Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2018, Volume 6, Issue 4, pp 609-630

Evaluation of Sustainable Design Strategies Based on Defined Indexes at a District Level

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Cite as: Sözer, H., Kükrer, E., Evaluation of Sustainable Design Strategies Based on Defined Indexes at a District Level, J. sustain. dev. energy water environ. syst., 6(4), pp 609-630, 2018,
DOI: https://doi.org/10.13044/j.sdewes.d6.0208

ABSTRACT

In this research paper, design strategies of retrofitting activities were evaluated based on specified district sustainability indicators. The main objective is to identify the existing conditions of the selected district within the scope of applied indexes to develop new strategies for retrofitting. The district is represented by 3 buildings with 20,000 m^2 conditioned area which contains similar building characteristics as remaining residential buildings in the city. Accordingly, energy models of selected buildings were created and analyzed where hourly dynamic simulation tool was used to assess energy indicators. The intention is to have detailed calculations of the energy index with reference to indoor comfort, greenhouse gas emission and the economical index with reference to return on investment. The findings of this assessment reveal a number of significant implications for the improvement of the overall building performance. The most explicit finding of this study is to show that 65% energy saving, correspondingly 69 kg/m^2year greenhouse gas emission reduction with 5.16 years return on investment can be achieved by the well-defined and precisely calculated district sustainability indicators.

KEYWORDS

Sustainability, District sustainability indicators, Renewable energy integration, Energy efficiency.

INTRODUCTION

Rapid urbanization has greatly accelerated energy consumption growth and created various environmental problems from the local to the global scale [1]. According to International Energy Agency statistics, global total primary energy supply has increased by 150% between 1971 and 2014 [2]. What is worse, energy consumption is mainly dependent on fossil fuels by 82% [3]. Moreover, buildings are responsible for more than 40% of global energy use and correspondingly one third of greenhouse gas emissions [4]. Consistently, in Turkey, where the case district is located, residential consumption covers nearly 31% in national energy consumption [5]. In this context, sustainability in the city environment is one of the most promising topics for obtaining efficient and long-term solutions to energy and environmental problems [6]. Therefore, it becomes very critical

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to evaluate the building design decisions within well-defined District Sustainability Indicators (DSI) to minimize their environmental effects correspondence to energy, economic and indoor comfort conditions.

Several strategies have been obtained based on various studies on defining indicators, identifying their importance and evaluating their effects based on created scenarios within the characterized districts. Neves and Leal [7] presented a research review concerning the role of indicators in energy planning. In the study, local energy sustainability indicators are evaluated with testing of the selected sustainability indicators with pilot municipalities. In the study, 18 indicators are considered such as energy intensities, Greenhouse Gas (GHG) emission emissions from energy use or renewable energy share. As a conclusion, a detailed framework of local energy sustainability indicators is proposed. Uihlein and Eder [8] investigate EU-27 stock models to assess not only the possible environmental impact in the field of energy and GHG emissions, but also cost. The study emphasizes that residential building renovation strategies such as replacement of existing glazing and roof with better thermal properties and concludes with their effect on increasing energy efficiency and reducing Carbon dioxide (CO_2) emissions by 30%. Additionally, the net costs are found out to be negative after 25-30 years, in economic assessment.

Similar approaches are applied to selected researches although comprehensive data is provided about the buildings by focusing on a specified case building instead of a buildings' group. Gallachoir *et al.* [9] investigate simple performance indicators to evaluate buildings' energy performance and trends via a case study. Zavadskas *et al.* [10] address an approach to determine the retrofit effectiveness of the houses on the basis of both expected energy savings and market value of retrofitted buildings. In the study, a set of retrofit scenarios is developed for various districts and saving to investment ratios are compared for each scenario. Similarly, Pikas *et al.* [11] consider the possible office building design solutions, not only in the sense of energy efficiency but also cost optimality. The research also takes into account alternative measures to reach nearly zero energy buildings' level and recommends design guidelines for office buildings in order to obtain sustainability in the office buildings in a district. Kılkış *et al.* [12] analyse two building clusters in campus area, with four different energy supply scenarios that include renewable systems. The study is carried out on the basis of exergy analysis and results are compared in terms of energy and environmental index. The scenarios showed 9.6 GWh energy savings and 2,663 tons of CO_2 reduction are achievable.

Moreover on a bigger scale, Samuelson *et al.* [13] study high-rise residential buildings in urban context by applying different strategies. In the research, more than 90,000 simulations have been carried out including various windows to wall ratios, orientation, glass type, building shape and wall insulations. Parametric results have been compared and revealed the significance of pre-design decisions on building energy performance.

The results of the calculated indicators are evaluated in more inclusive way by Choon *et al.* [14]. The set of indicators are formed to develop in the scope of sustainability assessment specifically for the major cities of Malaysia [14]. The numerical performances of the cities highlight weaknesses and strengths as represented in the research of Passer *et al.* [15]. In an additional quantitative study, the energy consuming parameters and the interventions are pre-defined with their quantitative data in kWh unit in the existing structure [16]. Also, the relationship of interventions as variables and weight are explained in detail by Gouveia *et al.* [17]. With a different approach, conceptualization of the use of indicators taken into consideration in an analytical framework is applied further in an actual indicator system by Gudmundsson *et al.* [18].

Alternatively, analyzing a single building for sustainability provides further detailed information about building characteristics. For example, Marjaba *et al.* [19] identified the effect of selected sustainability indicators in building level to see their impact to each other. Likewise, in another research, sustainability indicators are designed according to semi quantitative model of simulation that is led by experts who judge the impacts of indicators to the total and to each other [20]. Also, building level identification gave chance to analyze the technology integration and its impact on sustainability. It is indicated that new technologies in building retrofitting can save up to 40% of primary energy demand and related emissions [21]. Building energy performance is lowered by building users on calculated energy consumption. However, it is important to know which indicators are used to obtain energy efficiency which leads the building use towards sustainability [22]. In fact, the decrease of the energy consumption of energy conservation measures reflects the effects of interventions [23].

In order to have a greater impact, sustainability indicators for each district should be identified precisely in both building level and district level as conducted in this research. Accordingly, energy models of selected buildings were created and analyzed where hourly dynamic simulation tool was used to assess energy indicators. The intention of these is to have detailed calculations which derived accurate results of the energy indicator with reference to GHG emission and the economic indicator with reference to the return on investment respectively.

DISTRICT SUSTAINABILITY INDICATORS

Sustainability has been one of the most discussed topics in our days. Yet, its origin relies on a report of the World Commission on Environment and Development which states that “sustainability is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [24]. In sustainable development, districts are considered as one of the most promising fields. In this regard, DSI take a significant place in the sustainable development [25]. The indicators can be used to assess both the present situation and also future implications planned for the district. When choosing the indicators, extensity and measurability should be taken into consideration [26]. In order to analyze the ability of urban ecosystem an index system must be formed to examine the effects of the combination of different sustainability indexes [27]. Sustainable development in cities does not regard only one exact point of view. Comprehensive approach from different topics should be taken into account to promote healthy urban development together with the environment [28]. Renovation projects usually do not simply target to reduce energy consumption of the buildings, rather target the improvement of comfort level, while decreasing negative environmental impacts [29]. The reduction of long term costs should be considered along with the health of residents in the renovated building [30]. The valuation of the selected indexes comprises the degree of their importance while balancing different systems of indexes [31].

