OPTIMAL ENERGY DESIGN AND RETROFIT RECOMMENDATIONS FOR THE TURKISH BUILDING SECTOR

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ABSTRACT

This paper introduces methodologies and optimal strategies to reduce the energy consumption of the building sector with the aim to reduce global energy usage of a given region or country. Many efforts are underway to develop investment strategies for large-scale energy retrofits and stricter energy design standards for existing and future buildings. This paper presents a study that informs these strategies in a novel way. It introduces support for the cost-optimized retrofits of existing, and design improvements of new buildings in Turkey with the aim to offer recommendations to individual building owners as well as guidance to the market. Three building types, apartment, single-family house and office are analyzed with a novel optimization approach. The energy performance of each type is simulated in five different climate regions of Turkey and four different vintages. For each vintage, the building is modelled corresponding to local Turkish regulations that applied at the time of construction. Optimum results are produced for different goals in terms of energy saving targets. The optimization results reveal that a 50% energy saving target is attainable for the retrofit and a 40% energy saving target is attainable for new design improvements for each building type in all climate regions.

KEYWORDS

cost optimization, building sector, energy performance, retrofit

1. INTRODUCTION

In Turkey, buildings consume 33% of the total energy use (Republic of Turkey Ministry of Energy and Natural Resources, 2015). This percentage is approximately 40% in Europe (EC 2017) and in the United States (EIA, 2019). At the start of the century, the European Union (EU) launched the Directive on the Energy Performance of Buildings (EC, 2003) to make the building stock more energy efficient and reduce carbon emissions. In 2010, the recast of the Directive (EC, 2010) added the ambitious target to make all new buildings in Europe nearly zero energy buildings (NZEB) by 2020. NZEB is defined as *"a building that has a very high*

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energy performance… The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" in this directive. The exact definition of the NZEB shall be detailed by the Member States reflecting national, regional or local conditions, and including a numerical indicator of primary energy use expressed in kWh/m^2 per year. Furthermore, quantitative definitions of "very high energy performance" and "a very significant extent by energy from renewable sources" and "nearby" have to be given by Member States (D'Agostino and Mazzarella, 2019; Zsalay and Zöld, 2014). This flexibility for the definition allows the Member States to draw up their national plans to increase the number of NZEBs (Atanasiu, 2011). NZEBs have technically and reasonably achievable national energy use and it makes them more applicable than the zero energy buildings (ZEB) which have 0 kWh/m^2 non-renewable primary energy use (Kurnitski, 2013). The recast of the Directive has been amended in 2018 with Directive (EU) 2018/844 (EC, 2018). A long-term renovation strategy is added in this new Directive. According to this strategy, each Member State shall set out a roadmap to reach a highly energy efficient and decarbonized national building stock to ensure the effective transformation of existing buildings into NZEBs by 2050. Turkey, which is a candidate member of the EU, announced a local Energy Performance Regulation of Buildings in 2008 (BEP, 2008). This regulation was put into practice in 2010. It uses a static monthly calculation methodology to evaluate the existing building energy performance and determine energy performance of new buildings (Güçyeter and Günaydın, 2012). According to this regulation beginning from 01/01/2011, every new building which has a floor area larger than 1000m^2 must have an energy certificate. For the existing building stock, this certificate, issued by local authorities must be obtained before 2020. These developments are an indication of the high priority that the authorities give to reducing the energy usage of buildings in Turkey both of existing as well as new designs.

With the help of new technologies and advances in construction techniques, it is feasible to develop new buildings that are NZEBs. Whether it is cost-effective at the small and large-scale to accomplish such an ambitious goal is however questionable. Moreover, the existing building stock will remain in service for decades and will be responsible for most of the energy consumption. This realization is important to keep the right perspective on new design versus retrofits. McGrath et al. (2013) studied this comparison by considering the embodied energy. They proved that embodied energy of the retrofit is lower than newly designed buildings. Besides, this additional embodied energy of the retrofit is "paid back" over time (Balouktsi and Lützkendorf, 2016). Asadi et al. (2012) notes that the retrofit of existing buildings is a guaranteed way to achieve large-scale energy reduction. Buildings harbor many energy consumers that offer essential services such as lighting, space heating and cooling, water heating etc. In addition, there are many "direct" consumers in buildings that are life and work related and hard to influence by building improvements. These comprise all devices that consume electricity directly through the outlets installed in the building. In this study behavior adaptations will not be addressed that could affect this life/work related electricity consumption. Rather, the focus is on the services that are "mediated" by the building, i.e., where a more efficient delivery of these services has a significant impact on the overall building energy consumption. The biggest challenge in building retrofit is the selection of the optimal set of retrofits from a wide range of options. The initial set of applicable retrofit alternatives is quite large. They all come with specific associated costs and lead to different energy savings. Energy performance improvement of a building is however not additive over different discrete options. Rather, a chosen set of options work together in an integrated manner, leading to a certain performance improvement. The best mix of options can only be found as the solution of an optimization over all possible combinations of options. The most common optimization objectives are minimizing cost and maximizing energy savings and the optimization model is subjected to net present value (NPV), initial investment and energy target constraints (Malatji et al., 2013).

This research provides a new methodology for the cost optimization of the retrofit of existing buildings and the energy improvement of new buildings with the aim to offer recommendations for the Turkish building sector. For this study, three different buildings types are selected as archetype buildings to represent the national building stock of Turkey. Optimization is applied for each building type in different climate regions of Turkey for the various vintages to reach different energy saving targets.

The remainder of this paper is outlined as follows. The literature is critically reviewed in Section 2. In Section 3, material and methodology is presented, elaborating the archetype buildings, energy modelling and the novel optimization process. Section 4 provides the selected optimization results of the archetype buildings and discusses the results as compared with the literature. Finally, Section 5 summarizes the conclusions of the study.

2. LITERATURE REVIEW

Kumbaroğlu and Madlener (2012) used a techno-economic evaluation method based on NPV for the energy retrofit of buildings. In that study applied to an office building, Monte Carlo simulation was used for energy price uncertainties. Wang et al. (2014) presented a multi-objective optimization model for life-cycle cost analysis and the retrofitting planning of buildings. The objective function of the optimization is NPV in this study as well and a differential evolution algorithm is proposed to solve the optimization problem. Diakaki et al. (2008) used the multi-objective optimization approach and focused on the window type and wall insulation for improving the energy efficiency of buildings. Ascione et al. (2015) proposed a new methodology for the evaluation of the cost-optimality, using multi-objective optimization of the energy performance of buildings coupled with EnergyPlus and MATLAB for implementing a genetic algorithm for the optimization procedure. A case study of the optimization is applied on a modelled building which is intended to represent the residential buildings in European countries without any insulation. The energy technologies that are used as variables in the optimization are roof insulation, wall insulation, windows, boilers and chillers. Gossard et al. (2013) and Asadi et al. (2014) used an artificial neural network (ANN) method in addition to genetic algorithms for the multi-objective optimization of a building retrofit. Pikas et al. (2014), Congedo et al. (2015) and Ferrara et al. (2014) presented cost-optimal methods for NZEBs in their works and applied their methods to an office building in the Estonian cold climate, an office building in the Italian warm climate and a single-family house in a French cold climate respectively. Ferreira et al. (2016) compared cost-optimal and net-zero energy targets in the retrofit of a typical multifamily building in Portuguese housing stock which was built without any insulation before the implementation of the thermal regulation.

Ashrafian et al. (2016) and Sağlam et al. (2017) introduced cost-optimal approaches for the retrofitting of buildings in Turkey. In both these works, they used EnergyPlus for energy calculations, but no tool is used for optimization. They prepared retrofit packages and applied these various cost packages into the detached apartment and high-rise apartment case study buildings respectively for the three of five different climate regions of Turkey. Case study buildings are selected similarly for the vintage of the buildings that were constructed before 1999 which have no insulations. They both included the user profiles to calculate the operational energy usages based on some statistical data and some assumptions. Ashrafian et al. (2016) used only wall and roof insulations and window improvements for the retrofit packages; however, Sağlam et al. (2017) used an extensive package including heating, cooling systems and domestic hot water (DHW) systems, solar collector, photovoltaic (PV) and lighting systems in addition to the technologies that were used in Ashrafian et al.'s (2016) work.

The current state of practice presents that optimization approaches for the retrofitting of buildings or NZEB designs are applied for single building cases and vintage. In most studies a limited range of technology types such as window, wall and roof installations and boiler and chillers is used to improve the energy efficiency of the buildings. This study builds specifically on the approach presented in (Simmons, 2012) and applies it to building types and climate regions in Turkey. Simmons (2012) modelled two proto-typical buildings, an apartment and office in Korea. He applied the Korean building code to each building to define his baseline and then he optimized it over many applicable technologies and achievement levels per technology to find the technology mix that meet energy saving targets at minimal cost. In his study, the optimization is coded into a custom MATLAB script to test different technology combinations (in this case 16 different energy saving technologies containing between two to seven accomplishment levels). The 16 energy saving technologies capture all applicable energy saving technologies pertaining to the major building components (envelope, heating, cooling, lighting, ventilation, DHW, appliances and building controls). He also included solar thermal and photovoltaic systems with the levels of achievements and cost. In this study archetype buildings are modelled and optimized for various vintages to represent the major building stock of Turkey which were constructed according to the corresponding regulations at the time of construction.

