Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2020, Volume 8, Issue 1, pp 1-21

Calculation of the Sensitivity Factors within the Defined Indexes in a Building Level

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Cite as: Sözer, H., Takmaz, D., Calculation of the Sensitivity Factors within the Defined Indexes in a Building Level, J. sustain. dev. energy water environ. syst., 8(1), pp 1-21, 2020, DOI: https://doi.org/10.13044/j.sdewes.d7.0265

ABSTRACT

Energy efficiency at the city level is mainly dependent on buildings and requires sustainably designed strategies. In this research, an energy index that leads to a classified measurement of sustainability at a building level is defined and evaluated based on a selected building in Istanbul. Sensitivity analysis is assisted by determining the precision of the outcome when certain interventions are applied to improve the building energy efficiency. Each intervention's energy consumption is evaluated based on the overall building energy consumption, which includes all building related energy consuming parameters. There are 6 different scenarios which are composed of various combinations of 8 interventions affecting 7 energy consuming parameters. A matrix is prepared for conducting sensitivity analysis with the particular effects of the applicable interventions. Furthermore, specific values are evaluated to find their sensitivity to affect the building energy performance. The most important improvements among all interventions are automation and monitoring with an energy consumption reduction of 26.07%, ground source heat pump at 16.43% and light emitting diode lighting with sensors at 9.26%. These interventions are also remarked as highly sensitive. As a result, the prepared matrix directly describes the effect of variables in the system numerically, which also assists to determine each intervention's sensitivity levels.

KEYWORDS

Building indexes, Sensitivity analysis, Sensitivity factors, Energy performance analysis of buildings.

INTRODUCTION

Increasing energy concerns create further awareness for the quality and operation of buildings for implementing sustainable development. Hence, key factors that influence the building energy performance are taken into close consideration to evaluate and represent the diverse criteria from various building characteristics. Recently, most emphasis is given on sustainability indicators. In addition, their qualitative and quantitative results on the building performance are well defined in the literature. The purpose of evaluating the indicators in most of the research in the literature is to recognize the problem in advance of its realization. The variety of research has scaled

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from the building to the city level and has shown that the links between indicators, such as economy, environment and society, are vulnerable.

Evaluation of the indicators at the city level

The importance of forecasting the indicators from a bigger scale is highlighted in a number of studies, especially in the context of energy efficiency. The contribution of renewable energy systems begins to widen from the building scale towards neighborhood and district scales where the annual energy demand is lower than annual energy supply from local renewable energy sources via metrics and decision supporting tools [1]. In the Province of Chieti, within the Public Private Partnership framework, the reduction of energy consumption of buildings by implementation of renewable energy and optimization of public lighting systems was achieved at 20% with respect to baseline values improving environmental quality [2]. In the case of Turin, existing energy systems and their impact on energy sustainability are examined and possible solutions to handle energy demand with a few renewable energy sources are identified considering energy risks, vulnerabilities and resilience. Roof integrated solar thermal collectors are taken into account to decrease energy consumption [3].

Evaluation of the impact between the indicators

In Huang *et al.* [4], sustainability indicators are designed according to a semi quantitative model of simulation that is led by experts who judge the impacts of indicators to the total and to each other. Conversely, Choon *et al*. [5] formed the set of indicators in the scope of sustainability assessment specifically for the major cities of Malaysia. Passer *et al*. [6] take it further to evaluate the numerical performances of the cities to highlight their weaknesses and strengths. Similarly, in the criteria matrix that was developed for a city called Ping-Ding in China, the effect of variables, such as water pollution, recycling and local security to criteria, such as economy, energy and natural balance, are classified as "not applicable, partly applicable and fully applicable [7]". Scores are then summed up to describe the sensitivity of the criteria in the scope of variables. Afterward, the variables are evaluated amongst themselves as "no significance, low significance, medium significance and high significance", and expressed as 0, 1, 2, and 3. The scorings are determined by consensus at the end of group discussions consisting of residents, experts and planning faculty. Further, the effect of one variable to another, which is called as active sum and one variable being affected by other variables called passive sum is used to determine the sensitivity of variables. As a result, the product and quotient of active sum and passive sum directly describe the role of variables in the system numerically.

Alternatively, a multi-criterion framework was developed for evaluating the sustainability for the application of social choice to the difficult policy problems of the millennium. The foundations of Social Multi-Criteria Evaluation (SMCE) are set up by referring to concepts from complex system theory and philosophy, such as reflexive complexity, post-normal science and incommensurability. The research emphasizes that measuring sustainability is dependent on quantitative criteria scores, number of criteria, weight of variables, and also the relationship of variables [8]. Also, the relationship of interventions as variables and weight are explained in detail by Gouveia *et al.* [9]. With a different approach, the conceptualization of the use of indicators that are taken into consideration in an analytical framework is applied further in an actual indicator system [10].

Evaluation of the indicators on a building level

On a building level, Ferrari *et al.* [11] indicate that new technologies in building retrofitting can save up to 40% of primary energy demand and related emissions.

Building energy performance is reduced by building users based on calculated energy consumption, however, it is important to know which indicators are used to obtain energy efficiency and which leads the building users towards sustainability [12]. In fact, the decrease of the energy consumption of energy conservation measures reflects the effects of interventions [13]. The amount of the interventions' effect which will then be assigned as sensitivity factors will be the most important criteria to decide on the availability of the indicators [14]. In addition, the energy consuming parameters and the applicable interventions are pre-defined with their quantitative data in kWh unit in the existing structure [15].

Thomsen and Meijer [16] identified the effect of indicators at both building and city levels to create corresponding improvements. Sözer and Kükrer [17] evaluated the design strategies for sustainability based on defined indexes at the city of Kartal. Quantitative results are represented corresponding to specific indicators.

Multiple research also emphasizes the importance of automation and monitoring integration in the buildings, which has major improvement on building energy performance. Ippolito *et al.* [18] studied the impact of the building automation control systems and technical building management systems on the energy performance ranking of a residential building case study in Italy. They found that applying these systems can improve the energy performance of the building and upgrade its energy ranking, but this effect is influenced by many factors like the type of the energy appliances and the type of the heating and cooling systems applied in the building. Rocha *et al.* [19] compared smart building energy management systems with normal energy management systems. They concluded that the smart energy management systems are more effective at reducing energy consumption and carbon dioxide (CO_2) emissions, and also the cost of installing the smart building energy management systems is relatively low. Podgornic *et al.* [20] studied the effect of customized energy consumption monitoring on the low-income occupants' energy efficient behavior in the residential sector. They showed that this customized feedback saved about 22% to 27% of the electricity consumption and it reached 37% by stimulating the efficient behavior by complementary measures. Ahmad *et al.* [21] reviewed the state-of-art of the building energy metering and environmental monitoring. They discussed the metering and sensing technologies for buildings. They found that wireless area network is an effective and low-cost technology for home automation and Heating, Ventilating and Air Conditioning (HVAC) system monitoring. Kantarci and Mouftah [22] studied the performance of an in-home energy management application compared with optimization based energy management. They concluded that the monitoring and managing of the energy performance reduced the expenses of the consumer and improved the network performance compared to the case without energy management. Marinakis *et al.* [23] applied an integrated system for buildings' energy-efficient automation customized to the users' requirement and building characteristics. This system achieved significant decrease in the operating cost of A/C system in a tertiary sector building, while maintaining desirable comfort, in line with recent guidance and decisions for discounts in their energy bill. Marinakis *et al.* [24] also focused on building automation and control systems and how those systems will improve the building's energy performance. In particular, they proposed the design and implementation of a building automation and control tool for remote and real time monitoring of energy consumption towards energy-efficient buildings. They expected that the advantages of the effective management of energy data in the buildings of which the automation and monitoring are main parts will be clear in a real life case study.

