energies

Article

A Comprehensive Approach to Nearly Zero Energy Buildings and Districts: Analysis of a Region Undergoing Energy Transition

Georgios Martinopoulos [1,2,*], Alexandros Tsimpoukis [1], Vasileios Sougkakis [1], Petros Dallas [1], Komninos Angelakoglou [1], Paraskevi Giourka [1] and Nikolaos Nikolopoulos [1]

1 Chemical Process and Energy Resources Institute, Center for Research and Technology Hellas, Thermi, GR-57001 Thessalonik, Greece; a.tsimpoukis@certh.gr (A.T.); sougakis@certh.gr (V.S.); dallas@certh.gr (P.D.); angelakoglou@certh.gr (K.A.); giourka@certh.gr (P.G.); n.nikolopoulos@certh.gr (N.N.)
2 Merchant Marine Academy of Macedonia, Néa Michanióna, GR-57004 Thessaloniki, Greece
* Correspondence: g.martinopoulos@certh.gr

Abstract: This paper explores the development of positive energy communities using Eordaia, Greece, as a case study. The approach combines building and district-level energy analysis to achieve nearly zero energy performance through retrofitting, district-level storage systems, and renewable energy technologies. A parametric analysis utilizing RETSCREEN Expert and EnergyPlan software determines the optimal mix of technologies based on technical and financial parameters, with Eordaia, a region in energy transition and part of the RESPONSE Horizon project, illustrating the practical benefits. It includes a neighborhood of 105 mixed-use properties and two municipal buildings where a range of renewable energy sources and energy efficiency measures are applied. Insulation, photovoltaic systems, LED lighting, predictive thermostats, and windows coated with nanotechnology are some of the key interventions considered. The findings show considerable reductions in CO_2 emissions and energy use, with payback periods ranging from 8.7 to 9.6 years. This study underscores the value of district-level strategies over individual building retrofits, highlighting cost savings and improved energy performance. These findings offer valuable insights for urban planners and policymakers aiming to transform urban areas into sustainable, positive energy districts, supporting the EU's 2050 net-zero emissions goals.

Keywords: positive energy; energy efficiency; smart and green buildings and districts; urban development; sustainability; retrofitting; renewable energy

check for updates

Citation: Martinopoulos, G.; Tsimpoukis, A.; Sougkakis, V.; Dallas, P.; Angelakoglou, K.; Giourka, P.; Nikolopoulos, N. A Comprehensive Approach to Nearly Zero Energy Buildings and Districts: Analysis of a Region Undergoing Energy Transition. *Energies* **2024**, *17*, 5581. https://doi.org/10.3390/en17225581

Academic Editors: Ala Hasan and Hassam Ur Rehman

Received: 22 October 2024
Revised: 4 November 2024
Accepted: 5 November 2024
Published: 8 November 2024

1. Introduction

The ambitious goal of the European Union is to reach net-zero greenhouse gas (GHG) emissions by 2050. As of 2023 [1], the EU revised goals for 2030 aim to raise the share of renewables in the EU's final energy consumption to 42.5% and set an ambitious energy efficiency target of reducing final energy consumption by at least 11.7% [1] compared to the projected energy use for 2030 (based on the 2020 reference scenario). The building sector, responsible for over 35% [2] of GHG emissions, will play a crucial role in achieving these goals.

Although there is a continuous emphasis on increasing energy efficiency at the building level, there is a growing recognition of the importance of improving energy performance at the community level. Urban regions play a critical role in achieving emissions targets, as they are responsible for 70% of GHG emissions and two-thirds of energy consumption [3]. Furthermore, cities accommodate approximately 75% of the EU's population, a figure projected to increase to 80% by 2050 [4].

Near Zero Energy Districts (NZED) have emerged as a promising approach to reducing energy consumption and carbon emissions at the district scale. Several studies have explored various aspects of NZED, including the impact of urban morphology on building energy performance [5], the use of urban sustainability simulations and building energy modeling [6], and the assessment of district-scale energy modeling tools [7] and certification schemes [8].