3. MATERIAL AND METHODOLOGY

The material and methodology of this study consisted of three parts. The archetype buildings as the representative building stock of Turkey were developed and selected (Section 3.1). The energy simulation tool to evaluate the energy performance of the archetype buildings is presented (Section 3.2). The optimization process is developed in three steps (Section 3.3.). First, the energy technology mix of Turkey is prepared according to the local technologies with related cost data. Second, the extent of the optimization is determined for different climate regions of Turkey, various vintages and different energy saving targets. Finally, the new optimization tool (TechOpt) which works as an added feature in the energy simulation tool is presented.

3.1 Archetype Buildings

Becchio et al. (2014) indicates that the main purpose of a reference building is to represent the typical and average building stock in a certain State/Country. Archetypes are used as reference buildings for which results will be presented that are thus applicable to a large set of similar buildings. It can be argued that every building is so specific that it warrants its own retrofit or design optimization. The tool used in this study does indeed enable this, but the aim of this analysis is to show general trends and rank technologies for the set of chosen reference buildings. A reference building must reflect correctly the present national building stock so that the methodology can deliver representative results (Becchio et al., 2014). However, there is no study available that has definitively catalogued a set of representative reference buildings for Turkey (Ganiç et al., 2013). Three different types of buildings: apartment, single-family house and office designs are chosen in this study to represent a large part of the building stock and new designs in Turkey. In the Building Census (2000) of Turkey, residential and mixed but predominantly residential buildings constitute more than 85% of the national building stock. After the inclusion of an office reference building, most of the national building stock of Turkey is represented. The resulting reference buildings are introduced below. They are derived by studying architectural handbooks and general observation and deemed representative of the national building stock of Turkey.

The archetypical apartment design is a nine-story building, with four apartment units on each floor (Figure 1). In Turkey, most of the apartment buildings constructed after the 1980s are more than eight-story buildings, including 2–4 units on each floor with an area of 100–180 m^2 for each unit. For this reason, the building in Figure 1 is considered as representative of the apartment buildings in Turkey. The archetypical single-family house design is a two-story building (Figure 2). The residential buildings except apartment buildings in Turkey

FIGURE 1. Typical floor plan (a) and east elevation (b) of the apartment building.

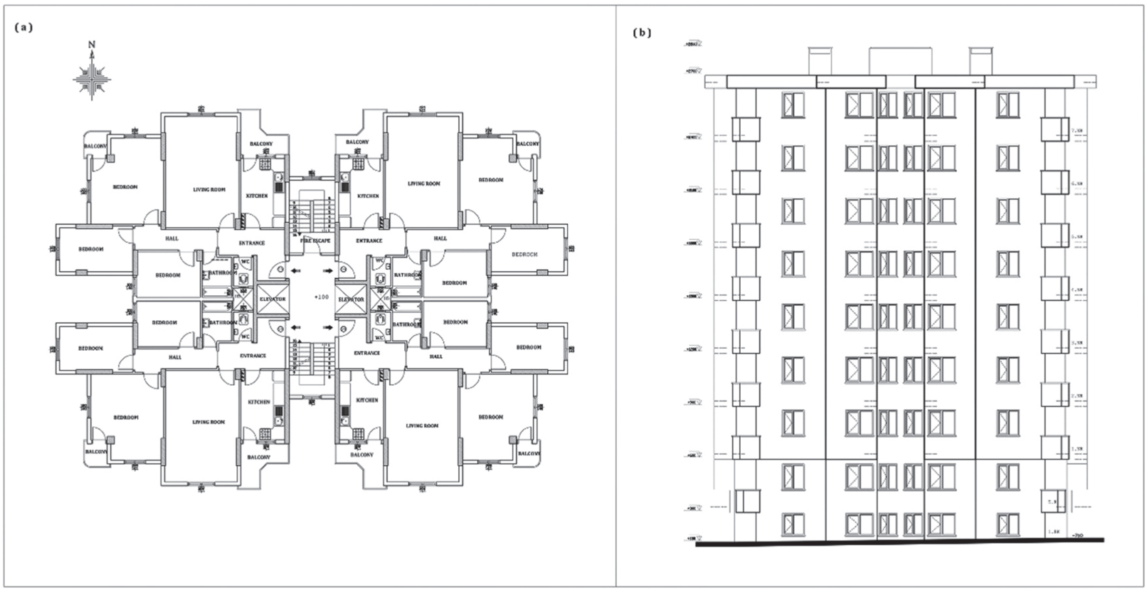
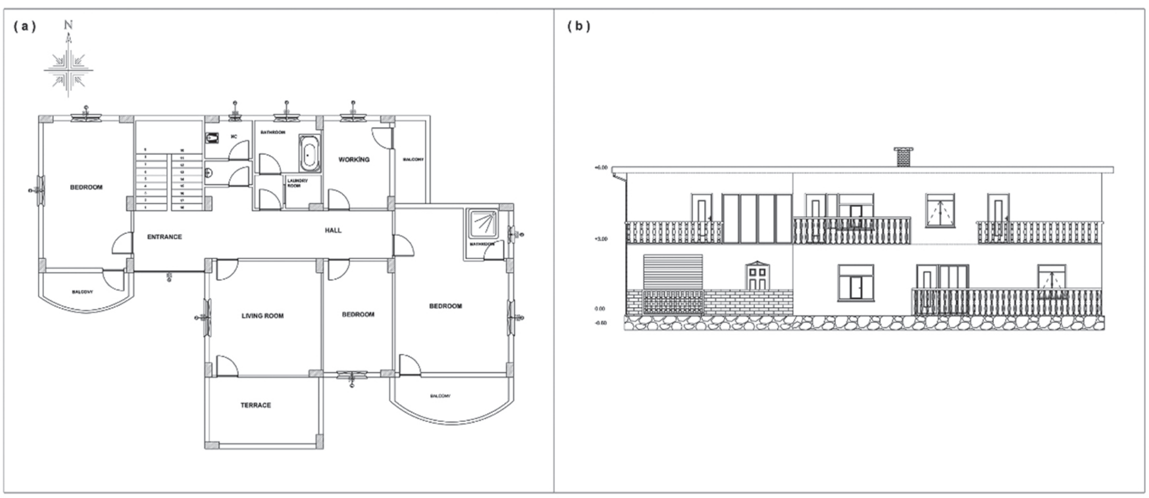


FIGURE 2. First floor plan (a) and south elevation (b) of the single-family house building.



are commonly two-story buildings with a total area between 200–400 m^2 according to general observation. The building in Figure 2 is deemed as representative of a single-family house. In contradistinction to apartment and single-family house buildings, there is not a common view in Turkey on office buildings regarding the number of floors and floor/unit area. Therefore, an office building is selected from architectural handbooks with a floor area and height among apartment buildings and single-family house buildings. Figure 3 presents the archetypical office building with a typical floor plan. It is a five-story building which predominantly facilitates an office function except on the ground floor. Detailed information of the archetypical buildings is presented in Table 1.

3.2 Energy Performance Simulation

The core of the technology optimization strategy is a monthly energy simulation tool, which can generate the energy saving for any mix of improvements. For this purpose, the Energy Performance Calculator (EPC) which is an energy performance assessment toolkit developed

FIGURE 3. Typical floor plan (a) and northwest elevation (b) of the office building.

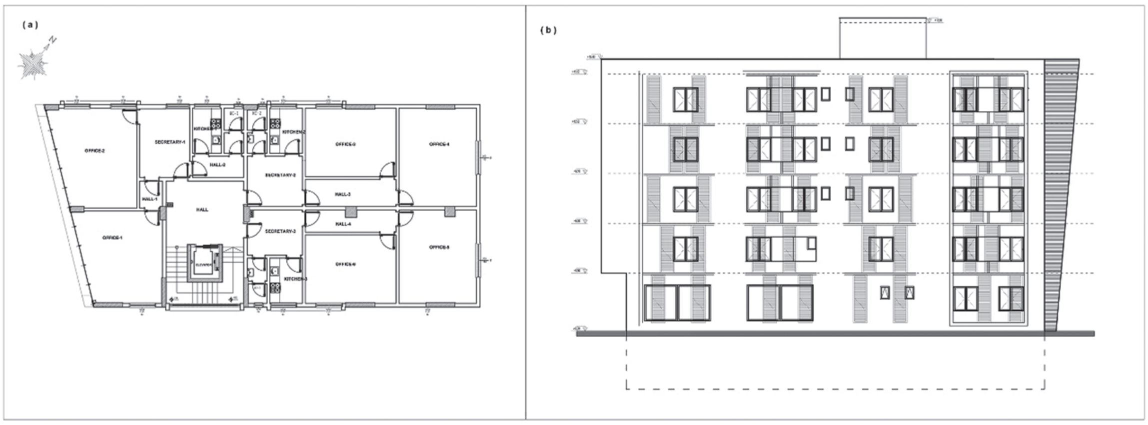


TABLE 1. Archetypical buildings information.

