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TRANSFORMATION MODEL TOWARDS ENERGY POSITIVE PUBLIC BUILDING

Petar KISYOV

University of Food Technologies, 26 Maritza Blvd, Plovdiv, Bulgaria

Corresponding author email: petar.kisyov@yahoo.com

Abstract

Positive Energy Buildings and neighbourhoods are having an important role in the clean energy transition and cities' green energy system transformation. The aim of this paper is to design and evaluate a scenario for the transformation of a single administrative public building located in Plovdiv, Bulgaria into Positive Energy Building. This is achieved through the implementation of set of passive and technological measures, including renewable power, so to decrease building`s demand and to fully electrify it and finally to cover buildings total energy demand by renewable mean. This work evaluates the efficiency, impact, investment costs and rate of return of a number of energy conservation measures being designed to be applied. Finally, techno-economic analysis and results are discussed and compared.

Key words*: building transformation models, positive energy buildings, renewable energy.*

INTRODUCTION

Buildings in the EU are responsible for over 36% of the greenhouse gas emissions and about 40% of the total final energy consumption (European Commission, Energy efficiency in buildings, 2020). Reducing these emissions through energy efficiency measures and renewables is crucial in order to achieve zero-emission buildings stock in 2050. (European Council, 2024; Fit for 55 Infographic). To do so, the EC introduced the Fit for 55 Package, which sets policy actions, so as to decrease greenhouse gas emissions by at least 55% in 2030, while further increasing the share of renewable energy in the final energy consumption. On the other hand, European Commission's 2040 impact assessment, evaluated that electricity should account for 50% of final EU energy consumption to meet climate goals, with 35% by 2030. An important role for achieving these ambitious targets is within the building sector. With the revision of the Energy Performance of Buildings Directive (EPBD), part of the Fit for 55 package, more ambitious energy efficiency standards for building renovations of existing and construction of new buildings are set (European Council, 2023; Fit for 55 package).

Bulgaria continues to be one of the most energy-intensive economies in the EU, with a large percentage of greenhouse gas emissions generation. Thus, opportunities exist for significant energy savings through targeted investment in the building sector, as well as increased investment in clean energy infrastructure. According to the "Energy efficiency" dimension set in the Integrated Energy and Climate Plan of the Republic of Bulgaria 2021-2030, Bulgaria's efforts are aimed at achieving energy savings in the final energy consumption, by improving the energy characteristics of the most inefficient buildings. Within the plan, a goal to reduce the final energy consumption with 11.1% compared to the reference scenario in 2020 is set (Integrated Plan in the Area on Energy and Climate of The Republic of Bulgaria, 2021-2030).

The goal requires the demonstration of cost-effective models for transformation of the existing buildings into highly efficient, such as the Positive Energy Buildings (PEBs). Currently there is a lack of an official definition for a PEB. However, there are range of publications in literature on the PEBs concept, which is considered as evolution of the nearly-zero-energy buildings concept and is introduced as the next level of certification for highly efficient and sustainable buildings (Zhang et al., 2024; Kumar, 2021).

PEB is defined as “an energy-efficient building that produces more energy over the course of a year than the building requires for heating, cooling, ventilation, domestic hot water and auxiliary systems". Thus, PEBs are requiring the implementation of energy efficiency measures, where a large share of the consumed energy is generated from renewable sources, while there is also excess energy available. Fulfilling the goal, high self-consumption rates and high energy flexibility has also to be achieved (Juusela et al., 2023). It can be summarized that for achieving PEB the implementation of the following three approaches is extremely essential - envelope passive strategies, energy-efficiency measures, highly efficient heating, cooling and ventilation technologies and renewable energy generation.