Nonetheless, all the existing research has revealed that a consideration of the effect of intervention on overall building energy efficiency is critical in a precisely determined approach as well as their effect on each other.

Aims of the research

This research paper identifies the sensitivity level of the building energy consumption parameters when certain interventions are applied to improve the building energy efficiency. Each intervention's energy consumption is evaluated based on the overall building energy consumption, which includes all building related energy consuming parameters that are defined such as lighting, miscellaneous equipment, space heating, space cooling, pumps, ventilation fan, and Domestic Hot Water (DHW). A matrix is prepared for sensitivity analysis focusing on an energy index with the particular effects of applicable interventions, such as exterior wall insulation, underground wall insulation, window change, Light Emitting Diode (LED) lighting with sensors, solar thermal systems, as well as automation and monitoring systems. The indicators of an energy index were calculated by using energy performance simulation tools and scheming. Existing conditions were evaluated and retrofitting scenarios were introduced accordingly. Based on the energy performance result, the most effective scenario, the individual effects of interventions and their effect to the total energy consumption is calculated. First, the indicators were considered in equal weight. Yet, the indicators have different possessions of weight which have an effect on the calculation.

One of the important results is that LED lighting has a negative effect on space heating and domestic hot water's energy loads. In addition, LED lighting with sensors causes extra load on space heating. Another side effect based on the insulations that are applied on exterior and underground walls, is the creation of extra load on space cooling. On the other hand, highly sensitive interventions are calculated as automation and monitoring on space heating, ground source heat pump on space heating, LED lighting with sensors on lighting and LED lighting on lighting, respectively.

The research, therefore, provides differences from the literature by identifying the indicators with their sensitivity to each other to minimize the unexpected side effects in advance.

METHODS

In this paper, a building, as the leading integral part in a city, and its features are reviewed to investigate the critical factors of building energy consumption by means of sustainability. Existing features to determine the weaknesses of the building are carefully determined by analysing the overall building energy consumption. Afterwards, improvements of building energy performance by integration of interventions are numerically shown while their effect on each energy consuming parameter is identified in detail.

Uncertainty is directly related with the unexpected side effects of the interventions. The purpose of this research is to minimize these unexpected side effects in advance with their detailed analysis, which will bring a distinct perspective to the existing literature.

Improvement in the overall energy performance is expected when certain interventions are applied. Yet, any positive and negative effect of each intervention to each other with their sensitivity level is the critical aspect to evaluate. A multi directional effect approach is implemented for the investigation by considering interdependence and relationship of Energy Conservation Measures (ECM).

The following steps are taken to discover the interventions' positive and negative effect on overall energy consumption as well as on each other:

- Identification of the existing features of the building prior to the interventions – A detailed energy performance model is developed including the specific values of the building and its constituent elements, such as environment information, thermal characteristics of the envelope and the specifications of building systems;
- Development of the building energy simulation model and energy efficient scenarios – Energy performance of the building is calculated based on an energy

index which is defined with the final energy demand and consumption. Final energy demand or consumption is referred to the final uses of energy for different areas of application within the buildings and correspondingly the district. Energy consumption of the buildings is composed of four components: space heating, space cooling, DHW heating, and electrical appliances.

Final energy demand covers all of the above-mentioned components. Final energy demand or consumption of the building can be represented using the following approach in eq. (1) as given in the CONCERTO Guidelines [25]:

$$EN_{l,t} = \frac{\sum_{iEl} EN_{i,t} \times Cap_l}{Cap_l} \tag{1}$$

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

The energy performance of the existing building is performed by utilizing the dynamic simulation model. Energy efficiency scenarios are developed by application of ECM and analysed with the goal of energy saving. The performance of each scenario is represented with comparison;

- Evaluation of the interventions effect on defined energy consuming parameters – Energy consuming parameters are defined as lights, miscellaneous equipment, space heating, space cooling, pumps, ventilation fan and DHW. Each intervention's energy consumption is evaluated based on their energy consumption;
- Preparation of a matrix for forming the weight scheme – As a result, a matrix is prepared to show the effect of the interventions on each other. All interventions and energy consuming parameters are taken in equal weight amongst themselves. After calculation of the total loads for energy consuming parameters and their effects on interventions, the weight scheme is formed according to their contribution. The percentage effects of the interventions to energy consuming parameters are calculated as the key points to develop the matrix. The matrix also represents the top beneficial individual performances that decrease the energy consumption furthermost in addition to the positive and the negative effects of the interventions.

  Moreover, the results are classified as:
    - The top beneficial individual performances that decrease energy consumption represent the highest values;
    - Positive effects of interventions on energy consumption represent the moderate-above zero values;
    - No effect, which represents zero;
    - Lowest beneficial in which an extra load of the intervention is caused on energy consumption as a side effect of the intervention application represents a negative value.

  Also, the cumulative total of each intervention is calculated.

  The top beneficial effects of interventions as the cumulative total, including the sum of negative and positive effects of interventions on energy consumption, are calculated;
- Defining the effect of the intervention with their sensitivity level – Based on the results of the matrix, each intervention is classified as not sensitive, partly sensitive, reasonably sensitive and highly sensitive.

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The evaluation of interventions and their effect on overall building energy consumption as well as on each energy consumption parameter are summarized in Figure 1.

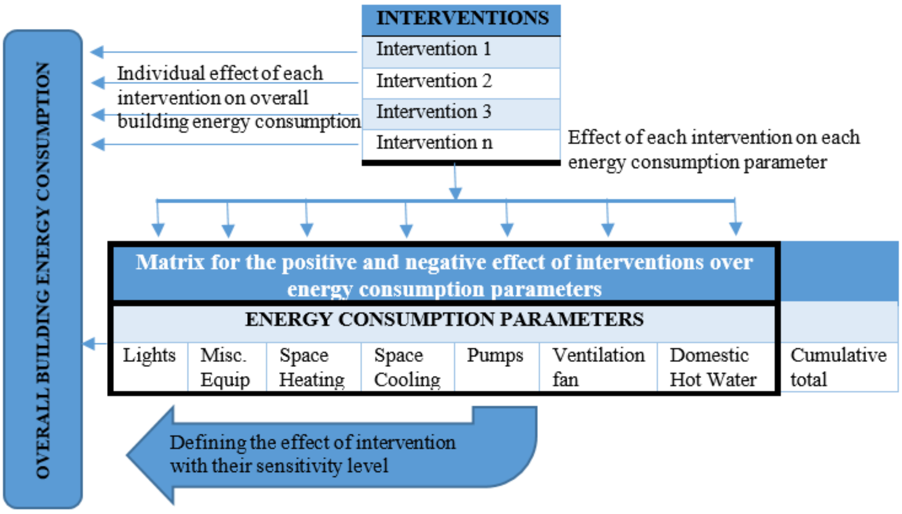

Figure 1. Summary of interactions between interventions, defined matrix and sensitivity levels

The formulation of the individual effect of each intervention on building energy consumption parameters is given in eq. (2):

$$e = \frac{b - i}{b} \times 100 \tag{2}$$

where e [%] is the effect of each intervention, b [W/m^{2}K] is the energy consumption of each parameter for base case and i [W/m^{2}K] is the energy consumption of each parameter for the intervention case.