	Apartment Building	Single-Family House Building	Office Building
Floor area (m^2)	3960	371	1504
Building Height (m)	27	6	15.5
Building Volume (m^3)	93798	2228	23312
Façade surface area (m^2)	2613.6	390	1226.3
Roof Area (m^2)	528	225.5	288
Window Area (m^2)	500.4	55.5	349
Window-to-Wall Ratio (%)	19.14	14.23	28.45

by the Georgia Institute of Technology based on the EN ISO 13790 (2008) standard is used (Heo et al., 2011). CEN-ISO standards are developed by the collaboration of the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) to calculate the energy performance of buildings (Lee et al., 2013b). The standard defines the quasi-steady state monthly and dynamic hourly method for the calculation of macro energy flows. EN ISO 13790 (2008) is superseded by EN ISO 52016-1 (2017) with a new specific hourly calculation method, which is basically same monthly calculation method with some additions. Nevertheless, the EPC calculation has not been updated with the new standard. For this reason, EN ISO 13790 (2008) is used for energy calculations. Supporting calculation standards are EN ISO 13789 (2007) for transmission and ventilation heat transfer, EN 15241 (2007), EN 15242 (2007) for ventilation of buildings, EN 15243 (2007) for cooling and ventilation systems, EN 15193 (2007) for lighting, EN 15316-3 (2007) series for DHW, and EN 15316-4 (2007) series for heating systems (Lee et al., 2011). Lee et al. (2013b) describe the EPC as a computer translation of the CEN-ISO standards. The monthly version of EPC calculates the monthly energy demand for heating and cooling and presents the overall energy consumed by the building as a sum of all consumer services, i.e. "delivered energy to site" for ventilation, lighting, pumps, heating, cooling and preparation of DHW. In addition, primary energy depletion and carbon dioxide (CO_2) emissions at source are also calculated. EPC has been used in several research papers (Heo et al., 2011; Heo et al., 2013; Heo, 2011; Lee et al., 2013a; Simmons et al., 2013; Simmons et al., 2015; Tian et al., 2015; Zhang and Augenbroe, 2018b) both as a normative energy performance simulation tool for energy benchmarking or as a low resolution simulation tool after removing the normative stipulations. Heo (2011) proved that normative energy models can evaluate energy retrofit options accurately compared with dynamic energy simulation (Lee et al., 2013b). EPC's output is energy use intensity (EUI), i.e. yearly energy consumption per floor area in kilowatt-hours per square meter per year (kWh/m^2/year) (Simmons, 2012). EUI is based on total delivered energy. It is a whole building energy modelling approach and convenient to use for the optimization across many candidate energy saving technologies the combination of which typically forms a large combinatorial space. Each technology plays an integral role in the whole building performance and any evaluation must recognize the complex interaction of the different technologies.

3.3 Optimization Process

3.3.1 Energy technology mix development

Based on Simmons's (2012) work a similar approach is followed with as a first task being to define the applicable energy saving technologies for buildings in Turkey. The verification of local technologies, available contracting specialties, local cost data etc. resulted in an extensive and very time-consuming data analysis leading ultimately to Table 2 which was developed with Turkish regulations as the primary input, i.e.

- Turkish Energy Performance Regulation of Buildings (BEP 2008)
- Turkish Standard, Thermal Insulation in Buildings (TS 825 2013)
- Turkish Regulation of improving the efficient usage of energy and energy resources (2011)

TABLE 2. Energy technology mix for buildings in Turkey.

Technology type	Parameters	Technology options	EPC input	Cost data
Daylighting/ Occupancy Factors	Sensor	A0 (Null) Baseline Daylighting/ Occupancy Sensor	1	0
		A1 Fully Automated Daylighting/ Occupancy Sensor	0	35TL (each sensor)
Heating System with Building Energy Management System	COP	B0 Baseline Standard Hot Water Boiler	Heating COP = 0.92, BEM = 1	Boiler capacity and cost are changeable according to the building type and region respectively
		B1 Super-Heated Water Boiler	Heating COP = 0.95, BEM = 1	
		B2 Condensing Boiler	Heating COP = 1.10, BEM = 1	
		B3 Standard Hot Water Boiler + Zoned thermostat	Heating COP = 0.92, BEM = 2	185 TL (each proportional thermostat)
		B4 Super-Heated Water Boiler + Zoned thermostat	Heating COP = 0.95, BEM = 2	
		B5 Condensing Boiler + Zoned thermostat	Heating COP = 1.10, BEM = 2	
Infiltration/ Building leakage level	Air Tightness	C0 Baseline Air Tightness	4 (Q4Pa 4 $m^3/h/m^2$)	0
		C1 Infiltration improvement 1	2 (Q4Pa 2 $m^3/h/m^2$)	2.62 TL/m^2
		C2 Infiltration improvement 2	1.2 (Q4Pa 1.2 $m^3/h/m^2$)	4.35 TL/m^2
		C3 Infiltration improvement 3	0.6 (Q4Pa 0.6 $m^3/h/m^2$)	9.68 TL/m^2
		C4 Infiltration improvement 4	0.5 (Q4Pa 0.5 $m^3/h/m^2$)	11.6 TL/m^2
DHW Generation system	COP	D0 Baseline Boiler	0.61	Boiler capacity and cost are changeable according to the building type and function respectively
		D1 Natural Gas Boiler	0.75	
		D2 Electric Boiler with Tank	0.75	
		D3 Cogeneration Boiler	0.9	

TABLE 2. *(Continued)*

Technology type	Parameters	Technology options	EPC input	Cost data
PV Module	Surface Area (m^2)	E0 (Null) Photovoltaic Modules	0	0
		E1 Photovoltaic Modules 6 Units-1.47 KW settle kit	9.00 m^2	9326.72 TL
		E2 Photovoltaic Modules 9 Units-2.205 KW settle kit	13.50 m^2	12264.44 TL
		E3 Photovoltaic Modules 12 Units-2.94 KW settle kit	18.00 m^2	15360.76 TL
		E4 Photovoltaic Modules 18 Units-4.41 KW settle kit	27.00 m^2	21598.72 TL
		E5 Photovoltaic Modules 24 Units-5.88 KW settle kit	36.00 m^2	28421.95 TL
		E6 Photovoltaic Modules 30 Units-7.35 KW settle kit	45.00 m^2	33950.01 TL
		E7 Photovoltaic Modules 36 Units-8.82 KW settle kit	54.00 m^2	38960.76 TL
		E8 Photovoltaic Modules 42 Units-10.29 KW settle kit	63.00 m^2	46142.72 TL
		E9 Photovoltaic Modules 66 Units-16.17 KW settle kit	99.00 m^2	66808.76 TL
		E10 Photovoltaic Modules 90 Units-22.05 KW settle kit	135.00 m^2	85586.81 TL
Lighting	Irradiance (W/m^2	F0 100% Incandescent Bulbs	Due to the lighting calculations	16.5 TL (each bulb with fixture)
		F1 100% CFL Bulbs	Due to the lighting calculations	31.5 TL (each bulb with fixture)
		F2 100% LED Bulbs	Due to the lighting calculations	Between 36.5 TL–71.5 TL according to W (each bulb with fixture)

TABLE 2. *(Continued)*

Technology type	Parameters	Technology options	EPC input	Cost data
Roof Insulation	U value	G0 (Null) Baseline Non-insulated Concrete Roof	U = 1.779 W/m^{2}K	0
		G1 Roof Improvement 1 (40mm EPS insulation)	U = 0.41 W/m^{2}K	9.51 TL/m^2
		G2 Roof Improvement 2 (50mm EPS insulation)	U = 0.72 W/m^{2}K	11.61 TL/m^2
		G3 Roof Improvement 3 (60mm EPS insulation)	U = 0.34 W/m^{2}K	13.71 TL/m^2
		G4 Roof Improvement 4 (70mm EPS insulation)	U = 0.313 W/m^{2}K	15.81 TL/m^2
		G5 Roof Improvement 5 (80mm EPS insulation)	U = 0.286 W/m^{2}K	17.79 TL/m^2
		G6 Roof Improvement 6 (100mm EPS insulation)	U = 0.25 W/m^{2}K	22.11 TL/m^2
		G7 Roof Improvement 7 (100mm XPS insulation)	U = 0.233 W/m^{2}K	27.36 TL/m^2
Wall Insulation	U value	H0 (Null) Baseline Non-insulated Brick Wall	U = 1.344 W/m^{2}K	0
		H1 Wall Improvement 1 (30mm carbon EPS insulation)	U = 0.608 W/m^{2}K	32.39 TL/m^2
		H2 Wall Improvement 2 (40mm EPS insulation)	U = 0.573 W/m^{2}K	33.11 TL/m^2