The indicators calculated in this study are to provide simplified aggregated information for urban planners to take relevant precautions against possible setbacks and to progress towards national and international sustainable goals [32]. District sustainability indicators can be discussed under various titles. Mainly the indicators are investigated in energy, economy, comfort, social, environmental and urban scales in many research and guidelines [33].

As this paper aims to represent, each indicator must be identified appropriately at the precise stage when carrying out a renovation process in the district scale. Hereafter, all indicators that are considered in the scope of DSI for energy, economy, environment, and comfort, and their subcategories are represented in Table 1.

Table 1. List of the considered DSI

Indicators		Description	Unit
Energy	EN1	Final energy demand and consumption	[kWh/m^2]
	EN2	Density of final energy consumption	[kWh/m^2]
	EN3	Peak load of the electricity demand	[kW]
	EN4	Peak load of the thermal demand	[kW]
Economy	ECO2	Return on investment	[year]
Environment	ENV1	GHG emissions	[kg/m^2]
Comfort	CO1	Predicted mean vote	[-]
	CO2	Percentage of people dissatisfied	[%]
	CO3	Percentage of outside range	[%]

Energy indicators

Energy indicators are significant when addressing the energy consumption of a district. In the literature, energy indicators in residential sector vary according to main aim and scope of the application. Thus, mainly energy demand and consumption, peak energy demands [34], energy policies and energy managements are categorized as significant indicators in various researches [35].

In this study, energy indicators are investigated in four different titles, final energy demand or consumption, density of final energy consumption, peak load and load profile of the electricity demand and peak load and load profile of the thermal demand. In the city scale, energy indicators' calculation methods are defined in CONCERTO Premium indicator guide which is a funded project by EU under the research framework program. This guide provides mathematical description of aggregated indicators and standardizes different types of indicators by providing an indicator area [33].

<u>EN1: Final energy demand and consumption [kWh/m^2]</u>. Final energy demand or consumption DSI is referred to the final energy uses of the energy for different areas of application within the buildings and correspondingly the district. Energy consumption of the buildings in a district is composed of four components:

- Space heating (AA1);
- Space cooling (AA2);
- Domestic Hot Water (DHW) heating (AA3);
- Electrical appliances (AA4).

Final energy demand covers all the above-mentioned components. The indicator is used when assessing the energy efficiency of the building. Final energy demand or consumption of the building can be represented using following approach as given in CONCERTO Guidelines [33]:

$$EN_{I,t} = \frac{\sum_{i,EI} EN_{i,t} \times Cap_I}{Cap_I} \tag{1}$$

where $EN_{I,t}$ is the final energy demand/consumption of set I of buildings based on annual data of year t [kWh/m^{2}year], $EN_{i,t}$ is the final energy demand/consumption of building i based on annual data of year t [kWh/m^{2}a] and Cap_I is the area or number of set I of buildings I [m^2].

The variable notation for the set of buildings is denoted as I and for one building is denoted as i.

EN2: Density of final energy consumption [kWh/m^2]. Density of final energy consumption corresponds to the ratio of final energy demand for heating, cooling and DHW annually. When evaluating density of final energy consumption, total energy consumption is divided into total conditioned floor area as in eq. (2) [33]:

$$DEN_{\mathrm{EC},I,t} = \frac{\sum_{\mathrm{AA=AA1}}^{\mathrm{AA4}} In_{\mathrm{EC,AA},I,t}}{Cap_I} \tag{2}$$

where $DEN_{\mathrm{EC},I,t}$ is the density of final energy demand/consumption of a set I of buildings in year t regarding Energy Carrier EC [kWh/a], $In_{\mathrm{EC,AA},I,t}$ is the input (> 0) energy flow into set I of buildings for application area AA in year t regarding EC [kWh/a] and Cap_I is the area or number of set I of buildings I [km^2 territory area, buildings].

As depicted in CONCERTO Premium Guide, density of final energy demand can be evaluated in a set of buildings.

EN3: Peak load and load profile of electricity demand [kW]. As well as district's final energy consumption, peak loads are significant since the building applications must be designed to cover the peak loads. The load profile describes the demand characteristics over time and can be given as in eq. (3) [33]:

$$LP_{I,\mathrm{EC=electricity},t,\Delta t_k} = \frac{\sum_{\mathrm{AA1}}^{\mathrm{AA4}} In_{\mathrm{EC,AA},I,\Delta t_k}}{\Delta t_k \times 8{,}760} \tag{3}$$

where $LP_{I,\mathrm{EC=electricity},t,\Delta t_k}$ is the load of set I of buildings regarding EC = electricity in Δt_k $(k = 1, \ldots, k)$ as part of a partition of year t [kW], $In_{\mathrm{EC,AA},I,\Delta t_k}$ is the input (> 0) energy flow into set I of buildings for application area AA in Δt_k $(k = 1, \ldots, k)$ as part of a partition of year t [kWh/y].

Peak load corresponds to a sustained period in which instant energy consumption reaches the highest values and is as given in the following equation:

$$LP_{I,\mathrm{EC=electricity},t,\max} = \max_{k=1,\ldots,k}\left(LP_{I,\mathrm{EC=electricity},t,\Delta t_k}\right) \tag{4}$$

where $LP_{I,\mathrm{EC=electricity},t,\max}$ is the peak load of a set I of buildings regarding EC based on a partition of year t [kW], $LP_{I,\mathrm{EC=electricity},t,\Delta t_k}$ is the load of set I of buildings regarding EC = electricity in Δt_k $(k = 1, \ldots, k)$ as part of a partition of year t [kW].

EN4: Peak load and load profile of thermal demand [kW]. Parallel to electricity peak loads and load profiles, thermal load profiles and peak loads are evaluated using a similar methodology. Thermal load profile is represented in eq. (5) [33]:

$$LP_{I,\mathrm{AA},t,\Delta t_k} = \frac{\sum_{\mathrm{EC}} In_{\mathrm{EC,AA},I,\Delta t_k}}{\Delta t_k \times 8{,}760} \tag{5}$$

where $LP_{I,\mathrm{AA},t,\Delta t_k}$ is the load of set I of buildings regarding application area AA in Δt_k $(k = 1, \ldots, k)$ as part of a partition of year t [kW], $In_{\mathrm{EC,AA},I,\Delta t_k}$ is the input (> 0) energy flow into set I of buildings for application area AA in Δt_k $(\mathrm{k} = 1, \ldots, \mathrm{k})$ as part of a partition of year t regarding EC [kWh/y].

Similarly, thermal peak load can be written as follows:

$$LP_{I,\mathrm{AA},t,\max} = \max_{k=1,\ldots,k}\left(LP_{I,\mathrm{AA},t,\Delta t_k}\right) \tag{6}$$

where $LP_{I,\mathrm{AA},t,\max}$ is the peak load of a set I of buildings regarding application area AA based on a partition of year t [kW], $LP_{I,\mathrm{AA},t,\Delta t_k}$ is the load of set I of buildings regarding application area AA in Δt_k $(k = 1, \ldots, k)$ as part of a partition of year t [kW].