The formulation of the individual effect of each intervention on the overall building energy consumption is given in eq. (3):

$$e = \frac{b - i}{T} \times 100 \tag{3}$$

Here, T equals the overall energy consumption of the existing case [W/m^{2}K].

A comprehensive work has been done to identify and analyze the building as represented in the following sections. Basically, the existing situation of the building is reviewed with the building envelope and the system in terms of energy efficiency. Then, the scenarios are developed with suggested ECM's which have several interventions. After the interventions are investigated individually, the ECM groups are formed and accordingly scenarios are developed by the combination of ECM's to find out the best energy performance for the building.

When the overall effects of interventions on energy efficiency are considered, it is also valued to precisely identify the individual effect of each intervention beside their effect on each other as is the aim of this study. Accordingly, the sensitivity level of energy consuming parameters is specified and represented with a case study.

Case study

The selected building is located in southeast of Istanbul metropolitan area of Kartal. The building is a residential building and constructed in 2005 as a single concrete block and has 8 stories. The total conditioned area of retrofitting is 18,108 m^2. The building had

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very poor external wall insulation that represents the main problem related to energy losses. The quality of building systems is fairly reliable while lighting applications and DHW production systems may require major revision [17]. Therefore, energy efficiency strategies were set according to a detailed analysis of existing conditions. Figure 2 shows the front view and the location of the building in Turkey.

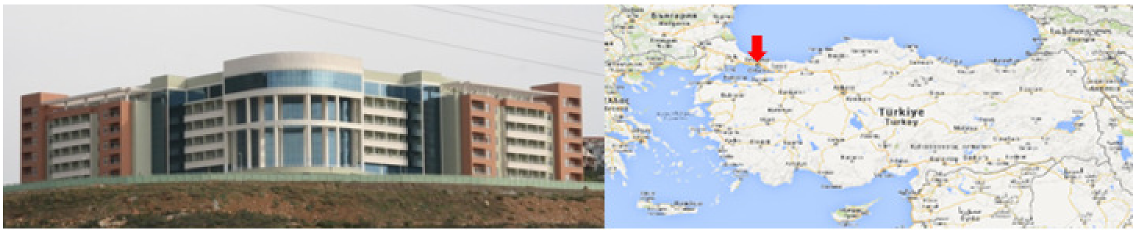

Figure 2. The front view of the building and the location of the building

In Kartal, the climate is warm and temperate. The average temperature during the year varies by around 17.6 °C. The rainfall in Kartal is mostly in the winter. The average rainfall is observed in December with an average of 117 mm of rainfall [26].

Features of the building prior to the interventions

The existing building features are identified with emphasis on their architectural and thermal characteristics. The building envelope in terms of roof, walls and window types and their insulation, the type of the mechanical systems and their application purposes and electrical properties related with lighting and fire protection system are mentioned below.

<u>Building envelope</u>. The building walls have two different characteristics:

- External walls of the residence rooms are insulated with 5 cm low density Expanded Polystyrene (EPS), which is a low-density insulation material;
- External walls of the common spaces do not have any level of thermal insulation.

The 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 also have curtains to protect from extra solar radiation and heat gain as well as to respect residents' privacy.

<u>Mechanical systems</u>. 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 and ventilation in the restaurant (located on the fifth floor), in the swimming pool and the conference room (located on the first basement floor).

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

Building energy simulation

Energy analysis of the 18,108 m^2 building was carried out by a dynamic simulation modelling software called e-Quest© for 365 days and 8,760 hours per year. All factors that affect heating/cooling loads were modelled comprehensively to get precise results for energy consumption. Building geometries, weather conditions, HVAC systems, internal loads, operation strategies and schedules were defined in e-Quest© [27]. Specifications of mentioned components were estimated based on the actual condition of the buildings. It should be noted that in the building system configuration, not only selecting the correct system, but also configuring the system compatibilities is important. With convenient systems and appropriate optimizations, energy efficiency of the buildings, consequently, of the district is improved and represented within the energy index calculation. By the summation of the data mentioned above 7,760.815 kWh of energy consumption per year is calculated by e-Quest©.

Applied interventions and scenario details

Improvement on energy performance of the building is evaluated with the application of different interventions and their application with suggested scenarios.

All applied ECM's are shown in the Table 1 below.

Table 1. Summary of main solutions for the building

Solution	Code
Thermal insulation	ECM1
Radiant heating	ECM2
Solar thermal systems	ECM3
Building appliances and lighting systems	ECM4
Energy automation and monitoring system	ECM5
Windows replacement	ECM6
Application of water saving systems	ECM7
Heat pump	ECM8

ECM1: Thermal insulation. The purpose of this intervention is to decrease building heat loss with integration of new insulation material. In order to investigate façade insulation alternatives, different *U*-values with different insulation materials have been analyzed, respectively. Considering an exterior wall, three *U*-values are examined in addition to this, in respect to soil contact wall, and one alternative is considered. Changes in energy consumption of the building were compared by employing different *U*-values.

ECM2: Radiant heating. The aim of this intervention is to reduce space heating loads with a modern and energy efficient system while providing comfortable indoor spaces based on radiant heating and cooling.

ECM3: Solar thermal systems. The main benefit of this intervention is taking advantage of solar energy as a free resource. Solar thermal systems harvest the sun's thermal energy in order to produce DHW. The systems that will be considered for Kartal demo site consist of flat plate solar collectors.

ECM4: Building lighting systems. The concern of this intervention is to reduce energy consumption of lighting systems with integration of LED lighting and sensor technology. First, halogen lamps are changed to LED lighting appliances and then sensors are placed accordingly.

ECM5: Monitoring and building energy operating system. The function of this intervention is reducing energy demand of the building with integration of an automation and energy monitoring system.

ECM6: Windows replacement. The importance of this intervention is to reduce the building's heat loss with integration of double glazed and lower *U*-value window. In the baseline case, Building 1 has windows with specifications of 3.4 W/m^{2}K *U*-value. However, with this scenario, the *U*-value will be changed to 1.2 W/m^{2}K by application of better specified windows. Additionally, shading coefficient and solar transmittance values will be 0.29 and 0.58, respectively. ECM6 will be considered as the renovation of all windows.

ECM7: Application of water saving systems. The goal of this intervention is to decrease water consumption with water efficient equipment containing a rainwater reuse system and grey water reuse system to save water and more energy.

ECM8: Ground source heat pump. The target of this intervention is to decrease heating and cooling loads with the integration of a ground source heat pump.

RESULTS AND DISCUSSION

With the combinations of the ECM's, different scenarios are generated. They are explained in detail below and in Table 2.

The First scenario takes into account the building envelope in terms of thermal insulation of exterior and underground wall (ECM1).

The Second scenario is more extended than the first scenario, which includes thermal insulation, window retrofit and solar thermal applications (ECM1, ECM3 and ECM6).

The Third scenario consists of thermal insulation, window retrofit, solar thermal applications and LED lighting (ECM1, ECM3, ECM4 and ECM6).