TABLE 2. *(Continued)*

Technology type	Parameters	Technology options	EPC input	Cost data
Wall Insulation	U value	H3 Wall Improvement 3 (40mm carbon EPS insulation)	U = 0.501 W/m^{2}K	33.90 TL/m^2
		H4 Wall Improvement 4 (50mm carbon EPS insulation)	U = 0.435 W/m^{2}K	35.41 TL/m^2
		H5 Wall Improvement 5 (60mm carbon EPS insulation)	U = 0.385 W/m^{2}K	36.93 TL/m^2
		H6 Wall Improvement 6 (80mm EPS insulation)	U = 0.357 W/m^{2}K	38.36 TL/m^2
		H7 Wall Improvement 7 (70mm carbon EPS insulation)	U = 0.345 W/m^{2}K	38.43 TL/m^2
		H8 Wall Improvement 8 (80mm carbon EPS insulation)	U = 0.308 W/m^{2}K	39.94 TL/m^2
Windows	U value Solar heat gain coefficient Visible Transmittance	I0 Baseline Single Window	U = 4.57 W/m^{2}K, SHGC = 0.56, VT = 0.78	0
		I1 Window improvement 1 (4+4 thick, 12mm, Low-E)	U = 1.6 W/m^{2}K, SHGC = 0.56, VT = 0.78	60.41 TL/m^2
		I2 Window improvement 2 (4+4 thick, 12mm, Solar Low-E	U = 1.6 W/m^{2}K, SHGC = 0.44, VT = 0.71	65.66 TL/m^2
		I3 Window improvement 3 (4+4 thick, 16mm, Low-E)	U = 1.3 W/m^{2}K, SHGC = 0.56, VT = 0.79	66.98 TL/m^2
		I4 Window improvement 4 (4+4 thick, 12mm, Solar Low-E)	U = 1.3 W/m^{2}K, SHGC = 0.44, VT = 0.71	71.56 TL/m^2

TABLE 2. *(Continued)*

Technology type	Parameters	Technology options	EPC input	Cost data
Solar Collector	Surface Area (m^2)	J0 (Null) Solar Boiler	0	0
		J1 2m^2 Aluminium Solar Collector-25% Roof	25% roof area of the building	475 TL (each collector)
		J2 2m^2 Aluminium Solar Collector-50% Roof	50% roof area of the building	475 TL (each collector)

TL = Turkish Lira, COP = Coefficient of performance, BEM = Building energy management, DHW = Domestic Hot Water, PV = Photovoltaic, SHGC = Solar heat gain coefficient, VT = Visible transmittance, EPS = Expanded polystyrene, XPS = Extruded polystyrene, Low-E = Low emissivity, CFL = Compact fluorescent, LED = Light emitting diode

The resulting Turkish energy saving technologies are comprised of 10 technology types including: daylighting/occupancy sensors, heating system jointed with zoned thermostats (building energy management system), infiltration, DHW generation system, PV system, lighting, envelope (roof and wall insulations, window), and solar collectors. As a distinct deviation from Simmons's technology set, appliances, dimmer switches, heat recovery systems and exhaust air recirculation systems are excluded from the Turkish mix. As stated in the introduction, this study is focused on the services that are mediated by the building. For this reason, appliances are excluded. Dimmer switches are not commonly used in Turkey. Most of the buildings in Turkey are heated with radiators or floor heating systems instead of heating, ventilation and air conditioning (HVAC) systems. Accordingly, heat recovery systems and exhaust air recirculation systems are excluded, and heat pumps are not considered in the Turkish mix. Besides, daylight and occupancy sensor systems are not separated. Cooling systems are only mandatory for those buildings (except residential) with a cooling load of more than 250 kW according to Turkish regulation (BEP, 2008). Besides, most of the residential buildings in Turkey (except 1st Region) do not have cooling systems. Therefore, cooling systems are not included in the technology set for the apartment building and single-family house as well as the office building. The latter exclusion was verified during the energy performance simulations of the office building, where it was found that the cooling load of the reference buildings in all climates did not reach the mandatory cooling system installation threshold. The building's temperature set-points for heating are scheduled as 22°C in the daytime and 20°C in the night-time for thermal comfort in every archetype building since a comfortable temperature value for spaces is considered to be between 20°C and 27°C (ASHRAE, 2013). Natural ventilation is accepted for every archetypical building as the source of fresh air supply. Technologies are linked to the EPC calculation through one or more EPC parameters that take on a different, prescribed and discrete value per technology and achievement level. Each technology and achievement level are defined with an incremental cost over a defined baseline. Necessary cost data of the technology types are obtained from annual parameters defined by the Republic of Turkey the Ministry of Environment and Urbanism (2016).

To implement the optimization, every technology is included in the set and linked to the EPC model for every archetype building to be analyzed. Daylight and occupancy sensors are enabled only in the office building according to Turkish regulation (BEP, 2008). Heating boilers are combined with zoned thermostats as part of a building energy management system. DHW boiler options are chosen according to data published by the Ministry. They are linked to the EPC parameters for daily hot water need in different types of buildings (reference values are chosen based on published averages). PV system cost data is obtained from a market search since they are not provided by the Ministry. Multi crystalline silicon PV modules are selected and orientated to the south with a tilt angle 30°. Lighting technologies are calculated according to the European standard EN 12464-1 (2011). For each space of the building, minimum lux levels are specified in the standard. These levels are converted to lumens and different types of bulbs are selected to meet the minimum lumen levels of each space. Total installed wattage in the light fixtures is then divided into the area of the building to find the input in W/m^2 as used in EPC for installed lighting density. All types of bulbs: incandescent, compact fluorescent (CFL) and light emitting diode (LED) bulbs have different incremental costs respectively. As a baseline, it is assumed that all the buildings have incandescent bulbs. Roof insulation and wall insulation options are developed according to the TS 825 (2013). The layers of the roof and wall are presented in Table 3 and Table 4. Expanded polystyrene (EPS), carbon EPS and extruded polystyrene (XPS) insulation materials are selected from the Ministry data with different thickness and incremental costs. Window options are developed by using the TS 825 (2013) and Turkish Ministry cost data. Solar collector technology is obtained with two different options related to the roof area of the building. In the optimization process a constraint is defined that limits the summed area of the PV panels and solar collectors to half the roof area of the building. This acts as a constraint in the optimization routine which is carried out by the in-built MS-Excel solver.

TABLE 3. Roof layers of energy technology mix of Turkey (TS 825, 2013).

Roof layers	d thickness (mm)	R values (m^{2}K/W)	U value (W/m^{2}K)
R_i	—	0.13	
Gypsum plaster	2	0.003	
Plaster	20	0.02	
Reinforced concrete	120	0.054	
Water insulation	2	0.01	
Insulation material	—	—	
Cement finish	80	0.265	
Mosaic	10	0.04	
R_o	—	0.04	
Total R		0.744	1.779
R_i = internal thermal resistance	R_o = outside thermal resistance		

TABLE 4. Wall layers of energy technology mix of Turkey (TS 825, 2013).

Wall layers	d thickness (mm)	R values (m^2K/W)	U value (W/m^2K)
R_i	—	0.13	
Gypsum plaster	2	0.003	
Plaster	20	0.02	
Brick	190	0.528	
Insulation material	—	—	
Insulation plaster	8	0.023	
R_o	—	0.04	
Total R		0.744	1.344
R_i = internal thermal resistance	R_o = outside thermal resistance		

3.3.2 Extent of the optimization

The Turkish Standard (TS) 825, thermal insulation in buildings, was first issued in 1999 and became mandatory in 2000 (TS 825, 1999). According to this standard, Turkey is divided into four different climate regions. The standard specifies per region the maximum allowable U-values for the building envelope. These maximum values are presented in Table 5.

TS 825 was then updated in 2008 and maximum U values for the buildings' envelopes were further decreased as shown in Table 6 (TS 825, 2008).

In 2013, TS 825 was updated again, and maximum U-values were decreased below the standard released in 2008 (Table 7). In addition to that decrease, a new climate region was added into the map as the coldest climate for Turkish cities. Figure 4 presents the new (5th) region on the Turkey map in pink (TS 825, 2013).

Three different case study buildings are analyzed and used for technology optimization in the five different climate regions of Figure 4. The major cities, which are marked as red circles in Figure 4, are selected in the analysis, since these cities have the highest number of buildings and therefore are the prime candidates for retrofit initiatives. Izmir is in the 1st region, Istanbul

TABLE 5. Max U-values of building envelope (TS 825, 1999).

TS 825-2000	U_w (W/m^2K)	U_r (W/m^2K)	U_f (W/m^2K)	U_g (W/m^2K)
1. Region	0.80	0.50	0.80	2.8
2. Region	0.60	0.40	0.60	2.8
3. Region	0.50	0.30	0.45	2.8
4. Region	0.40	0.25	0.40	2.8
	U_w = Wall U value	U_r = Roof U value	U_f = Floor U value	U_g = Window U value

TABLE 6. Max U-values of building envelope (TS 825, 2008).

TS 825-2008	U_w (W/m^{2}K)	U_r (W/m^{2}K)	U_f (W/m^{2}K)	U_g (W/m^{2}K)
1. Region	0.70	0.45	0.70	2.4
2. Region	0.60	0.40	0.60	2.4
3. Region	0.50	0.30	0.45	2.4
4. Region	0.40	0.25	0.40	2.4
	U_w = Wall U value	U_r = Roof U value	U_f = Floor U value	U_g = Window U value

FIGURE 4. City map of Turkey according to the climate regions (TS 825, 2013).