Synnefa et al. [9] examined four Net Zero Energy (NZE) settlements located in Cyprus, France, Italy, and the UK, revealing that these settlements were cost-effective and achieved both energy use and renewable energy production targets. Hachem [10] investigated how design elements can affect the performance of solar communities and successfully reduce GHG emissions. In Hachem-Vermette et al. [11], solar thermal, borehole energy storage, and photovoltaic technology were explored to produce energy in excess of consumption within a neighborhood in Canada. The financial implications associated with NZE settlements were also investigated by Isaac et al. [12], who developed a model for optimizing renewable technologies. This study revealed that although urban density had a complicated effect on costs, larger communities could still demonstrate energy savings. In evaluating retrofit techniques for enhancing the performance of NZEB, Paduos and Corrado [13] identified substantial cost savings alongside significant reductions in non-renewable energy consumption.

District-level energy system planning often requires optimization and iterative calculation methods. Evins [14] and Allegrini et al. [15] emphasized the importance of tools that facilitate decision-making in district energy modeling during the initial phases of planning. To assess the energy positivity of neighborhoods in Finland and France, Ala-Juusela et al. [16] employed a decision support tool defining positive energy communities as ones having an annual energy consumption that is less than the locally produced renewable energy. Rehman et al. [17] created a positive energy community model optimized for life-cycle cost and electricity import, integrating district heating, wind turbines, photovoltaic cells, and electric vehicles tailored to the Nordic environment. Angelakoglou et al. [5] proposed a model to assess the feasibility of the transition of districts to Nearly Zero Energy Districts (NZEDs), based on locally produced RES, identifying thresholds in terms of climate, population density, and solar efficiency, among other factors. Saarlos et al. [18] provided a techno-economic assessment applying NZED design principles to the National Western Center in Denver, USA, emphasizing strategies for maximizing solar potential and renewable thermal energy utilization. Iturriaga et al. [19] on the other hand, presented an optimization methodology for drafting renovation strategies at the district level, utilizing the Mixed Integer Linear Programming (MILP) model. Sougkakis et al. [20] investigated the feasibility of near-zero and positive energy communities in the Greek context providing a methodology grounded on technical and economic criteria.

The EU's shift to a carbon-neutral economy depends heavily on cities since they serve as hubs for innovation and present opportunities for systemic local transformation despite the inherent challenges this entails. The European Strategic Energy Technology Plan encourages the use of positive energy blocks and smart cities, utilizing building synergies to provide energy-efficient lighting, heating, and cooling [21].

This paper provides a holistic framework that goes beyond individual building retrofits, examining district-wide energy interventions. This district-level focus allows for optimization across multiple buildings, which is often more efficient and cost-effective than isolated building retrofits.

It presents the application of a comprehensive methodology originally developed by Sougkakis et al. [20] for evaluating and recommending various interventions to improve energy efficiency at various scales ranging from single buildings to entire districts within the Municipality of Eordaia, Greece, a Fellow City in the RESPONSE Horizon project [22].

By applying parametric analysis, this study identifies the optimal combination of energy technologies tailored to both technical performance and financial feasibility. This approach ensures that the proposed interventions are not only energy-efficient but also economically viable, which is crucial for wider adoption in real-world applications.

Eordaia serves as a case study to demonstrate and discuss the applicability and usefulness of the proposed methodology. By quantifying the CO_2 reductions and payback periods, the paper provides practical insights for policymakers and investors, aligning the findings with financial and environmental sustainability goals. This evidence-based approach helps justify initial investments by demonstrating the long-term cost savings and emissions reductions achievable.

The methodology incorporates data-driven modeling and Key Performance Indicators (KPI) to identify and replicate effective energy solutions, providing urban planners and city officials with a tool to evaluate different strategies to improve energy performance, taking also into consideration the Smart Readiness Indicator of the buildings.