The Fourth scenario combines heat pump with thermal insulation, window retrofit, and LED lighting (ECM1, ECM4, ECM6 and ECM8).

The Fifth scenario covers thermal insulation, window retrofit, LED lighting, heat pump and a solar thermal system (ECM1, ECM3, ECM4, ECM6 and ECM8).

Finally, the Sixth scenario incorporates, thermal insulation, window retrofit, LED lighting, heat pump, solar thermal system, radiant heating, monitoring and automation and water saving system (ECM1, ECM2, ECM3, ECM4, ECM5, ECM6, ECM7 and ECM8). Table 2 and Figure 3 represent the summary of scenarios and the energy savings achieved based on the existing case, which has no ECM application.

Table 2. ECM's of each scenario and savings for the building

	ECM1	ECM2	ECM3	ECM4	ECM5	ECM6	ECM7	ECM8
Scenario1	•							
Scenario 2	•		•			•		
Scenario 3	•		•	•		•		
Scenario 4	•			•		•		•
Scenario 5	•		•	•		•		•
Scenario 6	•	•	•	•	•	•	•	•

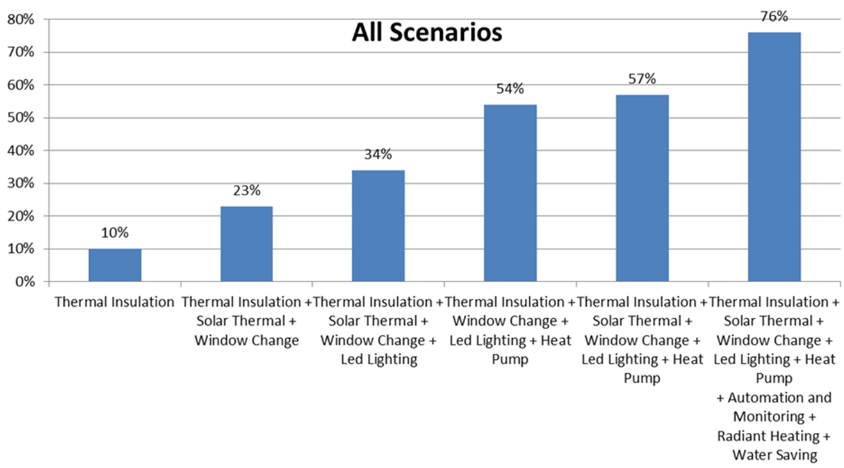

Figure 3. Applied scenarios with their interventions and energy saving ratios

Table 3 shows the changes caused by interventions in kWh. Table 4 indicates the percentage effect of each scenario to the energy savings by the addition of different ECM's. It is found that ECM2 (radiant heating) and ECM7 (application of water saving systems) has positive effects on energy saving but measures are ignored in the sensitivity calculations for this study. Their application on the retrofitting project was very limited because of technical problems. Radiant heating system only covered 80 m^2 heated area. The application of water saving systems on the other hand has a significant effect on water saving but very minimum effect on overall energy saving for electricity consumption of its pumps.

Table 3. Energy demand of scenarios for the building [kWh/year]

	Energy demand [kWh/year]						
	Base case	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Lighting	1,335,877	1,335,877	1,335,877	287,213	287,213	287,213	287,213
Misc. equip.	449,102	449,102	449,102	449,102	449,102	449,102	404,192
Space heating	3,674,672	2,950,762	2,465,705	2,958,111	1,354,815	1,354,815	352,015
Space cooling	904,417	921,601	701,828	436,537	271,526	271,526	155,560
Pumps	308,252	285,442	190,500	174,471	174,471	174,471	54,252
Ventilation fan	456,810	447,674	407,018	399,252	399,252	399,252	193,687
DHW	631,685	628,527	418,807	423,229	632,949	423,229	423,229
Total	7,760,815	7,018,985	5,975,828	5,122,138	3,569,975	3,337,150	1,862,596

Table 4. Energy demand of scenarios for the building

	Energy savings [%]					
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Lights	0	0	78.5	78.5	78.5	78.5
Misc. equip.	0	0	0	0	0	10
Space heating	19.7	32.9	19.5	54.2	54.2	88.1
Space cooling	−1.9	22.4	37.8	37.8	37.8	82.8
Pumps	7.4	38.2	43.4	43.4	43.4	82.4
Ventilation fan	2	10.9	12.6	12.6	12.6	57.6
DHW	0.5	33.7	33	−0.2	33	33
Total	10	23	34	54	57	76

Scenario 6 is chosen as seen in Table 4 since it decreases energy consumption the most. It includes LED lighting, exterior and underground wall insulation, all window changes, automation and monitoring, ground source heat pumps, radiant heating and water saving appliances.

Individual effect of each intervention based on energy performance

Exterior wall insulation. In exterior wall insulation, the exterior wall of the building facade is covered with better insulating material called EPS. The old exterior wall *U*-value was 0.6 W/m^2K. After the intervention, the *U*-value is decreased to 0.223 W/m^2K. Table 5 shows that exterior wall insulation leads to a dramatical decrease on space heating energy consumption and minor effects on space cooling, pumps, ventilation fan parameters. In other words, by preventing the heat loss to the outside of the building, exterior wall insulation provides 393,190 kWh and 10.7% energy saving for space heating. This intervention has very little negative effect on space cooling. Better insulation impedes the air transfer through walls. As a result, it increases space cooling consumption from 904,417.4 to 912,769.9 kWh by 0.9% that refers to 8,352.5 kWh, which is negligible when the total consumption is considered. On the other hand, exterior wall insulation decreased the pumps electricity consumption by 4.3% with an energy saving of 13,255 kWh. For the ventilation fan, 5,482 kWh energy saving occurs with a percentage of 1.2%. Figure 4 shows the effect that exterior wall insulation has on energy consumption parameters.

Table 5. Individual effect of exterior wall insulation on energy consumption parameters

Intervention/Energy consumption parameters	Lights	Misc. equip.	Space heating	Space cooling	Pumps	Ventilation fan	DHW
Exterior wall insulation (U = 0.223 W/m^{2}K)	0	0	10.7	–0.9	4.3	1.2	0