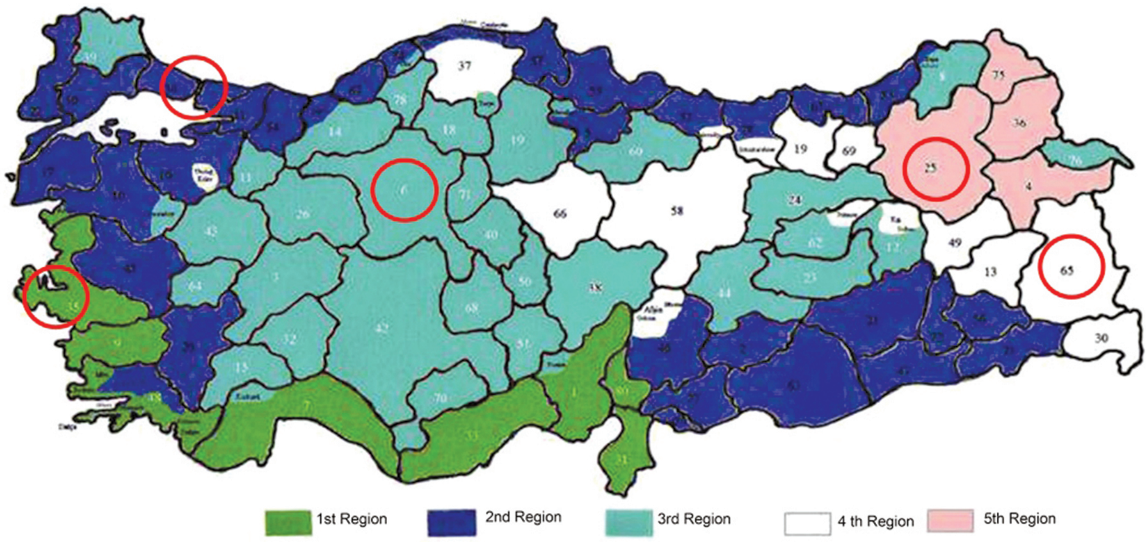


TABLE 7. Max U values of building envelope (TS 825, 2013).

TS 825-2013	U_w (W/m^{2}K)	U_r (W/m^{2}K)	U_f (W/m^{2}K)	U_g (W/m^{2}K)
1. Region	0.66	0.43	0.66	1.8
2. Region	0.57	0.38	0.57	1.8
3. Region	0.48	0.28	0.43	1.8
4. Region	0.38	0.23	0.38	1.8
5. Region	0.36	0.21	0.36	1.8
	U_w = Wall U value	U_r = Roof U value	U_f = Floor U value	U_g = Window U value

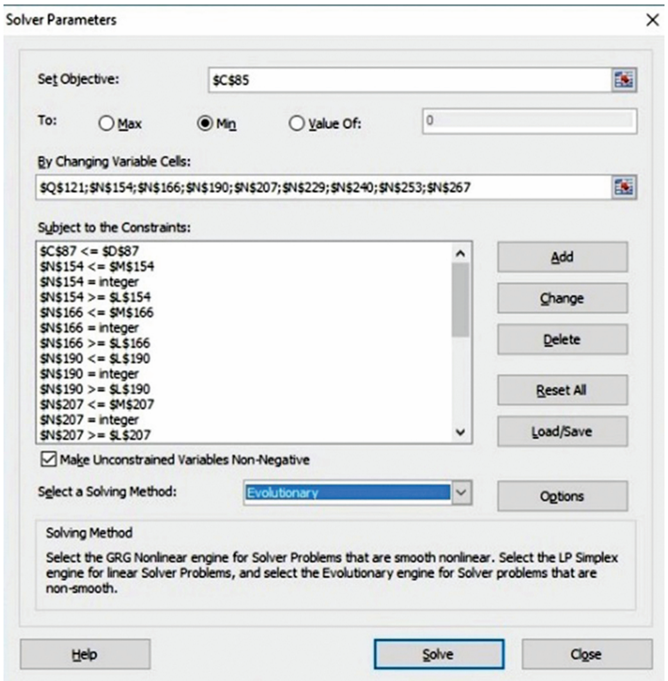
is in 2nd region, Ankara is in 3rd region, Van is in 4th region and Erzurum is in 5th region. All analyses are conducted based on the different governing standards that were released in different time periods. The archetype buildings are assumed to have no insulation if they were constructed before 2000. The baseline for these buildings reflects the absence of insulation. For the vintages 2000–2008 and 2008–2013 minimum U values, as mandatory at that time, are used in the baseline. For new building design, the latest release of the TS 825 (2013) and BEP (2008) standards and regulation requirements are reflected in the baseline for the analysis. Each archetype baseline building is modelled in EPC, with variations in the five different climate regions in accordance with the governing regulations in the four different vintages (before 2000, 2000–2008, 2008–2013, after 2013-new design). This results in 60 different baseline studies as a start of the optimization. All 60 different cases are cost-optimized for five different energy saving targets: 25%, 40%, 50%, 60%, and 75%. That results in a total of 300 optimization runs.

3.3.3 Cost optimization for energy savings target with TechOPT

Instead of the MATLAB script (that communicates with the EPC) which was used in Simmons's optimization, this study uses a new tool named TechOpt for the optimization. TechOpt was developed by the High Performance Building Laboratory at the Georgia Institute of Technology as an added feature in EPC. It was employed before by Zhang (2017) and Zhang and Augenbroe (2018a) for optimization studies. TechOpt adds a technology definition template in the EPC "input" worksheet. The template is populated with data related to the candidate technologies and their achievement levels that need to be considered in the optimization. TechOpt uses the "solver" add-in provided with Excel which in simple terms is a software tool for solving mathematical systems of equations for optimizations (Gottlieb, 2013). In the solver window (Figure 5), all variables are defined that take part in the optimization. Each of these variables links to the cells in the technologies template that define the technology and achievement level (usually a discrete, integer value). These variables are put into the "By Changing Variable Cells". The "Set Objective" cell is for the cost of the technologies to minimize. The constraints of the optimization are identified in "Subject to the Constraints" cell. The solver offers different techniques for the optimization algorithm. In this study the evolutionary solving method was used. It is a genetic algorithm that allows the user to specify the population size, mutation rate and random seed before starting the optimization. These values can typically be left at their default value, although it is good practice to experiment and run the optimization multiple times and with different starting values.

TechOpt activates the solver to find the optimal combination of solver variables that fulfills a desired target under some constraints (Figures 6 and 7). As each solver variable points to a technology and achievement level, the optimum variables represent the optimum mix of technologies to reach the savings target. The TechOpt template requires three classes of inputs: (1) technologies, achievement levels and costs (Figure 8); (2) the type and value of simulation model parameters for each technology and achievement level (Figure 8); (3) the optimization targets, such as cost and savings (Figures 6 and 7). The variables in TechOpt can be easily adapted to different situations. The optimization scenario can be set to any objective function specified by the user and restrictions can be added to the scenario. The orange colored cells in all three figures indicate cells that are linked to optimization parameters, i.e. they change as the algorithm is seeking an optimum. Green colored cells indicate problem specific parameters related to the building being analyzed. Figure 6 shows in the first line the overall objective function that is being minimized (total premium cost over baseline; the starting point being the baseline, this

FIGURE 5. Solver add-in interface in Excel.



cell shows a 0 value at the start of the optimization). Lines 2 and 3 show the constraints, i.e. the overall delivered energy and its target value, which in this case is a 60% saving over the baseline consumption of 656 kWh/m^2/yr. Line 3 shows the constraint that governs the application of solar collectors and PV technology, where the size of the solar collector and PV are used as in this case at a continuous achievement level. The baseline uses no solar collector or PV, whereas the restriction on potential solutions is 264 m^2 (the usable area of the roof). In a similar manner additional constraints can be added.

Figure 7 shows the values for the found optimum mix of technologies, i.e. the total cost is 133.506 TL (Turkish Lira), whereas the 60% saving target has been achieved.

Figure 8 shows a snapshot of the long list of technologies that is specified in TechOpt, including the color-coded legend for the cells. An example for the lighting control technology is given. It shows two achievement levels (index 1–2) with their cost factor when applied to the

FIGURE 6. Tech-OPT settings before optimization.

TECH-OPT settings

OBJECTIVE FUNCTION (premium cost of mix of technologies)	
0,00 ₺	These are defined by the problem or the user
OVERALL PARAMETER 1 (total delivered energy [kWh/m2/yr])	OVERALL RESTRICTION 1 [kWh/m2/yr]
656,93	262,77
OVERALL PARAMETER 2 (total area occupied on roof [m2])	OVERALL RESTRICTION 2 [m2]
-	264,00

FIGURE 7. Tech-OPT settings after optimization.

TECH-OPT settings

OBJECTIVE FUNCTION (premium cost of mix of technologies)	
133.506,15 ₺	These are defined by the problem or the user
OVERALL PARAMETER 1 (total delivered energy [kWh/m2/yr])	OVERALL RESTRICTION 1 [kWh/m2/yr]
262,11	262,77
OVERALL PARAMETER 2 (total area occupied on roof [m2])	OVERALL RESTRICTION 2 [m2]
-	264,00

FIGURE 8. Example of inputs for a discrete technology in TechOpt.