Economic index

Economic index is thought as one of the critical issues especially when building renovation is addressed [19]. In this study, the index is assessed through the combination of different economic investments which aims to predict economic analysis of the investments causing energy savings or energy production in comparison to baseline status. Accordingly, economic indicators are investigated in two indicators, investments and return on investment.

ECO1: Investments [EUR/m^2]. Investments correspond to the cost of the retrofitting interventions. ECO1 index is given in the terms of the size of retrofitted buildings such as net floor area or heated/cooled area in order to improve the comparability. ECO1 is calculated using the approach as given in eq. (7) [33]:

$$\bar{I}_{i,t1} = \frac{I_{i,t1}}{Cap_i} \tag{7}$$

where $\bar{I}_{i,t1}$ is the specific investment for building i, construction start in year $t1$, construction end in year $t2$, investment is discounted to year $t1$ [EUR/m^2], $I_{i,t1}$ is the investment for building I, construction start in year $t1$, construction end in year $t2$, investment is discounted to year $t1$ [EUR] and the Cap_i is the floor area of building i [m^2].

ECO2: Return on investment (year). Return on Investment (*ROI*) represents the benefit of the investment in the retrofitting activities by taking the actual lifetime of the retrofitting intervention into account. It is calculated by dividing the net profits of the intervention by the initial investment of the cost. *ROI* is calculated through eq. (8) [33]:

$$ROI = \frac{\sum E_\mathrm{s} + \sum C_\mathrm{OM} - I_{i,t1}}{I_{i,t1}} \tag{8}$$

where $\sum E_\mathrm{s}$ is the total energy savings for building i [EUR], $\sum C_\mathrm{OM}$ is the total operation and maintenance costs for building i [EUR] and $I_{i,t1}$is the investment for building i, construction start in year $t1$, construction end in year $t2$, investment is discounted to year $t1$ [EUR].

Environmental index

The environmental index considers the environmental performance of the district related to GHG emissions. Since increasing GHG emissions, and correspondingly global warming, are reaching alarming rates, environmental index in the district scale have gained importance. In this regard, GHG is addressed as an environmental index.

ENV1: GHG emissions [kg/m^2]. GHG emissions of the districts are composed of the emissions which are caused by different areas of the application such as space heating and cooling, DHW production and electricity use. GHG can be calculated using the approach given in eq. (9) [33]:

$$EM_{I,\mathrm{M},t} = \frac{\sum_{i,eI} \; EM_{i,\mathrm{M},t} \times Cap_i}{\sum_{i,eI} Cap_i} \tag{9}$$

where $EM_{I,\mathrm{M},t}$ are the emissions of material M by set I of buildings based on annual data of year t [t/m^{2}year], $EM_{i,\mathrm{M},t}$ are the emissions of material M by building i based on annual data of year t [t/m^{2}year] and the Cap_i is the floor area of building i [m^2].

In eq. (9), material M corresponds to CO_2 or CO_2 equivalent.

Comfort index

Today, as environmental and economic issues are considered as one of the most challenging problems, many researches emphasize mostly energy efficiency. However, as well as enhancing energy efficiency, thermal comfort of occupants is another issue which should be taken into consideration. As presented in many researches, people spend roughly 90% of their time indoors [36]. Based on this, health effects on indoor environmental quality is a significant issue in design and evaluation processes. Accordingly, three comfort indicators are addressed, predicted mean vote, predicted percentage of people dissatisfied and percentage of outside range.

Because case building is not being used, applications of survey for the residents' satisfaction were not possible to apply. Therefore, theoretical methods are applied to find the satisfactory level of the residents.

CO1: Predicted mean vote. Predicted Mean Vote (*PMV*) is a term which is developed by Fanger [37] and considered as a representative indicator for thermal comfort of occupants. Thermal comfort is achieved when the heat generated by a human body can dissipate, namely, when the thermal equilibrium with the surrounding is maintained. Factors influencing thermal comfort are heat conduction, convection, radiation and evaporative heat loss [37].

Fanger developed a system of equations which combines the effect of the six parameters in a single functional relationship to determine an indicator called *PMV*. *PMV* formula is given in eq. (10) [37]:

$$PMV = (0.303 \times e^{-0.114\,M} + 0.0275) \times L \tag{10}$$

where L is defined as the difference between the rate of metabolic heat generation and the calculated heat loss from the body to the actual environmental conditions assuming these optimal comfort conditions, with:

$$\begin{aligned} L = {} & q_{\mathrm{met,heat}} - f_{\mathrm{cl}} h_{\mathrm{c}} \times (\theta_{\mathrm{cl}} - \theta_{\mathrm{air}}) - f_{\mathrm{cl}} h_{\mathrm{r}} \times (\theta_{\mathrm{cl}} - \theta_{\mathrm{r}}) - 156 \times (W_{\mathrm{sk}} - W_{\mathrm{a}}) \\ & - 0.42 \times (q_{\mathrm{met,heat}} - 18.43) - 0.00077M \times (93.2 - \theta_{\mathrm{air}}) \\ & - 2.78M \times (0.0365 - W_{\mathrm{a}}) \end{aligned} \tag{11}$$

where *PMV* is the predicted mean vote, scale $q_{\mathrm{met,heat}} = M - w$, M is the rate of metabolic generation per unit DuBois surface area [Btu/h ft^2], w is the human work per unit DuBois surface area [Btu/h ft^2], f_{cl} is the ratio of clothed surface area to DuBois surface area [$A_{\mathrm{cl}}/A_{\mathrm{D}}$], h_{c} is the convection heat transfer coefficient [Btu/h ft^2 °F], θ_{cl} is the average surface temperature of clothed body [°F], θ_{air} is the air temperature, h_{r} is the radiative heat transfer coefficient [Btu/h ft^2 °F], θ_{r} is the mean radiant temperature [°F or °R], W_{a} is the air humidity ratio and W_{sk} is the saturated humidity ratio at the skin temperature.

The humidity ratio of the air in equilibrium with the skin under comfort conditions, $W_{\mathrm{sk,req}}$, is the saturated humidity ratio evaluated at the required skin temperature.

CO2: Predicted percentage of dissatisfied [%]. The Predicted Percentage Dissatisfied (*PPD*) index is derived from the *PMV* index and predicts the percentage of thermally dissatisfied persons among a large group of people. It should be noted that the minimum reachable *PPD* is 5%, even when the result is a neutral thermal sensation ($PMV = 0$) since it is not possible to satisfy everyone due to the inter-individual differences.

Fanger introduced the index of *PPD* as a quantitative measure for the thermal comfort of a group of people at a particular thermal environment. Fanger [37] related the *PPD* to the *PMV* in eq. (12):

$$PPD = 100 - 95\, e^{-\left(0.03353 \times PMV^4 + 0.2179 \times PMV^2\right)} \tag{12}$$

CO3: Percentage outside range [%]. The percentage outside range is defined as the period of time (*T*) in which indoor local thermal comfort is outside of the desired range according to the target category. Namely, it refers to discomfort hours (which is defined in CO3) percentage in a year (8,760 hours) [37].