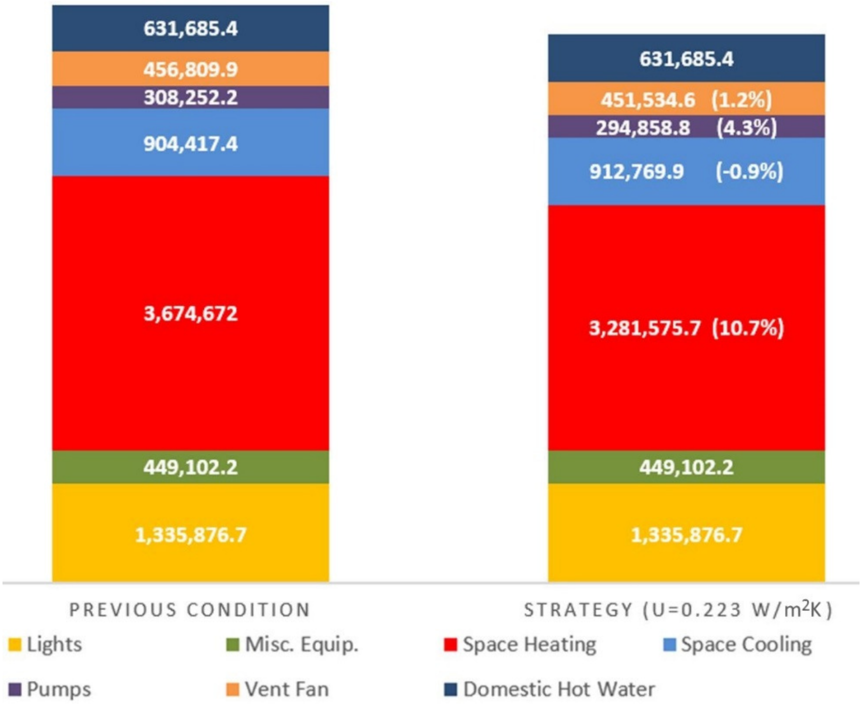

Figure 4. Exterior wall insulation's effect on energy consumption parameters

<u>Underground wall insulation</u>. Underground wall insulation in terms of U-value is improved from 0.959 W/m^{2}K to 0.482 W/m^{2}K. Table 6 shows that this intervention leads to a sharp decrease on space heating values. By preventing the heat loss from the ground floor, the energy saving in terms of natural gas is calculated as 330,720 kWh which is 9% of total space heating consumption. It increases space cooling slightly because in summer time, the ground is colder than the atmosphere so that by decreasing the heat transfer rate from the ground floor, this intervention increases consumption by 9,044 kWh, which is 1% of total space cooling consumption. In addition, the energy consumption of the pumps is decreased by 3.1%, which equals 9,556 kWh. The percentage effect of this intervention to ventilation fan is 0.8% which brings 3,428.9 kWh gain. The 0.5% gain from DHW leads to 3,158 kWh energy saving. Figure 5 shows the effect that underground wall insulation has on energy consumption parameters.

Table 6. Individual effect of underground wall insulation on energy consumption parameters

Interventions/Energy consumption parameters	Lights	Misc. equip.	Space heating	Space cooling	Pumps	Ventilation fan	DHW
Underground wall insulation (U = 0.482 W/m^{2}K)	0	0	9	–1	3.1	0.8	0.5

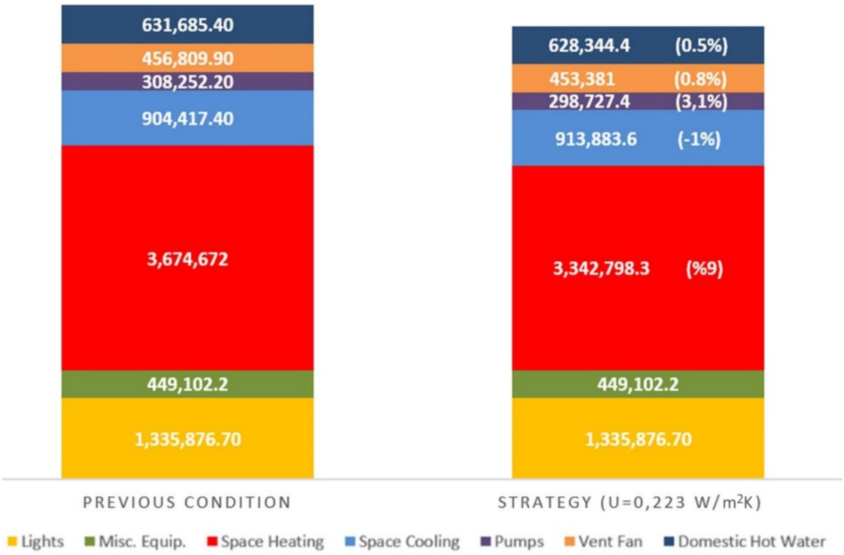

Figure 5. Underground wall insulation's effect on energy consumption parameters

Window change. All windows of the building have been changed. Table 7 indicates that changing of windows has changes in space heating energy consumption by 13.2% and 485,057 kWh by inhibiting heat loss to the outside. For the same reason, it decreases the space cooling consumption by 219,773 kWh, which is 24.3% of total space cooling consumption. The changing of all windows affects pumps consumption by 30.8% resulting in 94,942 kWh energy saving. For the ventilation fan, 8.9% decrease has been obtained implying 40,656 kWh. Figure 6 shows the effect that all window replacements have on energy consumption parameters.

Table 7. Individual effect of window changes on energy consumption parameters

Interventions/Energy consumption parameters	Lights	Misc. equip.	Space heating	Space cooling	Pumps	Ventilation fan	DHW
All window changes (U = 1.6 W/m²K)	0	0	13.2	24.3	30.8	8.9	0

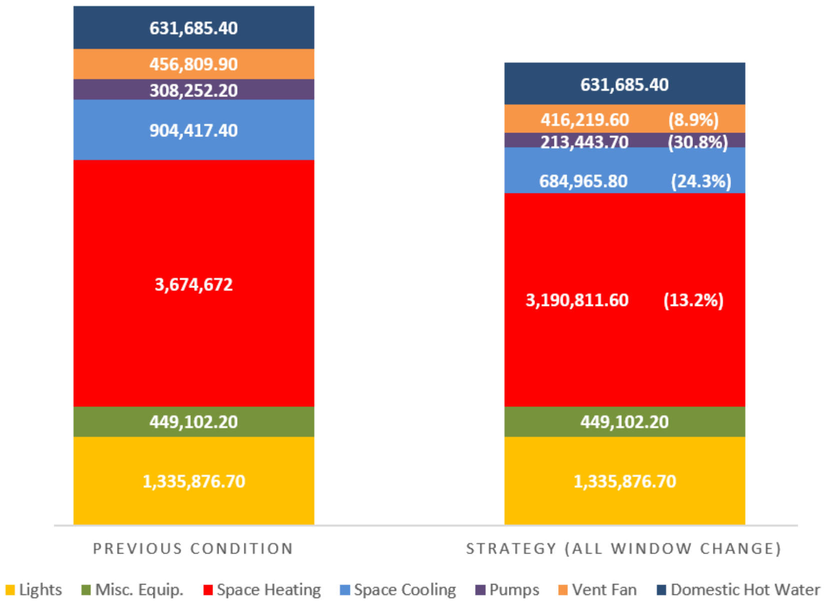

Figure 6. Window change effect on energy consumption parameters

LED lighting with sensors. All of the incandescent lights have been replaced by LED lighting. Also, motion sensitive and computer based controller sensors are linked with the LED lighting. Table 8 summarizes that the insertion of LED lights and sensors has no energy saving effect on miscellaneous equipment. However, this intervention dramatically decreases the lighting energy consumption and results in 1,048,663 kWh energy savings that represents a 78.5% reduction when compared to the previous condition. Therefore, LED technology and sensors decrease the electrical consumption in terms of watt per meter square. On the other hand, this intervention provides a negative effect for space heating. Incandescent lighting armatures are less efficient than LED lighting armatures in terms of energy efficiency luminous flux because incandescent lighting armatures lose their energy to heat. That heat will help heating spaces approximately by 12.9% and result in 474,033 kWh extra energy load. Because of the same reason that LED lighting armatures have cooling technology for the waste heat in electricity circuit in the light, it has positive contribution to space cooling by 15.4% resulting in 139,280 kWh energy savings. Pumps energy consumption is effected by LED lighting with sensors at 5.2% meaning 16,029 kWh energy saving. For the ventilation fan consumption, this intervention has little effect, about 1.7% and 7,561.2 kWh of energy savings. LED lighting without sensors negatively affects DHW energy consumption by 0.7% with an energy saving of 4,422 kWh. Figure 7 shows the level of effect that LED lighting with sensors causes on energy consuming parameters.