OPTIMIZATION	Green = opt. inputs	Orange = selected solution	Blue = to be linked with solver

Lighting control								
Technology levels	Index	Cost TL	Par.1	Par.2	Par.3	Min-index	Max-index	Variable
			C22	C23		1	2	1
A 0 - Baseline (NULL)	1	0,00	1	1				
A 1 - Fully autom. sensor	2	2205,00	0	0				
A 0 - Baseline (NULL)	1	0,00	1	1	0			

archetype building. It also shows the EPC model parameters (in this case contained in cells C22 and C23 representing daylighting and occupancy factor respectively) that is modified with the values shown for each selection of achievement level. The last line shows the starting point or (when the run is complete); the optimal selection for this technology. It should be noted that many technologies link to multiple model parameters that are being concurrently changed for a technology selection.

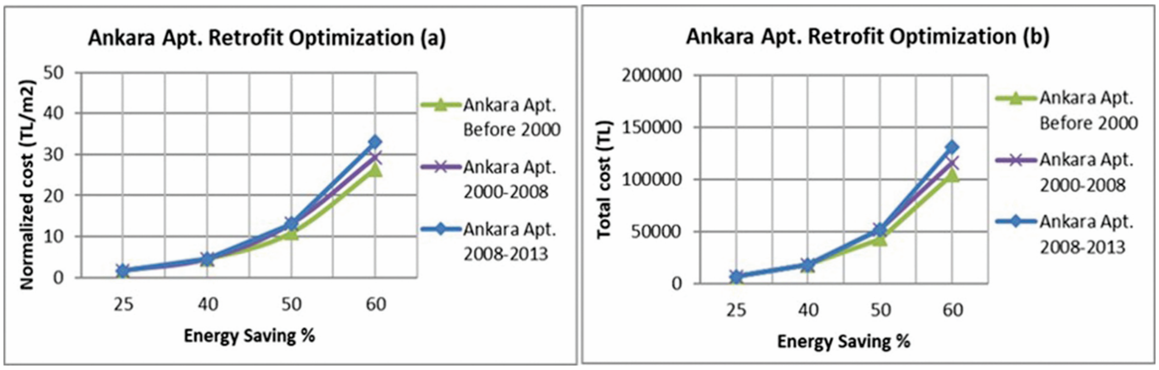
4. RESULTS AND DISCUSSION

The cost optimization for the three archetype buildings in five different climate regions for four different vintages and five different energy saving targets results in 300 cases. The results are assembled into normalized cost (TL/m^2) per energy saving (%) charts, and total cost (TL) per energy saving (%) charts for each case. It should be noted that cost is calculated as cost over a baseline, i.e. starting from the existing building for retrofit, or a standard design for new construction. The retrofit optimization and new design improvement optimizations are presented in separate charts, since marginal retrofit costs are significantly different from marginal costs design improvements. Due to the large number of results, only some of them are selected to be presented here. For each archetype building, selected optimization results for different cities are presented in the following sections.

4.1 Apartment Optimization Results

Apartment building retrofit optimization results in Ankara are presented in Figure 9. The results show that an apartment building in Ankara can save a maximum of 60% energy with

FIGURE 9. Optimization result of apartment retrofit in Ankara (a) per square meter cost (TL) of energy saving and (b) total cost (TL) of energy saving.



the retrofit of local technologies. Cost of the retrofit of the apartment building for 60% energy saving ranges between 25 TL/m^2 and 35 TL/m^2 dependent on the vintage. The total cost of the retrofit with 60% energy saving is in the range of 104000 TL to 131000 TL. Figure 10 presents the optimization results for new apartment design improvement in Ankara. It shows that newly designed apartment buildings can maximally save 40% energy with the selected technologies. This saving is realized at a total additional cost of 104000 TL.

Table 8 presents the optimization results, i.e. the technologies that are part of the optimal (most cost effective) mix for apartment retrofits and new design improvements in Ankara. It shows that the retrofit technology mix mostly remains the same for different vintages. Adding proportional zoned thermostats to the heating system can save 25% for apartment buildings. At the 40% energy saving target, reducing the infiltration is in the optimal mix for every retrofit scenario in addition to proportional zoned thermostats. Additionally, changing bulbs into CFL instead of incandescent and changing the boiler can move the savings up to 50%. Additional technologies to achieve 60% savings are window improvements and solar collectors. The optimal technologies for the 40% savings target of new apartment designs include window and wall improvements as well as solar collector installation.

Results for apartment buildings in other Turkish climate regions in large part resemble those for Ankara. In Erzurum, the apartment retrofit can reach the 75% savings target for

FIGURE 10. Optimization result of new apartment design improvement in Ankara (a) per square meter cost (TL) of energy saving and (b) total additional cost (TL) of energy saving.

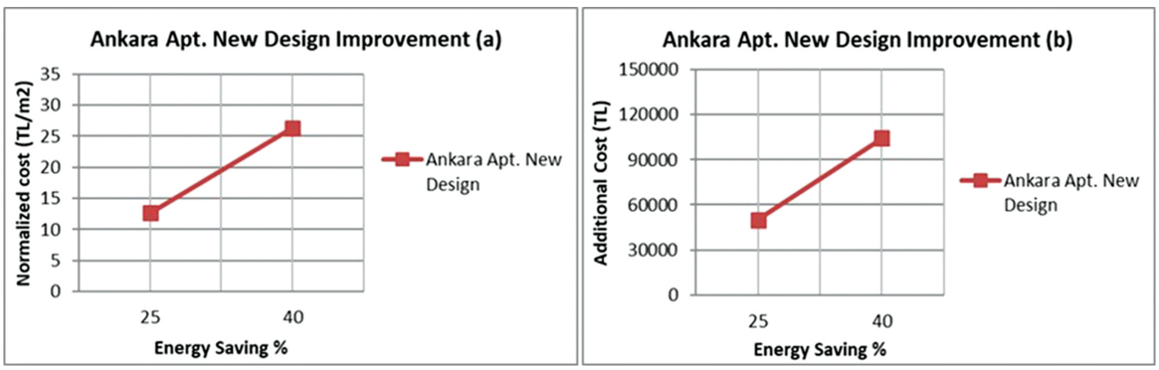


TABLE 8. Optimal technologies for apartment design improvement and retrofits for different vintages in Ankara (indices indicate achievement levels of technologies, refer to Table 2).

	Ankara apartment before 2000	Ankara apartment 2000–2008	Ankara apartment 2008–2013	Ankara apartment new design
25% energy saving	Zoned thermostat	Zoned thermostat	Zoned thermostat	Condensing boiler + zoned thermostat
				Infiltration improvement 1
				CFL bulbs
				Solar collector 25% roof
40% energy saving	Zoned thermostat	Zoned thermostat	Zoned thermostat	Condensing boiler+zoned thermostat
	Infiltration improvement 2	Infiltration improvement 2	Infiltration improvement 2	Infiltration improvement 2
				CFL bulbs
				Wall improvement 6
				Window improvement 3
				Solar collector 50% roof
50% energy saving	Condensing boiler + zoned thermostat	Condensing boiler + zoned thermostat	Condensing boiler + zoned thermostat	Not attainable
	Infiltration improvement 2	Infiltration improvement 3	Infiltration improvement 3	
	CFL bulbs	CFL bulbs	CFL bulbs	
	Roof improvement 1			
60% energy saving	Condensing boiler + zoned thermostat	Condensing boiler + zoned thermostat	Condensing boiler + zoned thermostat	Not attainable
	Infiltration improvement 2	Infiltration improvement 3	Infiltration improvement2	
	CFL bulbs	CFL bulbs	CFL bulbs	
	Roof improvement 1			
	Window improvement 1	Window improvement 3	Window improvement 2	
	Solar collector 25% roof	Solar collector 25% roof	Solar collector 50% roof	
75% energy saving	Not attainable	Not attainable	Not attainable	Not attainable

vintages 2000 and older. The cost of apartment retrofits in Erzurum is only half of the cost of retrofits in the other climate regions due to the limited number of technologies that are necessary to reach the savings target for older buildings. For apartments in Izmir and Istanbul constructed after 2000, it is found that the maximum attainable improvement is 50% energy savings. All other cases of apartment retrofit were shown to have a maximum attainable energy savings of 60%.

4.2 Single-Family House Optimization Results

Single-family house retrofit and new design improvement results are presented in Figures 11 and 12 for the Erzurum case. It is found that 75% energy savings by retrofit is only attainable for the vintage before 2000. This was found to be the case for all climate regions. Similarly, in all climate regions 50% energy savings is maximally attainable for new design improvement. The cost of 75% energy savings is between 50TL/m^2 and 60 TL/m^2 in Erzurum, Van and Ankara. It increases in warmer climates and reaches to 85–90 TL/m^2 interval in Istanbul and Izmir. In contrast to this cost difference between cold and warm climates, the cost of new design improvement is between 40TL/m^2 and 50 TL/m^2 irrespective of the climate region. This situation is the result of the new, stricter regulations for each climate location.

Table 9 presents the selected technologies for single-family house retrofits and new design improvements in Erzurum. Proportional zoned thermostats and infiltration reduction

FIGURE 11. Optimization results for single-family house retrofit in Erzurum (a) per square meter cost (TL) of energy saving and (b) total cost (TL) of energy saving.