The first step to reach PEB is to make the building highly energy efficient building with low energy demand (Rehman et al., 2022). Brucks indicates that building envelope retrofitting, such as insulation and multiglazed windows is among buildings optimal technology portfolio and is essential to achieve PEB, especially seen for buildings located in cold climates (Bruck et al., 2022). Retrofitted buildings have a higher self-coverage of the energy demand and react more flexibly to changes in the electricity tariff. This study also determines the value of retrofitting for PEBs is between 1.5 ÷ 2 EUR/m²*kWh reduced. In a study by Nundy smart and efficient windows are highlighted as a suitable technology in the PEB transformation (Nundy et al., 2021). Heat pumps with high coefficient of performance (COP) and low environmental impact are among the most suitable technologies for an efficient heating and cooling service for the building sector (Battaglia et al., 2023). PEBs also require photovoltaic systems to achieve energy self-sufficiency. The renewables can be either integrated into the building or supplied as external energy support to the building (Hu, 2016). However, the growing interest in on the on-site energy generation, which has led to the development of numerous research studies on the theme of PV in PEBs. Yang presents a bottom-up dynamic building model based on the implementation of insulation, renewable energy sources, and rooftop PV panels (Yang et al., 2022). The scenario evaluation shows that energy-saving measures together with renewable heat sources can reduce about 2/3 of the energy and 60-90% of GHG emissions for space heating, where nearly 80% of electricity demand could be met by PVs. In a recent study Zomer provides a performance assessment of the potential of BIPV in enabling energy positive buildings (Zomer et al., 2020). Barrutieta studies a decision-making methodology guiding the different stakeholders towards effective architectural decisions for PV system integration in the PEB design process (Barrutieta et al., 2023).

Special attention is paid on introducing methods for the optimization of the envelope for the best building integrated photovoltaics (BIPV) placement, while balancing roof and facade areas. Finally, an intelligent predictive control schemes, supported by monitoring and networking schemes are seen of high importance in order to achieve generation–consumption matching under real time conditions (Kolokotsa et al., 2011). In recent literature buildings possessing the four main energy functions, such as consumption, generation, storage, and flexibility are also called flexumers (Cai et al., 2024).

PEB topic has been highlighted in several recent researches. Magrini highlights the Positive Energy Building as the next challenge after adopting the Nearly Zero Energy Buildings (NZEBs) concept (Magrini et al., 2020). Bojić investigates a model for three residential buildings powered by electricity from PVs, where the main conclusion sets importance to the size of the PVs as a main element whether to achieve PEBs (Bojić et al., 2011). Johari concludes that net zero energy buildings with high share of PVs have three times more excess power in summer months compared to winter (Johari et al., 2024).

MATERIALS AND METHODS

The case study is an existing inefficient administrative public building - Municipal Administration building - Plovdiv (Figure 1). The building entered into operation in 1969 and currently is occupied by an average of 155 persons serving for administrative purposes. The building functions from Monday to Friday for an average of 11 hours a day.

The aim of this paper is to demonstrate an energy transformation paradigm of a single inefficient administrative public building to a

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PEB with zero emission generation by taking into effect the implementation of different energy conservation measures and technologies. To do so, the current energy performance of an administrative pilot building was carefully studied. The study served for the definition of a number energy conservation and renewable measures leading to a transformation towards positive energy and zero emission building.

Figure 1. Photos of the case study

In this publication, the connections between the following fields that are relevant for the PEB design process are carefully studied, so as to design building`s transformation model - geometry size, location and climate conditions, current energy consumption and state of the art of buildings heating and cooling systems. In order to evaluate the energy performance of the selected case study and the performance of the formulated scenario, the national energy performance certification methodology was applied. Subsequently, detailed impact evaluation of each of the proposed interventions, part of the transformation scenario, on consumer parameters was conducted.

RESULTS AND DISCUSSIONS

National energy performance policy

The indicators for energy consumption and the energy performance of buildings, as well as the minimum requirements for the energy performance of buildings with a view of achieving the levels of optimal costs, the technical requirements for energy efficiency and nearly zero energy buildings, are determined by (Regulation RD-02-20-3/9.11.2022 on the Technical Requirements for the Energy Characteristics of Buildings). The ordinance determines:

- the energy performance indicators and the energy requirements characteristics of buildings;
- the national calculation methodology for assessment of the energy characteristics of buildings;
- the scale of energy consumption classes with numerical limits for different purposes categories of buildings and the minimum requirements for energy efficiency in accordance with the scale for the relevant category of buildings;
- the energy efficiency requirements for the establishment of new buildings.

The methodology used for the evaluation of the case study building applies both actual measurements and complied with calculated energy consumption methods, so as to discover baseline scenarios. In this case this approach is applied for calculation of the ventilation demand.