Table 8. Individual effect of LED lighting with sensors on energy consumption parameters

Interventions/Energy consumption parameters	Lights	Misc. equip.	Space heating	Space cooling	Pumps	Ventilation fan	DHW
LED lighting with sensors	78.5	0	−13.4	15.4	5.2	1.7	0

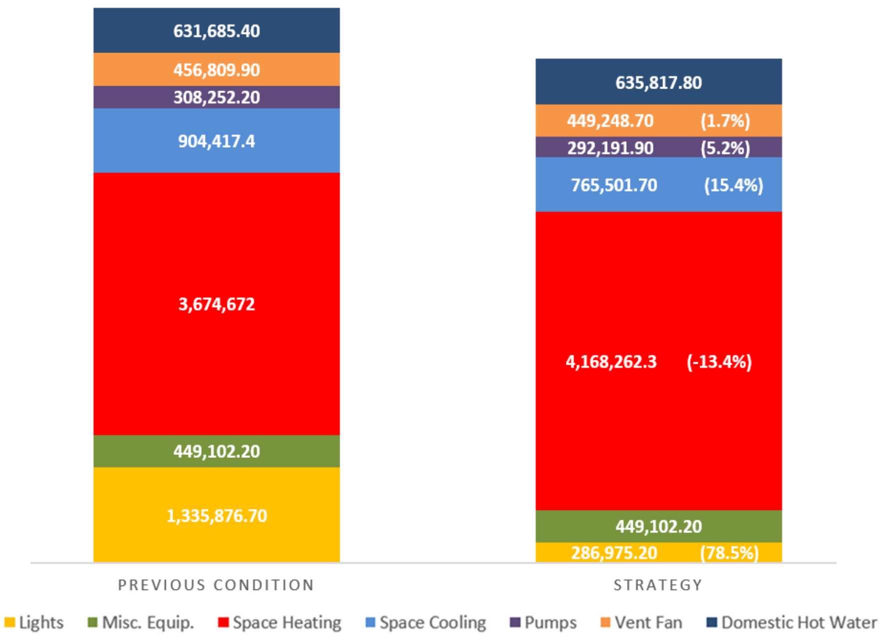

Figure 7. LED lighting with sensors' effect on energy consumption parameters

Solar thermal systems. Solar thermal panels are placed on the flat roof of the building to heat DHW. Table 9 summarizes that the solar thermal panels have decreased DHW energy consumption by 33.2% with an energy saving of 209,719 kWh. It has no effect on other energy consuming parameters as lighting, miscellaneous equipment, space heating, space cooling, pumps and ventilation fan.

The standard collector dimension is 1,235 × 1,935 × 10 mm. The area that absorbs sunlight is 2.4 m^2. The efficiency of the collector is 40%. Average daily global solar radiation energy intensity for Istanbul is calculated with the equation below as 4.17 kWh/m^2day. The roof area is the restricting factor for the number of panels. The panels are placed in the most efficient way that they do not put shade on each other even on 21st of December, when the length of shade is the longest over the year. To find the optimum energy that one panel produces to heat water, the average daily global solar radiation energy intensity is multiplied by panel efficiency and the panel area that absorbs sun radiation which results in 4.00 kWh/day. The area gives an opportunity to put just 150 solar thermal panels on the roof and 95% of the panels are able to emit sun radiation because there are junction points and optical losses on the surface of the panels. As a result, the total energy obtained from solar thermal panels is 219,000 kWh/year, which is 5% more than 209,719 kWh that is calculated for this project. Figure 8 indicates the level of effect that the solar thermal system has on energy consumption parameters. As shown in eq. (4), average global radiation for the city of Istanbul is 4.17 kWh/m^2day, which is the average value of 12 months in a year [28]:

$$\frac{2.00 + 2.57 + 4.20 + 5.28 + 6.30 + 6.79 + 6.79 + 6.07 + 5.09 + 3.74 + 2.37 + 1.8}{12} = 4.17\ \text{kWh/m}^2\text{day} \quad (4)$$

Table 9. Individual effect of solar thermal systems on energy consumption parameters

Interventions/energy consumption parameters	Lights	Misc. equip.	Space heating	Space cooling	Pumps	Ventilation fan	DHW
Solar thermal systems	0	0	0	0	0	0	33.2

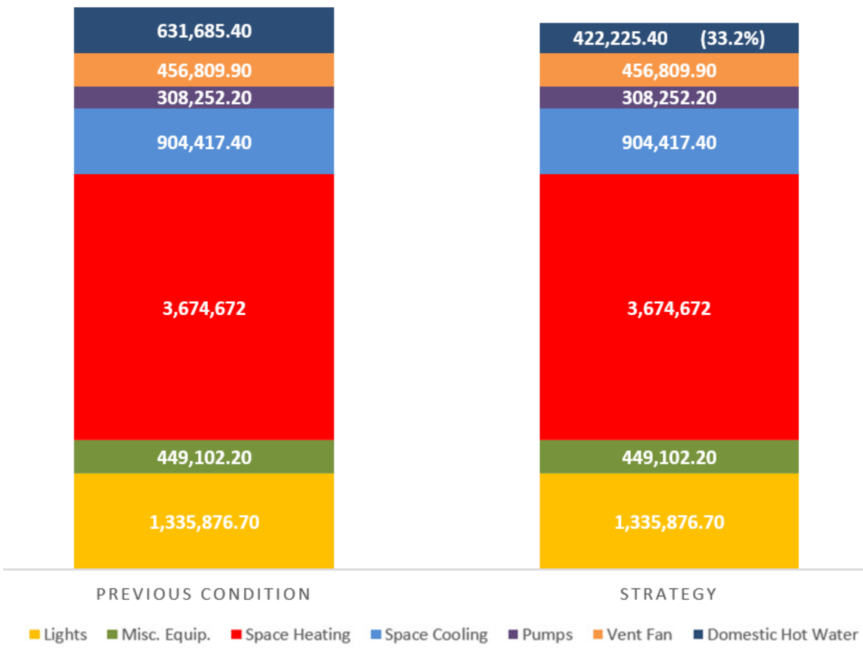

Figure 8. Solar thermal system's effect on energy consumption parameters

Automation and monitoring. Automation and monitoring systems are applied to observe energy consumption of mechanical systems, electrical systems and appliances to determine the system performances and possible maintenance problems. The system keeps the records of systems and gives warning to the building manager when there is any malfunction. Table 10 shows that automation and monitoring systems have no effect on lights and domestic hot water energy consumption. However, it brings a 10% decrease in miscellaneous equipment because it holds the daily work data of the equipment and provides an opportunity for correction to the user. The space heating is highly affected by approximately 34% which equals 1,245,714 kWh, the second largest individual influence in this project. By tracing the data and performance of heating appliances, such as heat pumps and radiant systems and the rate of air in heat transfer areas, automation and monitoring provide energy efficient solutions to the user. In addition to devices, the indoor air quality parameters are measured with the help of sensors and the data are compared to check the performance of the heaters. Because of similar reasons, space cooling is decreased by 45% meaning an energy savings of 406,988 kWh. Cooling performance is also analyzed by putting trackers to the devices and indoor air quality sensors which measures indoor temperature and relative humidity. Figure 9 shows the level of effect that automation and monitoring cause on energy consuming parameters.