Other indexes, which are not in the scope of this work

Besides with pre-mentioned indexes, there are other indexes that might be considered in the district scale such as social and urban indexes. Social indicators include socio-demographic features, housing, GDP level, employment and accessibility. Moreover, impact of the pedestrian public spaces and transport can be investigated in urban index. Yet, since it is not directly in the scope of this study, mentioned indicators were not addressed.

CASE STUDY

In order to evaluate district sustainability, Yakacik district of Kartal is selected as a case study in the research. The three residential types of buildings are introduced while a statement that these buildings will be treated as a set of buildings as represented with *I* in the above formula for the following analyses. All three building blocks were built and used as residential buildings. Location of the case study is given in Figure 1.

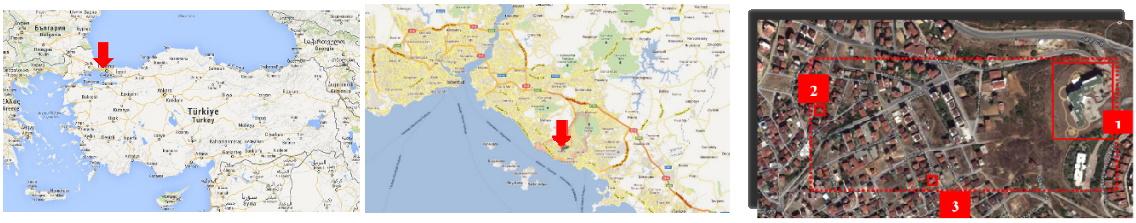

Figure 1. Location of the case study and representative buildings

The morphologic features of the selected area are mostly hilly and the average height above sea level is 190 meters. Istanbul has a mild weather, the winters are mostly rainy, with the temperatures in the range of 5-8 °C. Whereas, summers are warm and dry around averagely 25-30 °C. The monthly climate conditions of Kartal are given in Table 2, below.

Although, evaluations were done on three buildings to represent the district of a residential neighborhood, retrofitted conditioned area covers up to 20,000 m^2 as shown on above figure. Besides, selected buildings especially, Building 2 and Building 3 have very similar building characteristics with other residential in the district, which represent 70% of the residential buildings in Kartal municipality of Istanbul.

Three of the selected buildings were constructed as concrete blocks. Building 1 is the largest building with 8 stories, whereas Building 2 and Building 3 have five and four stories respectively. Building 1 has very poor external wall insulation while the other two buildings show appropriate insulation. Existing conditions of each building was investigated and a summary of the collected data is represented below.

Table 2. Monthly climate data of Kartal [38]

Istanbul/Kartal	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
	Average monthly temperatures between years 1950-2014											
Average temperature [°C]	5.6	5.7	7.0	11.1	15.7	20.4	22.8	23.0	19.7	15.6	11.4	8.0
Average highest temperature [°C]	8.5	9.0	10.8	15.4	20.0	24.5	26.5	26.7	23.6	19.1	14.7	10.8
Average lowest temperature [°C]	3.2	3.1	4.2	7.7	12.1	16.5	19.5	20.0	16.8	13.0	8.9	5.5
Monthly average rainy day	17.5	15.2	13.8	10.4	8.1	6.0	4.2	4.9	7.3	11.2	13.3	17.3

Building type 1

The building block 1 was built as an elderly home in 2005. The total conditioned floor area in the building is 18.110 m^2.

Building envelope. The existing building walls have two different characteristics:

- External walls of the resident rooms are insulated with 5 cm low density Expanded Polystyrene (EPS), yet, in most of the rooms material is either damaged or in a bad condition;
- External walls of the common spaces such as restaurants, corridors or lobbies do not have any level of thermal insulation.

Building has a pitched roof with asphalt based water insulation and EPS thermal insulation. There are different types of windows in terms of glass and window frame depending on the area of the building. Residential rooms are equipped with double glazed windows with aluminum frame and common areas have double glazed windows with vinyl frame. Residential rooms have also curtains to protect from extra solar radiation and heat gain as well as to respect residents' privacy.

Mechanical systems. Two-pipe fan-coil units are used for heating and cooling purposes in the entire building. In addition to these systems, air handling units are used for heating, cooling & ventilation in the restaurant (located on fifth floor), in the swimming pool and the conference room (located on first basement floor).

Electrical systems. Common spaces use fluorescent lamps while bedrooms use incandescent lamps. Fire protection sensors and electrical boards are located on each unit.

Building type 2

The building type 2 has five floors and hosts one residential unit at each floor (20 inhabitants live in the building). Each apartment unit is 99 m^2 while the staircase and elevator have an area of 40 m^2, thus the total floor area of one building is 139 m^2. The total conditioned floor area of the building is 396 m^2. The insulation is applied on the building envelope. Heating is supplied by natural gas with individual heating units and no cooling technologies are applied. The building uses incandescent lighting systems.

Building type 3

The building type 3 has four floors (3 typical floors, one basement) and hosts one residential unit for each floor (16 inhabitants live in the building). An apartment unit is 103 m^2 and the staircase and elevator have an area of 40 m^2, thus the total floor area of one building is 143 m^2. The total conditioned area is 309 m^2. The building envelope is insulated. Conditioning is provided with individual heating units and no cooling technologies are applied. The building uses incandescent lighting systems.

Renovation activities

In the context of district renovation activities, a set of Energy Conservation Measures (ECM) are applied to the mentioned buildings in the district. Eight interventions are considered for Building 1 (Elderly house) which are:

- Thermal insulation;
- Radiant heating and cooling;
- Solar thermal systems;
- Building appliances and LED lighting systems;
- Energy automation and monitoring system;
- Replacement of windows;
- Appliances of water saving systems;
- Heat pump systems.

In addition to elderly house, for Building 2: thermal insulation and solar thermal system; for Building 3: thermal insulation, solar thermal systems and LED strategies are considered.

Energy analysis of the district was carried out in dynamic simulation modelling software e-Quest [39]. All factors that affect heating/cooling loads were modelled comprehensively to get precise results for energy consumption. Building geometries, weather conditions, Heating, Ventilating and Air Conditioning (HVAC) systems, internal loads, operation strategies and schedules were defined in e-Quest. Specifications of mentioned components were estimated based on the existing condition of the buildings. It should be noted that in the building system configuration not only selecting the right system, but also configuring the system compatibilities is significantly important. With convenient systems and accordingly optimizations, energy index of the buildings, consequently, energy index of the district is improved.

After the generation of energy model for all buildings representing the district, results were evaluated for both existing condition and renovated condition in which all interventions are applied. The comparison can be seen from Table 3 and Figure 2.

Table 3. Energy consumptions for existing and final case

	Existing	After interventions	Savings [%]
Heating/cooling consumption	Boiler & chiller	Heat pump systems	67.5
DHW consumption	Hot water boilers	Solar thermal system	43.2
Lighting consumption	Incandescent lamps	LED	84.8

Given in Table 3 and Figure 2, applied interventions have a major effect on both heating/cooling, DHW and lighting energy consumption. Especially, renewable system integration leads to a significant reduction in the energy consumption of the district. Yet, with application of new system, heating was completely covered by integrated renewable systems. On the one hand, integration of heat pump system has reduced total annual energy consumption by 10.2%, but on the other hand, it has led to an increase electrical energy consumption. Especially the pump consumption has increased by 58%. Also DHW need of the selected buildings is utilized by solar thermal systems and air source heat pump systems which also lead to 43% decrease in annual energy consumption as it is indicated in Figure 2.