Buildings features and climate conditions

Plovdiv has a humid subtropical climate (Köppen climate classification) with considerable humid continental influences. There are four well established seasons with large temperature amplitudes, requiring implementation of both heating and cooling building infrastructure in order to achieve the all-season regulatory requirements. According to the climatic zoning of the Republic of Bulgaria under (Regulation No. RD-02-20-3/9.11.2022 on the Technical Requirements for the Energy Characteristics of Buildings), the city of Plovdiv belongs to climate zone 6, which is characterized by the following climatic features: a) average duration of the heating season of 175 days, starting October 24 and ending April 6; b) average heating degrees for the city of Plovdiv (DD) – 2400 at an average temperature in the building of 19ºC.

Building characteristics

The building is considered as a multi-connected integrated system that consumes energy for heating, cooling, lighting, domestic hot water generation and electrical internal loads needed for its administrative functions.

Building geometry
It is a twelve-floor main building and a two-floor supportive building holding a total heated area of 4876 m² and 12 741 m³ volume.

Envelope characteristics
The building is built of a monolithic reinforced concrete structure ($A_{opaque\ 1}$) with walls built of brick masonry of lattice brick, internally plastered and an outside stone cladding made of limestone slabs with no thermal insulation. A small part of the facade walls is reinforced concrete walls with a thickness of 25 cm, with a laid lime-sand plaster ($A_{opaque\ 2}$). The window frames of the building are entirely aluminium, filled with transparent glass glazing. The joinery is in poor technical condition and with thermal insulation characteristics that do not meet current national requirements. The poor condition of the joinery leads to a significantly higher infiltration. The roof of the building is a non-insulated cold flat roof built through two reinforced concrete slabs with an unheated non ventilated air gap, the upper one being inclined, covered with waterproofing. The current thermal properties, as well as the total area of the two types of external facades are shown below.
The envelope characteristics are presented in Table 1.

Table 1. Current thermal properties of the external facades and windows

	Orientation			
	North	South	East	West
$A_{opaque\ 1}$ [m²]	369	370	139	339
U [W/m².K]	1.50			
$A_{opaque\ 2}$ [m²]	17	195	212	174
U [W/m².K]	2.70			
A_{glazed} [m²]	767	663	110	255
U [W/m².K]	3.59			

Heating, cooling and ventilation
The building is heated by two means – the main heating systems consists of a convective heating installation thermally supplied by an onside substation that is connected to the district heating supply network of the city of Plovdiv. Due to the inefficiency of the main heating mean, in addition to the centralized heat supply, electricity is used through the operation of individual domestic air conditioners - air-to-air heat pumps supporting the heating in the individual rooms with individual schedules. During the cooling seasons the air-to-air heat pumps are also used for cooling. The building lacks of a centralized ventilation system for the supply of outside air. Fresh air is supplied through the opening of the windows and through the gaps in the window frames, as a result of its wear over time. These practices are leading to high rates of building infiltration and high energy loses.

Lighting
The lighting in the building premises complies with the requirements for minimum illumination. The lighting in the building is solved by means of many different types of lighting fixtures, mostly fluorescent lights. In general, it can be determined that they are inefficient, with reduced light output bringing to higher energy consumption compared to current lighting standards.

Domestic Hot Water (DHW) generation
Hot water for domestic needs in the building is provided by means of electric boilers in the sanitary premises. There are electric instantaneous and volumetric water heaters on 3 floors, and hot water is used only for domestic needs.

Energy consumption
The total energy consumption in the building has a relatively similar character over the 3 years timespan and reflects the loads in the building (Table 2). The electricity has a share of nearly 60%, while the thermal energy holds 40% share. 2021 was chosen as the base year for subsequent analyses.
An analysis of thermal energy and electricity consumption is applied.

Table 2. Energy consumption for the period 2020-2022

	2020		2021		2022	
	MWh	Share, %	MWh	Share, %	MWh	Share, %
Electricity	362.58	61.92	377.72	61.11	330.50	59.59
Thermal energy	223.00	38.08	240.34	38.89	224.13	40.41
Total demand	585.58		618.06		554.63	

Thermal energy consumption

The performed analyses of the monthly thermal energy consumption, demonstrates that the energy changes are adequate to the thermal load profile of the building and they correspondents to the building heating needs during the analysed months (Figure 1).