Table 10. Individual effect of automation and monitoring on energy consumption parameters

Interventions/Energy consumption parameters	Lights	Misc. equip.	Space heating	Space cooling	Pumps	Ventilation fan	DHW
Automation and monitoring	0	10	33.9	45	39	45	0

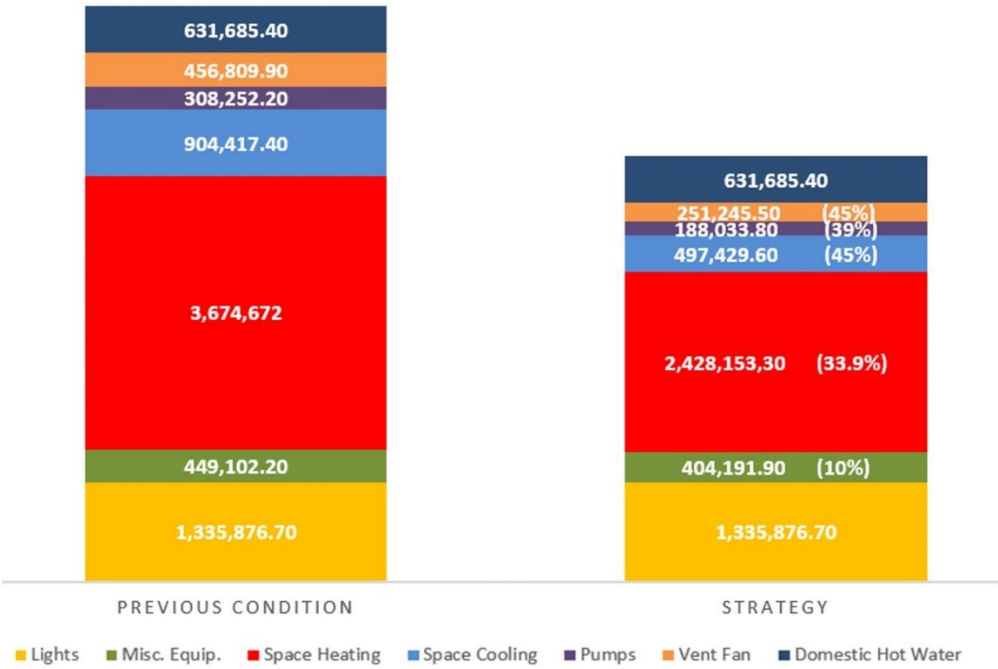

Figure 9. Automation and monitoring effect on energy consumption parameter

<u>Heat pump</u>. Ground source heat pumps are used to take advantage of thermal energy from underground. Table 11 shows that the addition of the heat pump has no effect on lighting, space cooling, pumps, ventilation fan and DHW energy consumption. When the comparison was done between the previous heating system and the proposed one, the electricity consumption of the existing system, which is defined under miscellaneous equipment, pumps and fans is very close to the electricity consumed for the proposed ground source heat pump. Thus, electricity consumption of the heat pump remained as in the previous system.

It is one of the most effective interventions amongst others. The heat pump intervention has its major effect on space heating. It decreases space heating consumption by 34.7% meaning an energy savings of 1,275,111 kWh. Table 12 shows the technical specifications of the ground source heat pump. Figure 10 shows the level of effect that the ground source heat pump causes on energy consumption parameters.

Table 11. Individual effect of heat pumps on energy consumption parameters

Interventions/Energy consumption parameters	Lights	Misc. equip.	Space heating	Space cooling	Pumps	Ventilation fan	DHW
Heat pump	0	0	34.7	0	0	0	0

Table 12. Details of ground source heat pump

Heating requirement [kW]	630.2
Heat pump COP [-]	4.5
Heat taken from ground [kW]	490
Unit heat transfer from ground [W]	80
Required well depth [m]	6,127
Depth of one well [m]	125
Total number of wells [-]	49.0

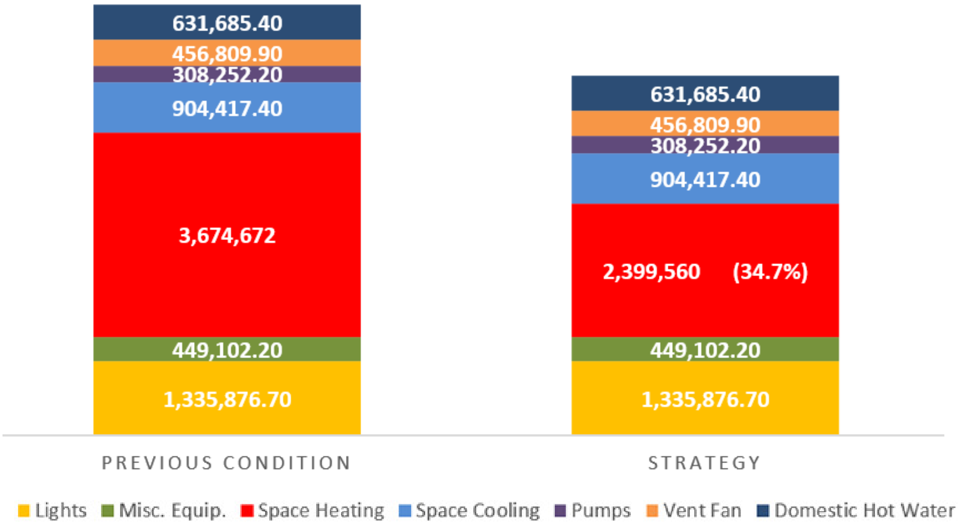

Figure 10. Heat pump effect on energy consumption parameters

The results are represented in a matrix, which is prepared to show the effects of interventions to energy consuming parameters in Table 13.

Specifically, intervention of exterior wall insulation and underground wall insulation has considerable positive impact on space heating but it has negative effect on space cooling. Another important finding is that LED lighting with sensors have great influence on energy decrease on lights and space cooling energy consumption but it has negative effect on space heating because LED lighting armatures give less waste heat to the environment than incandescent lighting armatures. Similarly, LED lighting has very little negative effect on domestic hot water.

The categories of A, B, C and D refer to the level of uncertainties that comes out from the interactions between interventions and energy consuming parameters. Exclusively, negative results could be an unexpected side effect and should be taken into careful consideration.

At first, all interventions and energy consuming parameters are taken in equal weight amongst themselves. After calculation of total loads for energy consuming parameters and the effects on interventions, the weight scheme is formed according to their contribution and ranked accordingly. When total effects of the interventions are considered, automation and monitoring takes first place with 26.07% and heat pump takes second place with 16.43%. LED lighting with sensors improves total energy demand by 9.26%.