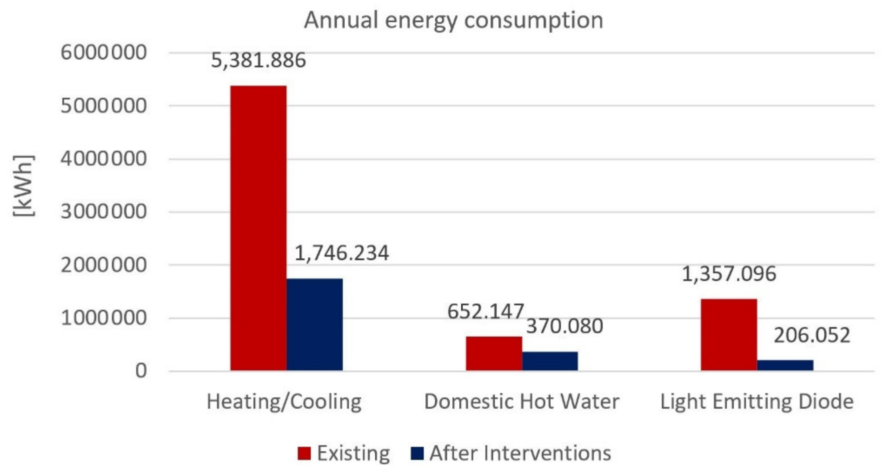

Figure 2. Energy consumptions for existing and after interventions case

Evaluation of indicators

All the above mentioned indicators within the energy, economic, environmental, comfort are calculated for existing and after interventions conditions for the selected district.

<u>EN1: Final energy demand and consumption</u>. As summarized previously, final energy demand and consumption indicator includes, space heating, space cooling, DHW heating and electrical appliances consumption of all buildings in the district with respect to per building area. Final energy demand of the district is evaluated by taking into consideration energy consumption components. Accordingly the profile of the buildings for existing and after intervention cases are given in Figure 3a. The achieved reduction after interventions on final energy demand and consumption is 48.3%.

<u>EN2: Density of final energy consumption</u>. As another sustainability indicator, density of final energy consumption of the district is evaluated based on the formula given in eq. (2). Differently from final energy consumption, density of final energy consumption corresponds to the average consumption of the district. Therefore, it is regarded as average consumption value of the three case buildings in per building area for existing and after intervention cases and given in Figure 3a below. The reduction after interventions on density of final energy consumption is 64.7%.

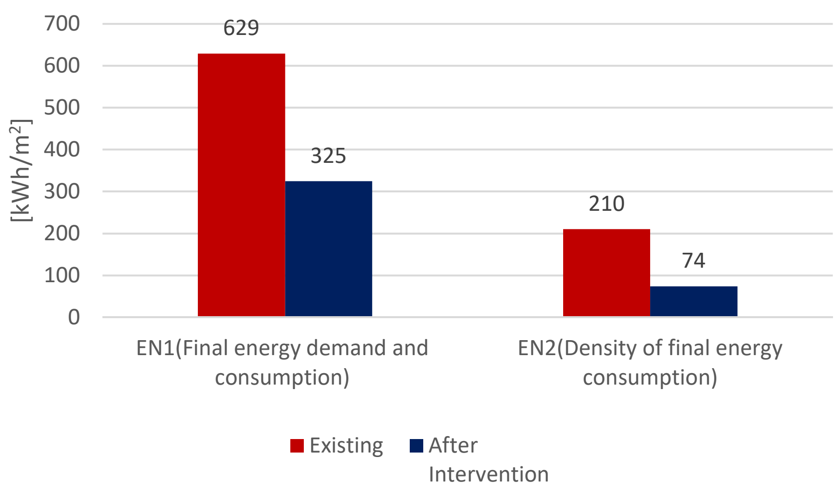

Figure 3a. Comparison of indicators EN1 and EN2

EN3/EN4: Peak load of the electricity and thermal demand. As well as demand and consumption, calculating peak loads precisely is important when investigating the district's energy indicators. When assessing the peak loads of the given buildings, loads and energy flow into set of buildings are considered. Results are taken from annually dynamic energy analysis. Thus, peak load profiles for electricity and thermal demands are evaluated for both existing and after intervention cases and represented in Figure 3b. The reduction after interventions on peak load profile of electricity demand is 7.3% while reaches up to 90.7% on peak load profile of thermal demand.

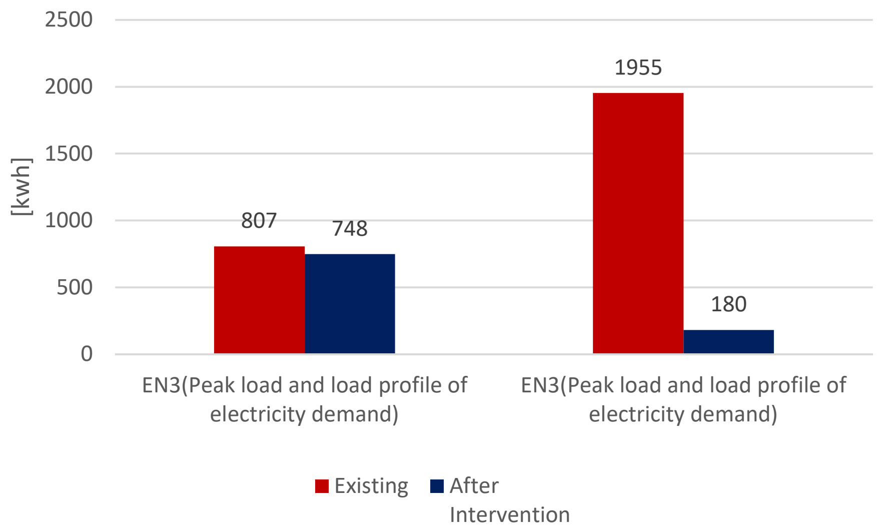

Figure 3b. Comparison of indicators EN3 and EN4

ECO1: Return on investment. As an economic indicator, *ROI* of the interventions is calculated. To calculate the *ROI* rate, firstly investment quantity, then cost savings on operational energy are calculated. Investment for all renovation works in district is assessed as 120.24 EUR/m^2. Investment cost is evaluated based on the application costs applied to the selected buildings. Cost of each application is given in Table 4 below from highest to lowest. The entire building façade of all three buildings are renovated by the application of insulation, while only problematic windows and water fixtures are replaced. Similarly, all lighting fixtures are replaced by LED lighting while the application of the solar thermal are done based on availability of the roof area. The calculation of building's energy performance is done precisely to evaluate the capacity of the heat pump to eliminate the cost of oversizing.