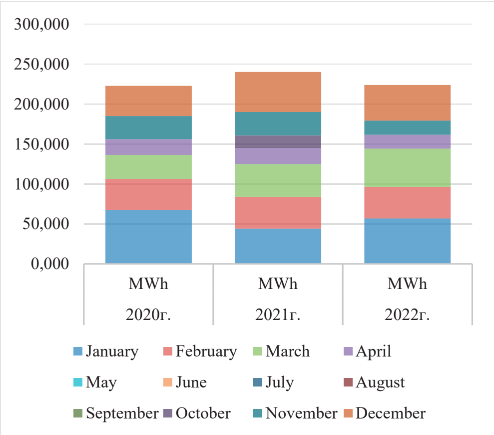

Figure 1. Annual consumption of thermal energy, MWh

Electricity consumption

The analyzes of the monthly electricity consumption demonstrates spikes in winter months when electricity is used for heating and spikes in electricity consumption in summer, when cooling is used (Figure 2 and Figure 3).

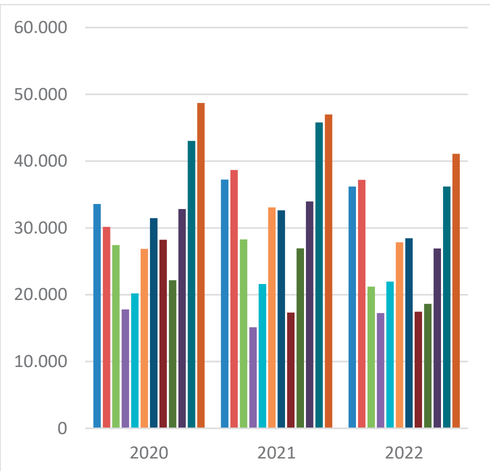

Figure 2. Monthly electricity consumption, kWh

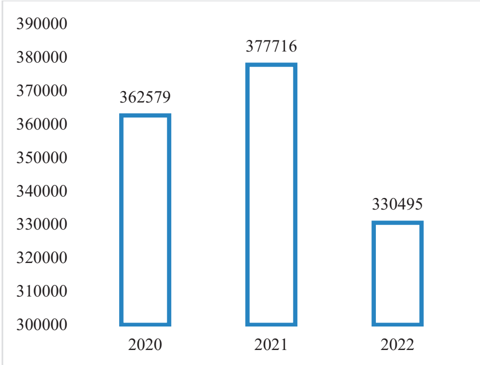

Figure 3. Annual electricity consumption, kWh

Buildings transformation model and related concept

The building can be transformed into PEB with zero emission generation following three main steps. Firstly, through reducing building`s energy demand by improving its energy efficiency, following the Energy efficiency first principle, which emphasis reduced and managed demand in a cost-effective way (European Commission, Energy Efficiency First principle, 2023). This can be achieved through very solid passive retrofitting, such as thermal insulation of the building walls, roof and underfloor and window replacements, which is the first step towards highly efficient buildings. Secondly, through building needs electrification by means of implementation of very efficient heat pumps for heating, cooling, ventilation and DHW. And third, by the transition towards high-share of local renewable energy generation for achieving an annual positive energy balance while having net-zero carbon emissions.

Related concept

The following 8 energy conservation measures (ECM) are envisaged, so as to transform the building into PEB:

- ECM-01: Thermal insulation of external walls – the measure envisages the installation of 15cm. stone wool external thermal insulation, coefficient of thermal conductivity $\lambda \leq 0.033$ W/m.K;
- ECM-02: Thermal roof insulation - installation of 15 cm glass wool thermal insulation, $\lambda \leq 0.033$ W/m.K;

- ECM-03: Thermal insulation of the basement - XPS with a thickness of 15 cm, λ ≤ 0.035 W/m.K;
- ECM-04: Replacement of existing windows and installation of smart sun protection blinds on the south and west facades;
    - Windows: Al windows U ≤ 1.10 W/m².K, with glazing consisted of 4 mm 4-seasons glass, 16 mm argon filling and 4 mm transparent glass.
    - Sun protection blinds holding protection with up to 75% dimming capability.
- ECM-05: Implementation of VRV/VRF direct evaporation systems for heating, cooling and heat recovery ventilation;
    - Average SEER of units ≥ 6.20 kW/Kw;
    - Average SCOP of units: ≥ 4.60 kW/kW;
    - Average seasonal heat recovery rate ≥ 75%.
- ECM-06: LED lighting - In order to achieve energy savings and to reduce the power consumed for lighting, it is necessary to redesign the lighting in the building, replacing all fluorescent lighting fixtures with high-efficiency LED energy-saving lighting fixtures;
- ECM-07 - Introduction of automation and energy management and monitoring system;
- ECM-08 - Implementation of a PVs (334.2 kWp total capacity) installation for own needs coupled to a lithium-ion energy storage system with a capacity of 60 kWh. The configuration envisages the following roof and facade systems:

a) Total foof capacity - 195.20 kWp (Figure 4)
  - Roof system east - 97.60 kWp
  - Roof system west - 97.60 kWp

b) Total BIPV capacity - 139.00 kWp (Figure 5, Figure 6 and Figure 7)
  - East - 22.14 kWp
  - West - 40.18 kWp
  - South - 76.68 kWp

In addition to the installation, a lithium-ion energy storage system with a capacity of 60 kWh is planned. The surplus generated in the solar hours will be stored in the batteries, which will have a life of more than 5000 cycles. The stored energy will be fed to the consumers during the hours of no or insufficient production. The battery is sized to cover the building's average nighttime load.

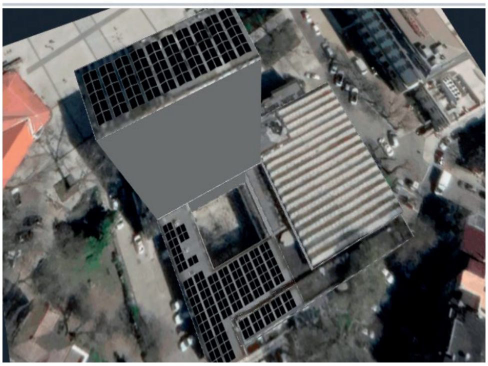

Figure 4. Planned roof system - 195.20 kWp

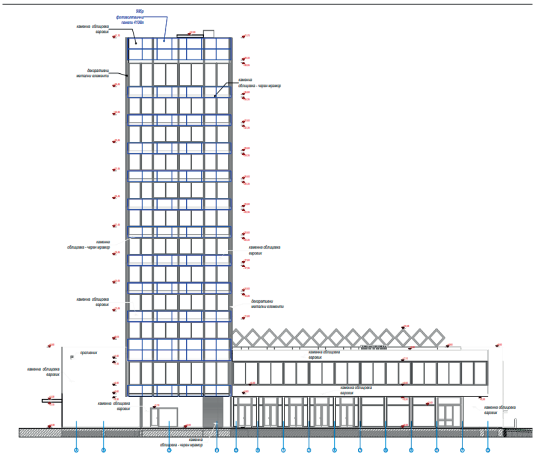

Figure 5. Layout of BIPV panels - west façade

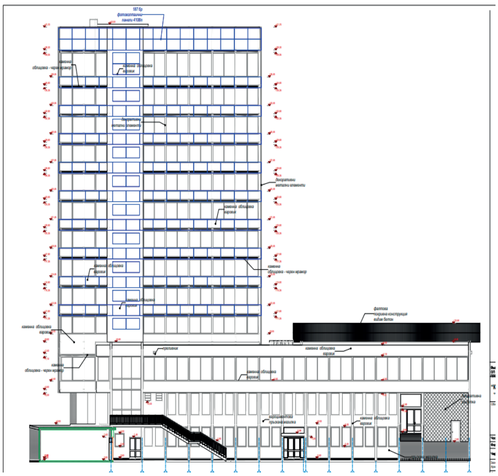

Figure 6. Layout of BIPV panels - south facade

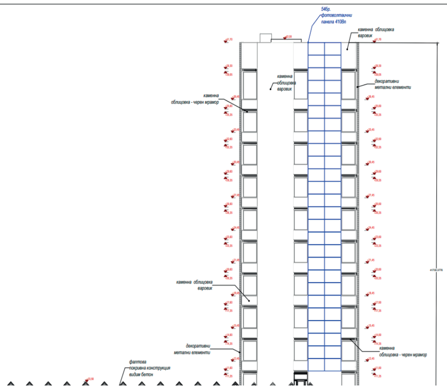

Figure 7. Layout of BIPV panels - east facade

Building energy simulation model

To evaluate the proposed scenario a model study of the energy consumption before and after the conversation measures is applied and tested using the software product EAB (the officially licensed product in Bulgaria). Through the applied computer simulation, a complex model of the energy consumption is created, on the basis of which the compliance of the buildings with the requirements for energy efficiency according to the Law on Energy Efficiency is established. The value of the integrated energy characteristic for energy consumption of the analysed building is defined as integrated (set of energy consumption indicators) according to:

- (Regulation No. RD-02-20-3/9.11.2022 on the technical requirements for the energy performance of buildings)
- (Regulation No. E-RD-04-2/16.12.2022 on energy efficiency auditing, certification and assessment of energy savings in buildings).

When creating the model, the building is considered as an integrated system. The general input data that is entered corresponds to the selection of climatic characteristics (according to the geographical area in which the building is located), type of building, mode of use of the building, characteristics of the enclosing structures. Based on the performed assessment the following distribution of the annual energy consumption per type of consumer was estimated (Table 3).

The main characteristics of the case study over which the model was build are demonstrated on Table 4.

Table 3. Distribution of the annual energy consumption – normalised line

Distribution of the annual energy consumption, %					
Heating	Ventilation	Cooling	DHW	Lighting	Internal loads
63.81	7.96	8.83	0.99	4.17	14.24

Table 4. Main characteristics of the case study before and after implementation of envisaged measures

Parameters	Value before	Value after	Unit
Heating/ Cooling area	4876		m²
Heating/ Cooling net volume	12741		m³
External walls area	1814		m²
Roof area	967		m²
Floor area	967		m²
Windows area	1796		m²
External walls U-value	1.90	0.19	W/m².K
Roof U-value	1.44	0.20	W/m².K
Floor U-value	0.99	0.28	W/m².K
Windows U-value	3.59	1.11	W/m².K
Glazing ratio	36.8		%
Warmth from residents	3.20		W/m²
Av. operational days	256	256	days
Working hours per day	11	11	h
Infiltration rate	0.70	0.50	1/h
Daytime internal heating temperature	22		°C
Nighttime internal heating temperature	18		°C
SCOP	1.60	4.60	W/W
Heating season	175		days
Heating degree days	2400		HDD
Daytime internal cooling temperature	25.0		°C
Nighttime internal cooling temperature	26.0		°C
SEER	3.20	5.00	W/W
Cooling season	184		days
Ventilation rate	1.0	1.0	m³/h.m²
Ventilation temperature	20.0	20.0	°C
Heat recovery	0.0	80.0	%

As a result of the model simulation the following energy consumption forecasts are derived per type of consumer before and after the implementation of the envisaged measures (Table 5).

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Table 5. Normalized annual consumption and estimated energy consumption after execution of ECM

System, facility	Normalized annual energy consumption		Annual energy consumption after ECM	
	specific energy use	total energy use	specific energy use	total energy use
	kWh/m^2	kWh	kWh/m^2	kWh
Heating	151.68	739 609	12.60	61 417
Ventilation	18.92	92 249	1.22	5 928
DHW	2.36	11 513	2.36	11 513
Fans, pumps	1.59	7 753	1.59	7 753
Lighting	9.91	48 334	5.10	24 861
Appliances	32.28	157 374	32.28	157 374
Cooling	20.99	102 369	6.58	32 100
Total	237.74	1 159 201	61.72	300 946

The measures applied will bring significant energy savings (74.04%) compared to the baseline scenario, as shown on the Table 6 and Figure 8.

Table 6. Estimation of energy savings

Normalized total consumption	Total consumption after ECM	Energy savings	Energy savings
kWh	kWh	kWh	%
1 159 201	300 946	858 255	74.04

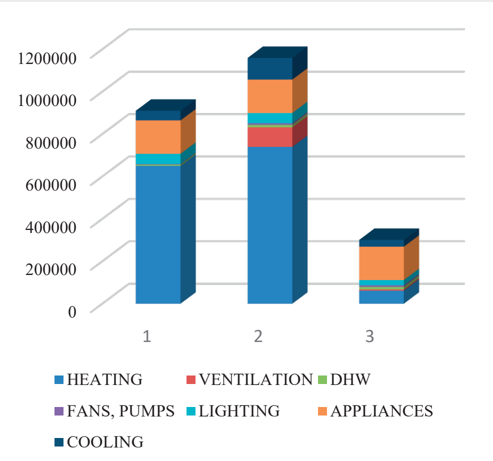

Figure 8. Annual distribution per type of consumer – current situation (1), baseline situation (2) and situation after ECM