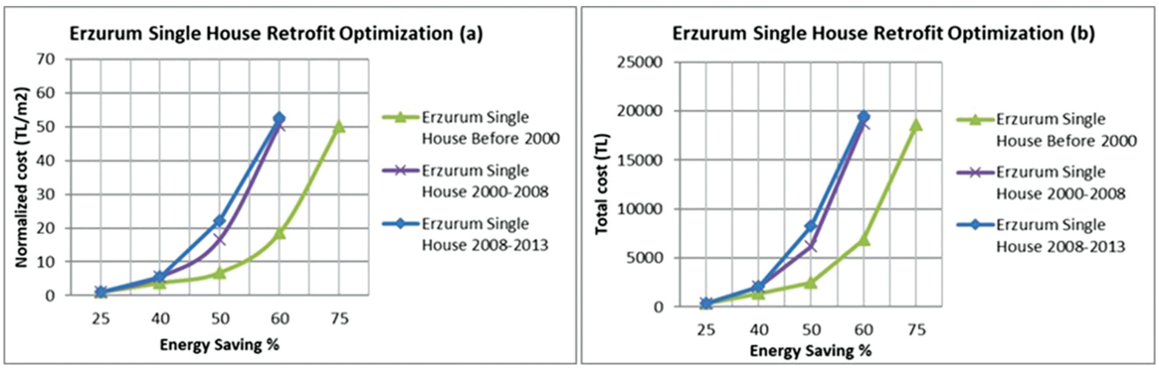


FIGURE 12. Optimization results for new single-family house design improvement in Erzurum (a) per square meter cost (TL) of energy saving and (b) total additional cost (TL) of energy saving.

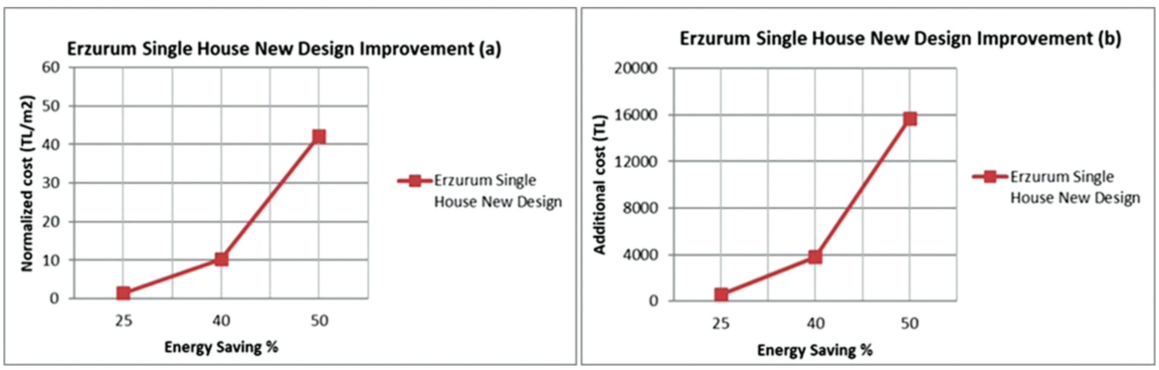


TABLE 9. Optimal technologies for single-family design improvement and retrofits for different vintages in Erzurum (indices indicate achievement levels of technologies, refer to Table 2).

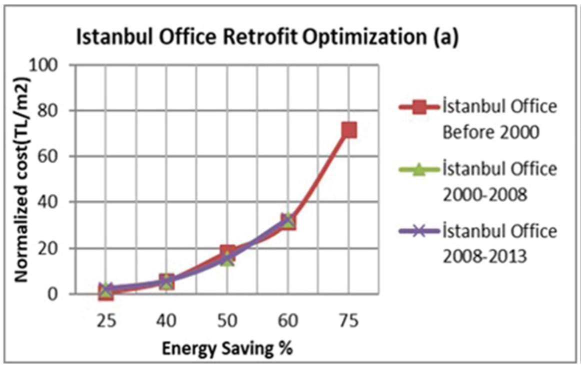
	Erzurum single-family house before 2000	Erzurum single-family house 2000–2008	Erzurum single-family house 2008–2013	Erzurum single-family house new design
25% energy saving	Zoned thermostat	Zoned thermostat	Zoned thermostat	Super heated water boiler+zoned thermostat
40% energy saving	Zoned thermostat	Zoned thermostat	Zoned thermostat	Super heated water boiler+zoned thermostat
	Infiltration improvement 1	Infiltration improvement 2	Infiltration improvement 2	Infiltration improvement 1
				Cogeneration Boiler (DHW)
				CFL bulbs
				Wall imrpovement 8
				Window improvement 2
50% energy saving	Zoned thermostat	Zoned thermostat	Zoned thermostat	Super heated water boiler +zoned thermostat
		Infiltration improvement 2	Infiltration improvement 4	Infiltration improvement 2
				CFL bulbs
		CFL bulbs		Wall improvement 7
	Roof improvement 1	Window improvement 1	Window improvement 1	Window improvement 2
				Solar collector 25% roof
60% energy saving	Zoned thermostat	Zoned thermostat	Super heated water boiler+zoned thermostat	Not attainable
	Infiltration improvement 1	Infiltration improvement 2	Infiltration improvement2	
	Roof improvement 1	Window improvement 1	CFL bulbs	
	Window improvement 1		Window improvement 1	
		Solar collector 25% roof	Solar collector 25% roof	
75% energy saving	Zoned thermostat	Not attainable	Not attainable	Not attainable
	Infiltration improvement 2			
	Roof improvement 1			
	Wall improvement 2			
	Window improvement 1			

technologies are selected for the 25% and 40% energy savings targets for retrofit. To reach the 50% and 60% energy savings targets, CFL bulbs, better windows and solar collectors are added. Due to the strict requirements expressed in the new regulations, it is harder to reach high saving targets for new design improvements. As a result, more technologies enter the optimal mix and the cost per saved kWh increases. It is found that the same technologies are part of the optimal mix and that the cost per square meter of new design improvement varies only slightly. At low saving targets, the optimal mix contains improvement of the heating system and zoned thermostats. As targets increase, infiltration improvement, CFL bulbs, window improvement and solar collectors are added in that order.

4.3 Office Building Optimization Results

Figures 13 and 14 show the cost of retrofit and new design improvement for an office building in Istanbul. The 75% energy savings target is attainable in all locations except Izmir for the vintage before 2000. Figure 13 shows that the cost per square meter of energy savings are similiar for all office retrofit scenarios in the Istanbul case. The 50% savings target for the new design improvement of the office building is attainable only in Izmir and Istanbul, which are located in the two warmest climate regions of Turkey. The cost of the 40% target for new design

FIGURE 13. Optimization result of office retrofit in Istanbul (a) per square meter cost (TL) of energy saving and (b) total cost (TL) of energy saving.



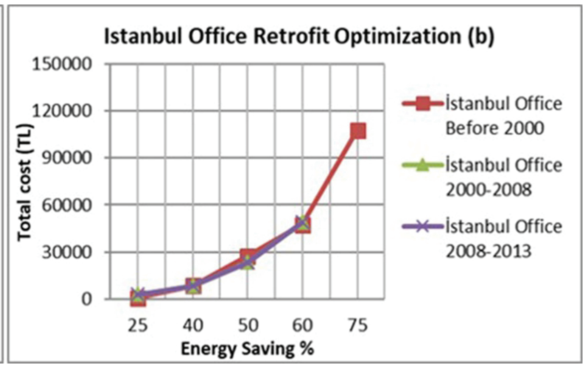
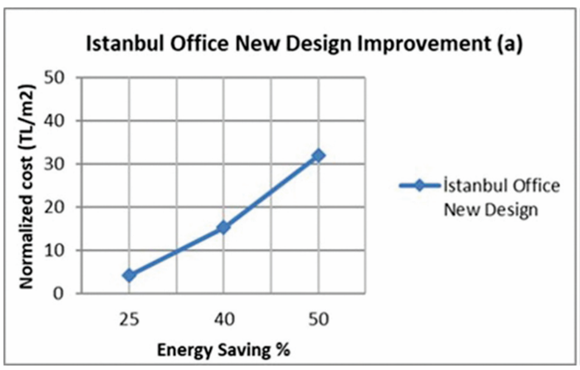


FIGURE 14. Optimization result for new office design improvement in Istanbul (a) per square meter cost (TL) of energy saving and (b) total additional cost (TL) of energy saving.



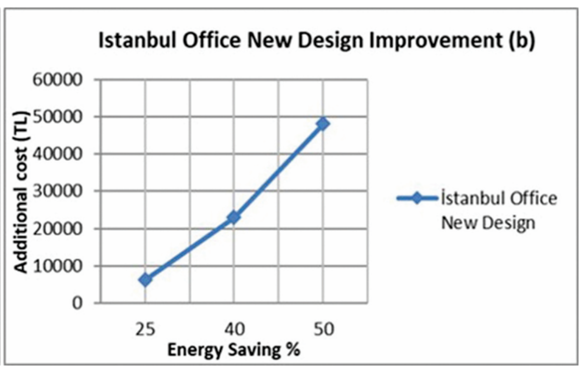


TABLE 10. Optimal technologies for office design improvement and retrofits for different vintages in Istanbul (indices indicate achievement levels of technologies, refer to Table 2).