Table 4. Cost of investments

Intervention	Cost (EUR)
Building envelope and façade systems	666.834
Heat pump installation	651.360
Windows glazing	446.372
LED lighting application	402.372
Automation & monitoring system	364.553
Solar thermal appliances	62.401
Water efficient fixtures	37.661

As far as operational energy cost is concerned, both natural gas and electricity consumption of buildings are taken into consideration according to Turkish Electricity Distribution Corporation (TEDAS) and Istanbul Gas Distribution Industry and Trade Inc. (IGDAS). IGDAS's current data for electricity and natural gas tariff, both operational energy cost is evaluated for existing and final case and represented in the Figure 4 [40]. The saving from operational costs is 218.113 EUR per year.

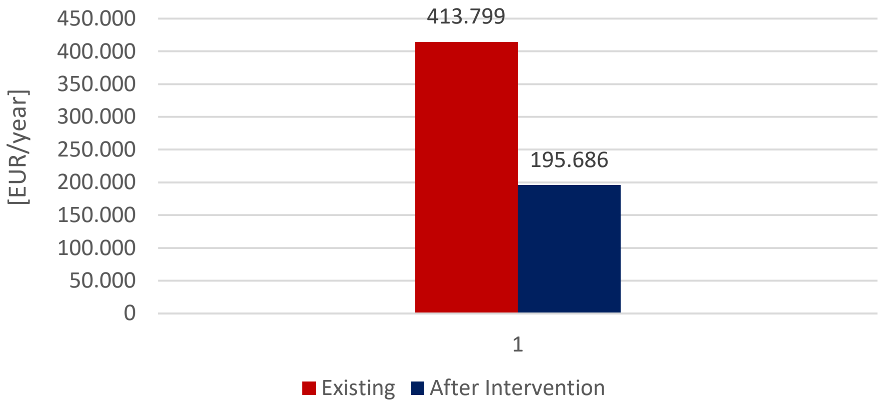

Figure 4. Cost of savings on operational energy indicator

Based on the calculation of methodology identified in eq. (7), *ROI* for interventions is calculated as 5.16 years. All of the investments for the interventions are done during the first month the construction started. The implementations of interventions are completed within a year.

ENV1: Greenhouse gas emissions. As an environmental indicator, greenhouse gas emissions are evaluated for both existing and renovated cases. Greenhouse gas emissions are caused by different areas of applications. Therefore, when the indicator is calculated, each consumption component's (i.e heating, cooling, ventilation) contribution to the greenhouse gas emission production is assessed separately. Results are given in the terms of kilograms of CO_2 production in per meter square and can be seen in Figure 5.

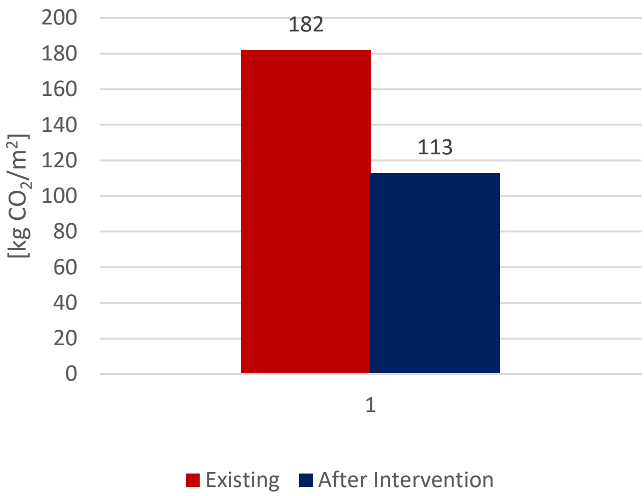

Figure 5. Greenhouse gas emissions indicator

Interventions have major effect on the greenhouse gas emissions released. Yet, it should be also noted that, air quality is another issue that should be taken into consideration as far as environmental index is concerned especially in the city scale. According to researches, CO_2 concentration in Istanbul is between 370-440 ppm depending on the both green areas and environmental factors [41]. With the strategies, it is possible to reduce CO_2 emissions by 38%, which causes positive effect on the outdoor air quality of the region. With the implementation of aforementioned interventions it is foreseen that CO_2 concentration in the district can be kept between 350-400 ppm. In addition to outdoor air quality, detailed explanation of air quality for the indoor conditions are given below, comfort index.

CO1: Predicted mean vote. As far as comfort is concerned, three indicators are evaluated for the district. Given in the identification of the indicator, *PMV* is determined based on the estimated metabolic rate, the clothing insulation, and performance indicators: the measured or predicted air temperature, mean radiant temperature, relative air velocity and air humidity. To evaluate the CO1 indicator, each of these parameters was defined based on the indoor comfort conditions [42]. As mentioned before, since case building is not in use, application of surveys is not possible in this case. Thus, with dynamic hourly simulation tools, thermal performance indicators of a building or a specific zone can be evaluated.

In *PMV* calculation, Design Builder [43] offers dynamic calculation of *PMV* scale according to Fanger's approach. To do this, physical conditions of structural elements and site-specific conditions (i.e., weather, solar irradiation, orientation, etc.) were integrated to the simulation model. Apart from this, thermal activity and average clothing values are defined to model. Using mentioned variables, Design Builder calculates *PMV* values both as a distribution for whole year and on average as well.

For the district, a simplified model of each building was created in Design Builder. According to Design Builder simulation model, *PMV* distribution amongst year was evaluated for each building for existing and the final case. Results are presented in Figure 6.

CO2: Percentage people dissatisfied. Based on the CO1 indicator, percentage of people dissatisfied is also investigated. *PPD* comparison of existing case and final status is given in Figure 6. Results show that implementation of all interventions has improved the indoor conditions since percentage of dissatisfied people are reduced from 18 to 15%.

CO3: Percentage outside range. Lastly, percentage outside range indicator is evaluated for existing and final cases. CO3 indicator corresponds to the percentage of discomfort hours during a years' time (8,760 hours). For the district, CO3 indicator is calculated in Design Builder taking PMV rates on the basis annually. According to Fanger and ISO 7730 Ergonomics of the thermal environment [44] thermal comfort is ensured in range of "$-0,5 < PMV < +0,5$" values. Therefore, exceeded hour percentages are referred as discomfort hours. Results are represented in Figure 6 as follows.

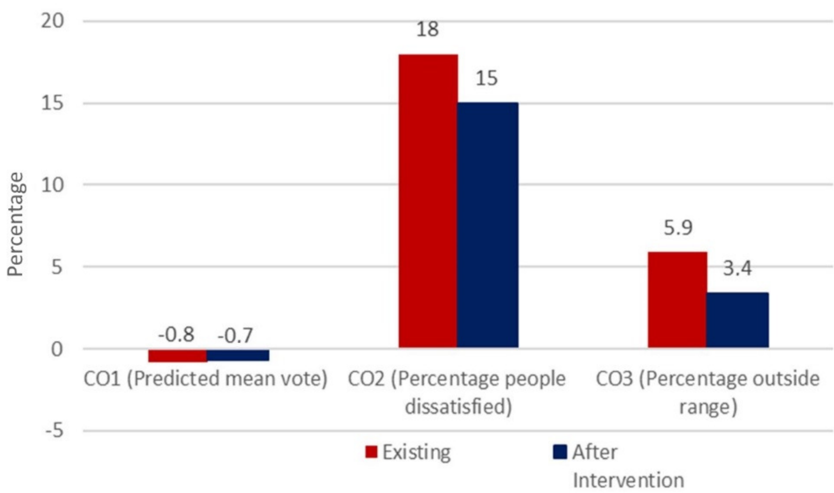

Figure 6. Comparison of comfort indexes

RESULTS AND DISCUSSION

A selected district from Kartal municipality was evaluated in the terms of energy, economic, environmental and comfort indicators to see the effect of interventions applied in the district. As calculated methods and their results discussed in this research, each indicator was addressed separately. Comparison was made between the existing case in which no intervention was applied in the selected buildings and final case which included all interventions. Consequences of the results from their comparison are given below.