The building will demand only electricity since measures are implemented, meaning that this electricity could be supplied through renewable mean. It is expected that the highest peak of electricity consumption will be during the daytime, which matches with the maximum PV electricity generation, meaning that the self-consumption of the produced energy will be high. Nevertheless, building optimization is highly important, since high PVs penetration levels may result in stress on the electrical grids during hours with high solar power generation. These technical issues can be effectively tackled by coupling PVs and battery energy storage systems (BESSs) on the side of the final consumer to store locally the energy that is not consumed during high generation periods. It has been validated that the deployment BESSs are significantly increasing the self-sufficiency of prosumers, as well as enhancing their autonomy (Kisyov, 2022). Thus, a PVs with a total installed capacity of 334.20 kWp coupled to a lithium-ion energy storage system with a capacity of 60 kWh will be implemented, as avoid large share of unbalanced power to be fed into the grid (Table 7).

Table 7. Estimation of generated energy by the PVs

	Roof PVs generation	Facade PVs generation	Total generation
	195.2 kWp	139.0 kWp	334.2 kWp
	kWh	kWh	kWh
January	8492	7581	16073
February	11120	7771	18891
March	19114	10467	29581
April	25080	10732	35812
May	28918	9956	38874
June	30754	9519	40273
July	32946	10553	43499
August	30550	11916	42466
September	22704	11501	34205
October	15724	10627	26351
November	10020	8676	18696
December	7792	7930	15722
Total	243 214	117 229	360 443

The total estimated generated electricity from both PV installations (facade and rooftop) is estimated at 360 443 kWh per year, meaning an excess electricity of 59 497 kWh is available for different purposes. There are possibilities the excess electricity is trade in the grid or provided to an adjacent building. Nevertheless, a very coherent load matching management is needed, so as to increase building self-consumption and self-sufficiency rates. The excess electricity available means the building could be considered as a PEB.

Financial estimations

Estimations of the payback period and the total investment required is provided in Table 8, where the payback period is calculated to assess the financial feasibility of the energy transformation model, where a payback period is the length of time it takes to recover the cost of an investment

Table 8. Estimation of payback period and total investment

Package 1	Energy savings	Financial savings	Investment with VAT	Payback
ECM-01	73 069	36 754	368 156	19.59
ECM-02	28 423	14 297	116 137	15.89
ECM-03	16 297	8 197	27 926	6.66
ECM-04	173 791	87 417	696 129	15.57
ECM-05	241 032	121 239	1 032 607	16.66
ECM-06	23 473	17 135	34 279	3.91
ECM-07	17 325	8 714	20 777	4.66
ECM-08	360 443	144 177	528 784	4.91
Total	933 853	437 930	2 824 796	12.62

CONCLUSIONS

The described transformative package of measures was applied to receive funding within the National Plan for Recovery and Sustainability. The project received an excellent score and contract will be signed in the second quarter of 2024. Thus, the envisaged measures will be applied within the next two years.

In overall, the building can be transformed to Positive Energy Building with an investment of 2 824 796 € bringing some 933 853 € of energy improvements. In this case the value of retrofitting for reach PEB is estimated at 3.02 EUR/kWh or 579 EUR/m².

In order to achieve the savings, a management and control system for the HVAC systems will be developed, through which monitoring, parameter settings, switching on/off of the system and/or fan convector and limiting the level of energy consumption will be carried out. Charging stations for electric cars or electric bicycles can be integrated to the project in for more intelligent utilization of the surplus generated by the PVs.

The next step in the building transformation and PEBs development process is seen in the transformation of districts to Positive Energy Districts (PEDs). The PEDs is consisted of groups of buildings with net zero greenhouse gas emissions generation, who are actively managing an annual surplus production of renewable energy (Guarino et al., 2023). Thus, the pilot case building can set the role model in Plovdiv for the formation of the first Positive Energy District.

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