of roof insulation		0.035
Thermal conductivity of walls insulation	W/mK	0.04
Thermal conductivity of floor insulation		0.04
Inflation rate	%	17
Interest rate	%	16
Exploitation (lifetime) year	Year	30
DHW demands	kWh/year	3000
Electricity consumption	kWh/year	6000

## 3 RESULTS AND DISCUSSIONS

The research revealed considerable differences in the Specific Annual Energy Demand as a function of varying levels of insulation. Results (Table 5) show a constant reduction in energy demand from 53.9 kWh/(m<sup>2</sup>×yr) at baseline to 34.6 kWh/(m<sup>2</sup>×yr) with an insulation thickness of 50 mm. Initial investment is negatively correlated with the payback period, with a corresponding decrease in payback period from 8.94 to 8.45 years with increased investment. Carbon dioxide emission also decreased significantly with increment in proportionate insulation levels, from 45.44 kg/(yr×m<sup>2</sup>) at baseline to 18.84 kg/(yr×m<sup>2</sup>) with 50 mm thickness. The above results emphasize the sustainability of increased building insulation and integration with renewable energy technologies, with PV panels and solar collectors to maximize energy efficiency in residential buildings.

Table 5: Results.

Specific annual energy demand. kWh/(m <sup>2</sup> ×yr.)	Initial investment, mln UZS	Payback periods, yr.	Saved CO2 emission. kg/(yr.×m <sup>2</sup> )
0	53.9	8.94	45.44
10	50.0	8.87	40.12
20	46.2	8.79	34.80
30	42.3	8.70	29.48
40	38.4	8.59	24.16
50	34.6	8.45	18.84

## 4 CONCLUSIONS

This study demonstrated that multi-objective optimization integrating building envelope retrofitting with renewable energy systems offers a highly effective pathway toward achieving nearly zero-energy residential buildings in Uzbekistan. Through simulation of a representative three-room house, it was found that increasing insulation thickness from 0 to 50 mm led to a consistent reduction in annual specific energy demand from 53.9 to 34.6 kWh/(m<sup>2</sup>·yr) and a notable decline in CO<sub>2</sub> emissions from 45.44 to 18.84 kg/(m<sup>2</sup>·yr). These improvements were accompanied by a modest decrease in the payback period from 8.94 to 8.45 years, indicating that enhanced energy efficiency can be achieved without compromising economic feasibility. The results clearly highlight that insulation improvements, when combined with solar photovoltaic panels and solar thermal collectors, can simultaneously reduce operational costs, energy dependency, and environmental impacts. The integrated optimization approach based on HDD/CDD analysis proved particularly suitable for Uzbekistan’s diverse climatic zones, enabling tailored solutions for both cold northern and hot southern regions. Such strategies can serve as a foundation for region-specific nZEB design standards, promoting a balance between cost, comfort, and sustainability. Moreover, the findings underline the importance of adopting national policies and incentive mechanisms that encourage the use of local insulation materials and solar technologies. Scaling up these retrofit and renewable integration measures across Uzbekistan’s residential building stock could lead to substantial reductions in national natural gas consumption and greenhouse gas emissions, supporting the country’s low-carbon development goals.

Future work should focus on extending this optimization framework to different building typologies (e.g., multi-story or rural dwellings), including dynamic simulations that consider

occupant behavior, real-time energy pricing, and lifecycle carbon assessment. Ultimately, the study provides an evidence-based framework for guiding policymakers, engineers, and designers toward a more resilient, energy-efficient, and sustainable housing sector in Uzbekistan.

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