Energy indicators

In the study, four different energy indicators were identified and evaluated, final energy demand and consumption, density of final energy consumption, peak load of the thermal and electricity demand. Results for existing and final case were represented in the Figure 7.

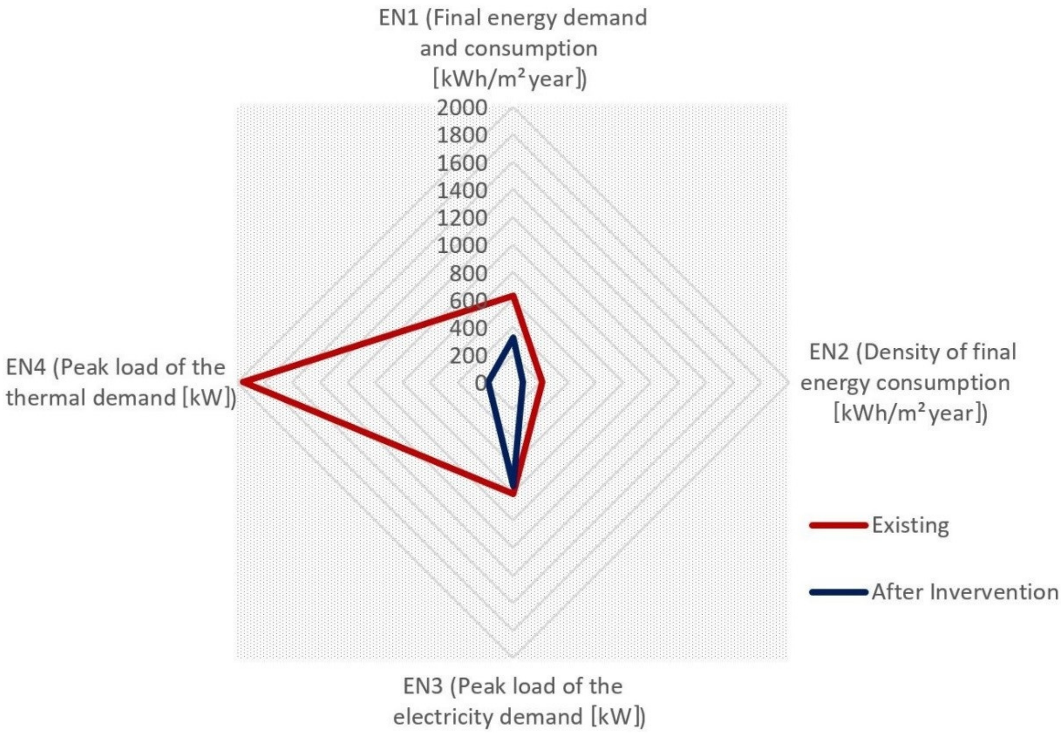

Figure 7. Comparison of energy indicators for existing and final case

As shown in Figure 7, interventions had significant impact on the energy indicators. Especially EN4, peak load of the thermal demand was reduced dramatically by 90.7%, due to the integration of the heat pump system to the Building 1. Since heat pump consumes electricity to utilize heating to the building, peak load of the thermal demand was decreased. In the final case, only DHW was supported by the natural gas boilers, accordingly natural gas consumption was rather low. Yet, in the baseline case all the heating had been covered with the conventional boilers that work with natural gas. In consequence of geothermal and air source heat pump installation, thermal peak load of the district was reduced substantially.

On the other hand, EN3, peak load of the electricity made only limited progress with 7% improvement. Even though, lighting interventions contributed peak load of the electricity positively, it was also affected by the integration of heat pump system which led to an electricity peak load increase.

As raising energy consumption is a critical issue in our day, one of the most important indicators can be addressed as final energy demand and consumption of the district.

In that sense, EN1 and EN2 indicators were evaluated. According to results, interventions led to 48.4% and 64.8% improvement in final energy consumption and density of final energy consumption in the district, respectively.

Economic indicator

Economical index was investigated under the indicator on *ROI*. According to analysis which has been completed on the basis of methodology, *ROI* rate was calculated as 5.16 years. To calculate the *ROI*, cost of operational energy and investments were taken into consideration. Here the remarkable output was the cost saving between existing and final case. Total natural gas and electricity costs are depicted in Figure 8.

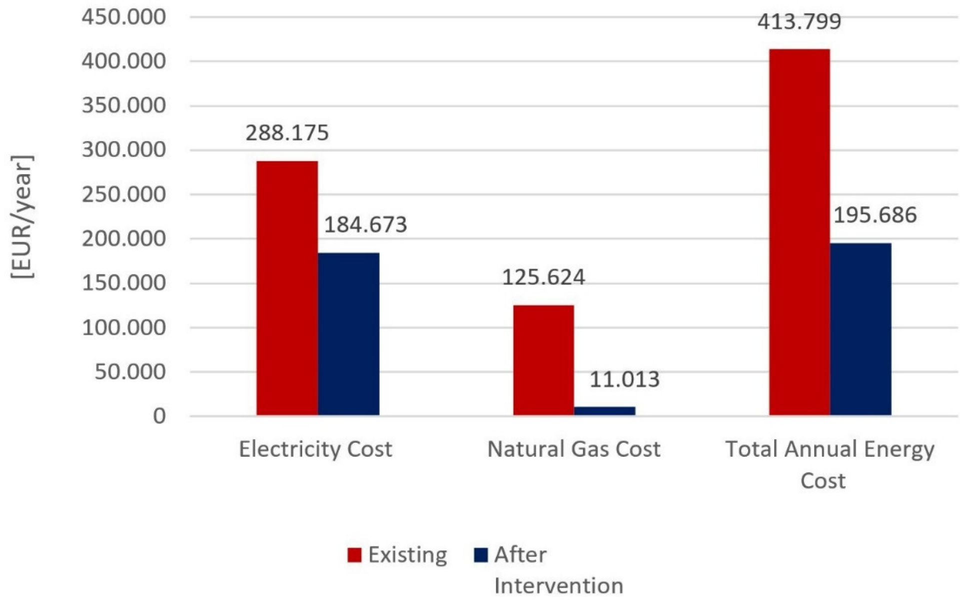

Figure 8. Energy costs comparison for existing and after interventions case

As seen in Figure 8, especially natural gas cost reduced substantially. In comparison to the existing case, 52% savings on the running energy was achieved via the proposed interventions through the district.

Environmental indicator

Another significant indicator in the terms of environmental index is greenhouse gas emissions. Results are represented in Figure 5. According to the results, more than 69 kg CO_2 emission per square meter was reduced with the integration of renewable appliances and innovative interventions. This value corresponds to 37.6% reduction in comparison with the existing case of the district.