	Istanbul office before 2000	Istanbul office 2000–2008	Istanbul office 2008–2013	Istanbul office new design
25% energy saving	Zoned thermostat	Daylight/occupancy sensor	Daylight/occupancy sensor	Daylight/occupancy sensor
				Infiltration improvement 2
		Zoned thermostat	Zoned thermostat	Roof improvement 3
				Wall improvement 4
40% energy saving	Daylight/occupancy sensor	Daylight/occupancy sensor	Daylight/occupancy sensor	Daylight/occupancy sensor
	Zoned thermostat	Zoned thermostat	Zoned thermostat	
	Infiltration improvement 2	Infiltration improvement 2	Infiltration improvement 2	Wall improvement 5
				Window improvement 3
				Solar collector 25% roof
50% energy saving	Daylight/occupancy sensor	Daylight/occupancy sensor	Daylight/occupancy sensor	Daylight/occupancy sensor
	Zoned thermostat	Zoned thermostat	Zoned thermostat	Condensing boiler+zoned thermostat
				Infiltration improvement 2
	Infiltration improvement1	Infiltration improvement1	Infiltration improvement1	Roof improvement 3
				Wall improvement 7
	Window improvement 1	Solar collector 25% roof	Solar collector 25% roof	Solar collector 25% roof
60% energy saving	Daylight/occupancy sensor	Daylight/occupancy sensor	Daylight/occupancy sensor	Not attainable
	Zoned thermostat	Zoned thermostat	Zoned thermostat	
	Infiltration improvement 1	Infiltration improvement 2	Infiltration improvement 2	
	Roof improvement 1			
	Window improvement 1	Window improvement 3	Window improvement 3	
	Solar collector 25% roof	Solar collector 25% roof	Solar collector 25% roof	
75% energy saving	Daylight/occupancy sensor	Not attainable	Not attainable	Not attainable
	Zoned thermostat			
	Infiltration improvement 3			
	Roof improvement 1			
	Wall improvement 5			
	Window improvement 3			
	Solar collector 50% roof			

improvement is 12 TL/m^2 and 15 TL/m^2 in Izmir and Istanbul respectively. In the other three (colder) climate regions the cost goes up to 20 TL/m^2.

Table 10 lists the technologies in the optimal mix for the retrofit and new design improvement of the office building in Istanbul. For retrofit the daylight/occupany sensor and zoned thermostat are selected at the 25% target. Infiltration improvement, solar collectors and window improvements are additionally selected for the 40%, 50% and 60% targets respectively. Roof and wall improvements are finally added at the 75% target level.

4.4 Discussion

The results of the 300-optimization run reveal that the 50% energy saving target is attainable in the retrofit of all three building types and all climate locations. Only in some retrofit cases the 75% target energy can be reached. This shows that a major reduction of the consumed building energy in Turkey is possible with affordable local technologies. If investments are limited to those with reasonable returns, it is found that the 50% energy saving target is reachable while being cost efficient. The cost at the 50% target for the apartment building ranges from 5TL/m^2 to 30 TL/m^2 depending on location and building vintage. At the same target, it is found that the costs are between 7TL/m^2 and 50TL/m^2 for the single-family house and between 8TL/m^2 and 20TL/m^2 for the office building. Retrofitting in colder climates is in general more economic than in the warmer climates due to the lax requirements of regulations that were enforced in the past. Comparing to the results of Ashrafian et al. (2016), they found that the colder climate (Erzurum) offers the biggest opportunity for achieving energy savings, which is the same as this study, however, their results show that reaching an optimum solution in this cold climate is twice as expensive than the milder climates i.e. İstanbul. This result predicts the opposite of this study, and it emerges from the lack of use of energy saving technologies (only wall-roof insulations and window improvement) for retrofitting in Ashrafian et al. (2016)'s work. These technologies are selected in the optimal mix for higher energy saving targets and related higher costs in this study.

New design improvements can reach the 40% energy savings target for each building type in all climate regions. This is not surprising given the stricter requirements in new building regulations. For a small number of cases, a maximum of 50% energy savings is still attainable though.

It should be noted that the optimal selection varies per building type, climate region and vintage. This is an important finding that can be used to offer guidance to the regulators, investors and construction industry about the best mix of technologies to accomplish a certain savings target per building type, climate region and vintage. For the retrofit of apartment buildings, adding proportional zoned thermostats as building energy management system and improving the infiltration is the best mix for colder climates (3rd, 4th and 5th Regions) to reach the 25% and 40% energy savings targets for all vintages. In warmer climates (1st and 2nd Regions), CFL bulbs and solar boilers are added to the mix for the same targets. This technology mix is applicable in the warmest climate region for a 50% energy savings target. A 75% energy savings target is only attainable in the coldest climate region (5th Region) for the vintage before 2000 by including all the technology types in the Turkish mix except DHW and PV systems. Improving the energy performance of the newly designed apartment buildings can have a maximum reach to a 40% energy savings target in all climate regions. Mostly window, wall and roof improvements are chosen in the mix with improved heating boilers, infiltration and CFL bulbs for this case. Newly designed single-family houses can reach 50% a energy savings target in all climate regions. In this case, the technology mix includes improved heating boilers with thermostats, improved infiltration, CFL bulbs, wall improvement types and solar boilers in all climate regions. Glazing improvement is added into this mix in the 4th and 5th climate regions. A 75% energy savings target is attainable for the retrofit of the single-family house in all climate regions for the vintage before 2000. For this case, the mix includes thermostat, improved infiltration types, CFL bulbs, roof-wall-window improvement types in all climate regions. Solar collectors are added to this mix for this target in warmer (1st and 2nd) climate regions. Daylight/occupancy sensor technology types are only enabled for the office building, and it is chosen in the mix for most retrofit and new building design cases for all vintages. This technology type is not in the mix for the retrofit of the office building in colder climates (3rd, 4th and 5th) regions for a 25% energy savings target and for a 40% energy saving target in the 5th region. For the retrofit of the office building daylight/occupancy sensor, improved infiltration and thermostats are the most used technology types for a 40% and 50% energy savings target. Solar boilers and improved glazing are added to the mix for warmer climate regions and for higher energy saving targets. Wall improvement is only selected by the optimization tool for the 75% energy savings target for the vintage before 2000.

It should be observed that contrary to Sağlam et al. (2017)'s results, PV panel systems are never found to show up in the optimal mix for retrofit or new design improvement of the three archetype buildings. The main reason for this is the high cost of the installation of these systems in the current Turkish market. The other reason is the achievement level restriction posed by the roof area. It is found that buildings do not typically have enough roof area to add PV panels to the solar thermal collectors which usually become part of the mix at higher saving targets. With the current low market pricing of solar thermal collectors versus PV panels, and given the relatively cold winters and resulting high heating loads, it is easily understood why PV does not enter the mix. However, Sağlam et al. (2017) showed that cost per square meter of solar collectors are higher than the PV panels in their work, and solar collectors did not become a part of the retrofit packages for any optimal solution in any climate. If PV panels became a part of the optimal mix, then a path would be achievable to transform the existing buildings into NZEBs in Turkey. However, Turkey as an EU candidate should detail the exact definition of NZEB according to national regulations and local climate data.

5. CONCLUSIONS

This research responds to the emerging mandate that every existing and new building in Turkey needs an energy certificate according. In addition, less dependence on energy is a priority for Turkey and reducing the energy consumed by buildings is an obvious way to meet that priority. Yet, no clear guidelines exist for the application of local retrofit technologies and what savings can be accomplished per invested lira with these technologies. This study offers the necessary guidance to make buildings in Turkey energy efficient within reachable targets, using established technologies and at affordable costs.

Three main building types in Turkey are optimized with a novel methodology to determine what technologies should be deployed to meet a given energy saving target. Building types are represented by archetypical buildings that are modified for different vintages and climate regions and subjected to simulation-based analysis. A list of applicable energy saving technologies with corresponding costs has been established and linked to the archetype simulation models. The resulting model is subsequently put into an optimization loop that finds the most cost-effective mix of technologies and their achievement levels given a saving target. This is diversified per building type and climate region, leading to the guidance for the improvement of new designs over the current code and retrofit of existing buildings.

Only a cross section of the outcomes of the study can be listed in this paper. It is expected that the graphs showing cost per energy saving, together with the optimal selection of technologies, provide crucial guidance for retrofitting and new design improvement of the buildings towards the broader objectives of the government, building regulators and investors. The practical use of the results by building owners and contractors is in developing retrofit proposals for individual building owners and municipalities that offer solid expectations of the technologies used and investments required. The results of this study can also play a role in the development of new specialties and technologies in the Turkish construction sector. Legislative authorities can follow up on this through the development of regulations towards high energy efficient buildings based upon a better recognition of the technologies and costs in the local markets.

The results can be used as a template for retrofit strategies and new design standards, differentiated for different building types and different Turkish climate regions. In addition, the methodology presented in this study could be applied and adapted to other countries, considering their national regulations with various building types and in different climate regions.

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