Table 13. The matrix for percentage contribution of energy consumption parameters in total consumption

Interventions/Energy consuming parameters	Lights	Misc. equip.	Space heating	Space cooling	Pumps	Ventilation fan	DHW	Cumulative total
Exterior wall insulation (U = 0.223 W/m^{2}K)	0.00	0.00	C 5.07	A −0.10	C 0.17	C 0.07	0.00	5.21
Underground wall insulation (U = 0.482 W/m^{2}K)	0.00	0.00	C 6.26	A −0.12	C 0.12	C 0.05	C 0.04	6.35
All window change (U = 1.6 W/m^{2}K)	0.00	0.00	C 4.25	C 2.83	C 1.22	C 0.52	0.00	8.83
LED lighting	C 12.92	0.00	A −6.11	C 1.67	C 0.18	C 0.09	A −0.06	8.69
LED lighting with sensors	B 13.50	0.00	A −6.34	C 1.79	C 0.21	C 0.10	0.00	D 9.26
Solar thermal systems	0.00	0.00	0.00	0.00	0.00	0.00	C 2.70	2.70
Automation and monitoring	0.00	C 0.58	B 16.05	C 5.24	C 1.55	C 2.65	0.00	D 26.07
Heat pump	0.00	0.00	B 16.43	0.00	0.00	0.00	0.00	D 16.43

Classifications	Meaning of classifications in Table 13
A	Lowest beneficial, extra load of the intervention on energy consumption (side effect)
B	Top beneficial individual performances that decreases energy consumption the most
C	Positive effects of interventions on energy consumption
	No effect
D	Top beneficial effects of interventions as cumulative total including the sum of negative and positive effects of interventions on energy consumption

The top beneficial individual performances that decrease energy consumption are the heat pump, automation and monitoring, and LED lighting with sensors. The ground source heat pump has the biggest effect on space heating at 34.7% and has 16.43% effect on total consumption, which is the biggest individual effect of the project. The second biggest individual decrease is seen in the effect of automation and monitoring on space heating at 33.9%, meaning an energy savings of a total of 16.05% in total energy consumption. LED lighting with sensors intervention takes 3rd place by decreasing the energy consumption of lighting by 78.5%. It seems as the best percentage decrease but in total, space heating energy consumption is much bigger than lights within the total energy consumption.

The results are also evaluated among each intervention based on their sensitivity level. Calculated outcomes were defined with percentage values that are the key points to form indexes for the weighting.

When the mean of the values in Table 14 is taken by neglecting 0 percentage effect of interventions to total energy consumption, the result is approximately 3%. It is clearly shown in Figure 11 that 0% scored interventions will be called non-sensitive.

Table 14. Percentage effects and sensitivity level of interventions

Percentage effects of interventions	Sensitivity level
0%	No sensitivity
Between −3%-0% and 0%-3%	Partly sensitive
Between −7%-−3% and 3%-7%	Reasonably sensitive
< −7% and > 7%	Highly sensitive

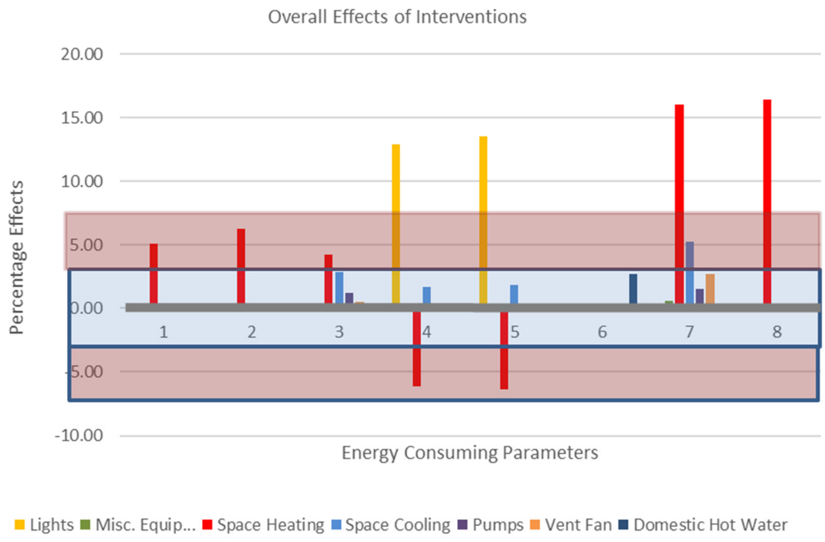

Figure 11. Percentage effects of interventions

The percentages less than 3% are classified as partly sensitive by not looking at the sum of the effects. On the other hand, the interventions that have percentages between 3% and 7% are accepted as reasonably sensitive, such as all window changes or underground wall change on space heating. There are 4 highly sensitive applications: automation and monitoring on space heating, ground source heat pump on space heating, LED lighting and LED lighting with sensors on lighting, respectively, which have more than 7% effect on energy consuming parameters individually.

CONCLUSIONS

Uncertainty is directly related with the unexpected side effects of interventions. Therefore, it is critical to identify all interventions' effect in a detailed approach. A multi directional effect approach is implemented to the energy conservation measures of the building by considering their interdependency and relationship to selected interventions.

As expected, each intervention has positive effect on overall energy consumption. However, when their effect on classified energy consuming parameters are analyzed, certain neutral or negative, which would be unexpected in some cases, are also revealed.

Specifically, the main purposes of exterior and underground wall insulation are to improve space heating by minimizing heat loss through the facade and through the ground. However, as represented, these two interventions have negative effects on space cooling. In addition, thermal insulation leads to minor improvement on energy consumption of pumps and ventilation fan. The small effect of underground wall insulation on DHW is also an unintended result.

The purpose of window changes is to enhance thermal performance of the building, such as space heating and space cooling, but pumps and ventilation fan are positively affected from the change.

LED lighting with sensors directly aims to decrease lighting consumption but it has a considerable increase on space heating loads, which is the biggest negative effect in this study. For the same reason, relatively small side effects are indicated on pumps and ventilation fan consumption. Exclusively, negative results are the unexpected side effect and should be taken into careful consideration during the implementation.

Unlike other interventions, the heat pump just affects the thermal performance of the building and has no side effects. Similarly, solar thermal system only decreases DHW consumption and has no side effects.

Automation and monitoring is applied to track the building systems' energy consumption. The changes related with automation and monitoring helps building managers or users to understand their system components and help them to take related precautions, which surely decrease energy consumption, especially space heating and space cooling. However, the most beneficial intervention came out from the analyses is automation and monitoring system. This would be expected when its effect on overall building energy consumption is compared with the literature. However, dramatic improvement are shown on reduction of heating consumption that is almost equal to the application of a new heating system, which would be an unexpected result that is discovered as a result of comparative analyses between interventions. Moreover, it has positive effect on other parameters as miscellaneous equipment, pumps and ventilation fans.

Conversely, when the sensitivity level of interventions based on their energy consumption are calculated, LED lighting, automation and monitoring system and heat pumps are classified as highly sensitive.

Even though results of the projects are expected, the applied method represents a comparative investigation that is revealed on critical aspects of intervention applications. It provides a precisely determined approach to determine intervention's effect on overall building energy efficiency as well as their effect on each other.

ACKNOWLEDGMENT

This paper is produced by using the data of a FP7 project called "R2CITIES: Renovation of Residential urban spaces: Towards nearly zero energy CITIES, Grant Agreement No: 314473". Some of the input data for the energy performance analyses are provided from the project deliverables.

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Paper submitted: 04.03.2018
Paper revised: 07.01.2019
Paper accepted: 17.01.2019