Comfort indicators

Lastly, comfort of inhabitants also were identified and evaluated for the district. Comfort indicators were evaluated under three indicators which are: predicted mean vote, percentage of people dissatisfied and percentage of outside range. The changes between the existing and after intervention evaluations indicate the greatest improvement to be in CO2 indicator (see previous Figure 6). When comfort index results had been compared amongst the existing and final case, it is possible to say that final case has a higher comfort degree in comparison with the baseline case. Namely, each suggested scenario had a positive impact of occupants' thermal comfort. As previously investigated, *PMV* scale refers to occupants' thermal sensation and calculated between −3 (cold) and +3 (hot) where "0" is neutral and most desired result. In baseline case, total annual average

PMV value of each building was "–0.87" which can be interpreted as "slightly cool". Each scenario contributed PMV scale to reach more natural zone and finally it reached up to "–0.7". Depending on the CO1 indicator, CO2 and CO3 were also affected positively. Compared to the existing case, both percentage of people dissatisfied and outside range was reduced which means that more comfortable environment was obtained for the occupants.

CONCLUSIONS

The research emphasizes the significance of sustainable development in the city environment which is very complex and requires precisely defined DSIs in different categories. Each indicator of these categories was identified based on its critical parameters and related formulas. The results showed that there are dramatic reductions on certain indicators, while expected improvements on others. Improvement on energy indicators were basically coming from the integration of major energy sources (such as heat pump systems, solar collectors or LED) which was the result of major building renovation. With the careful design strategies of all the mentioned building systems final energy consumption reduction was 65%.

Another critical issue to get this dramatic improvement is that the applied interventions are mainly dependent on renewable sources. For this concern, a set of energy conservation measures are designed and evaluated to both reducing energy consumption of the district and utilizing the required energy from the environment. With this purpose, solar thermal and heat pump systems are introduced into selected buildings. Solar thermal systems consist of flat plate solar collectors and contribute to domestic hot water needs of the case buildings. With the integration of solar thermal systems, analysis showed that it is possible to reduce DHW consumption by 44%. In addition to solar thermal systems, geothermal and air source heat pump systems also contribute to the energy efficiency and sustainability of the district. According to results of this research, nearly 65% energy savings in heating and cooling is achievable in the district which also has major effect on the environmental index, reducing the CO_2 emissions by 69 kg CO_2 per m^2 and economic index in terms of the return on investment 5.16 years. Besides, these interventions have positive impact on the comfort indicators in a direct way as represented in the comfort indicators.

Impact of achieved saving would be beyond expectation if decisions-makers planned with sustainability approach. Application of well-defined indexes provides whole building to district level evaluation method within the sustainability scope as investigated in this research. Decisions about applicable intervention should be made not only based on savings from energy or cost but also their impact on the environment and indoor comfort within the sustainable perspective. Therefore their applications are very critical for all projects.

Furthermore, with all this calculated data, it is found out that results of all the indicators have major sensitivity if there are certain changes on one of the indicators. Therefore, each indicator should be identified and evaluated not only based on its result, but also its effect on other indicators.

ACKNOWLEDGEMENT

This paper is produced based on a FP7 project called "R2CITIES: Renovation of Residential urban spaces: Towards nearly zero energy CITIES, Grant Agreement No: 314473". Data for economic calculations are reference to the project deliverables.

NOMENCLATURE

Cap_I	area or number of set I of buildings I	[m^2]

Cap_i	floor area of building *i*	[m^2]
$DEN_{\mathrm{EC},I,t}$	density of final energy demand/consumption of a set *I* of buildings in year *t* regarding energy carrier EC	[kWh/year]
$EM_{I,\mathrm{M},t}$	emissions of material *M* by set *I* of buildings based on annual data of year *t*	[t/m^2year]
$EM_{i,\mathrm{M},t}$	emissions of material *M* by building *i* based on annual data of year *t*	[t/m^2year]
$EN_{I,t}$	final energy demand/consumption of set *I* of buildings	[kWh/m^2year]
$EN_{i,t}$	final energy demand/consumption of building *i* based on annual data of year *t*	[kWh/m^2year]
f_{cl}	ratio of clothed surface area to DuBois surface area	[A_{cl}/A_D]
h_{c}	convection heat transfer coefficient	[Btu/h ft^2 °F]
h_{r}	radiative heat transfer coefficient	[Btu/h ft^2 °F]
$I_{i,t1}$	investment for building *i*, construction start in year *t*1, construction end in year *t*2, investment is discounted to year *t*1	[EUR]
$\bar{I}_{i,t1}$	specific investment for building *i*, construction start in year *t*1, construction end in year *t*2, investment is discounted to year *t*1	[EUR/m^2]
$In_{\mathrm{EC,AA},I,t}$	input (> 0) energy flow into set I of buildings for application area AA in year *t* regarding energy carrier EC	[kWh/year]
$In_{\mathrm{EC,AA},I,\Delta t_k}$	input (> 0) energy flow into set I of buildings for application area AA in Δt_k $(k = 1, \dots, k)$ as part of a partition of year t	[kWh/year]
$In_{\mathrm{EC,AA},I,\Delta t_k}$	input (> 0) energy flow into set I of buildings for application area AA in Δt_k $(\mathrm{k} = 1, \dots, k)$ as part of a partition of year *t* regarding energy carrier EC	[kWh/year]
$LP_{I,\mathrm{EC=electricity},t,\Delta t_k}$	load of set I of buildings regarding energy carrier EC = electricity in Δt_k $(k = 1, \dots, k)$ as part of a partition of year t	[kW]
$LP_{I,\mathrm{EC=electricity},t,\max}$	peak load of a set I of buildings regarding energy carrier EC based on a partition of year t	[kW]
$LP_{I,\mathrm{EC=electricity},t,\Delta t_k}$	load of set I of buildings regarding energy carrier EC = electricity in Δt_k $(k = 1, \dots, k)$ as part of a partition of year t	[kW]
$LP_{I,\mathrm{AA},t,\Delta t_k}$	load of set I of buildings regarding application area AA in Δt_k $(k = 1, \dots, k)$ as part of a partition of year t	[kW]
$LP_{I,\mathrm{AA},t,\max}$	peak load of a set I of buildings regarding application area AA based on a partition of year t	[kW]
$LP_{I,\mathrm{AA},t,\Delta t_k}$	load of set I of buildings regarding application area AA in Δt_k $(k = 1, \dots, k)$ as part of a partition of year *t*	[kW]
M	rate of metabolic generation per unit DuBois surface area	[Btu/h ft^2]

w	human work per unit DuBois surface area	[Btu/h ft^2]
W_a	air humidity ratio	[-]
W_{sk}	saturated humidity ratio at the skin temperature	[-]

Greek letters

$\sum C_{OM}$	total operation and maintenance costs for building *i*	[EUR]
$\sum E_s$	total energy savings for building *i*	[EUR]
θ_{air}	air temperature	[°F]
θ_{cl}	average surface temperature of clothed body	[°F]
θ_r	mean radiant temperature	[°F]

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Paper submitted: 29.08.2017
Paper revised: 14.03.2018
Paper accepted: 15.03.2018