Overall, this study provides a robust template for PED development, offering insights and data that can guide the implementation of similar projects across the EU and beyond, making it a valuable addition to both academic and practical efforts in sustainable urban development.

2. Methodology

The methodology encompasses two distinct levels of analysis: the first at the building level aimed at achieving Positive Energy Buildings (PEB) and the second at the district level aiming at achieving Positive Energy Districts (PEDs). Each level follows a systematic step-by-step process that includes data collection and the identification of the most appropriate retrofit solutions.

2.1. Methods of Retrofitting Analysis and Selected Software Tools

The process for assessing energy upgrades is outlined in the following steps and in Figure 1. Steps 1 to 5, referring to the building level analysis, should be repeated for different typologies of buildings within the examined district:

1. **Data Collection.** Data related to the building's envelope and electromechanical systems are collected through an in situ inspection to ensure understanding of existing conditions, such as:
   - The building's location, occupancy schedule, thermostat settings, and the fuel types that are consumed by the building during its use (e.g., natural gas, electricity, etc.)
   - Specifications of the heating and cooling systems installed in the building, i.e., heat pumps, boilers, district heating system, etc.
   - The end-uses, which consume energy and/or result in heat gains in the building. This involves information on the building envelope (walls, floors, roofs, windows, etc.) infiltration rates and ventilation losses, lighting gains, equipment gains, etc.
   - Specifications for any renewable systems installed in the building.
2. **Baseline Condition.** The baseline energy condition of the building is required and is determined through energy simulations. A suitable software, RETScreen Expert v.9 [23–25], is selected for the simulations at the building level, combining ease of use and the capacity to model a wide range of building technologies. This tool has been utilized in many studies focusing on the assessment of the energy performance of buildings, effectively accounting for the performance of various RES and energy efficiency technologies [20,26,27]. Due to its ease of use, RETScreen Expert can also be employed by non-experts, such as municipal officials.
3. **Smart Readiness Indicator (SRI) Calculation.** The Smart Readiness Indicator (SRI) is calculated for the buildings based on the available energy systems. The SRI evaluates the smart readiness of buildings by assessing their capability to perform three key functionalities: optimize energy efficiency, adapt operations to meet occupant needs, and respond to signals from the grid [28].
4. **Identification of RES technologies.** Innovative energy efficiency and renewable energy sources (RES) technologies are identified for potential installation in the buildings. The selection of the retrofitting measure includes both conventional and innovative technologies drawn from a curated pool of options demonstrated by the RESPONSE project [29].
5. **Performance Simulation Post-Retrofit.** Following the calibration of the model and identification of the applicable technologies, the performance of the building after the energy retrofit is simulated. The calibration of the model was concluded by comparing the results of the simulation for the initial state of the buildings with their energy

consumption (based on the energy bills) from the previous 2 years. The time step of the analysis was on a monthly basis. Then, the SRI is recalculated, taking into consideration the technologies to be integrated into the buildings.

6. **Estimation of District Energy Requirements.** The energy requirements for the entire district are estimated by aggregating the energy needs of residential, commercial, and other buildings within the designated area.
7. **EnergyPLAN Analysis.** The total annual district energy demand, expressed in terms of heating, cooling, and electricity obtained from the previous step, serves as the input for conducting the analysis using the EnergyPLAN software v16.22 [30]. This tool is specifically designed for conducting district energy analyses and can create detailed energy models at national or regional levels, offering a user-friendly interface that facilitates these processes.
8. **Key Performance Indicators (KPI) Calculation.** Finally, key performance indicators (KPI) are calculated to evaluate PEDs performance before and after the energy retrofit, providing a quantifiable measure of the improvements achieved through the implemented retrofit measures. The analysis of the KPIs provides valuable insights into the effectiveness of the various technologies and helps identify those that can contribute to the development of PEDs, leading to informed decision-making at the district scale.

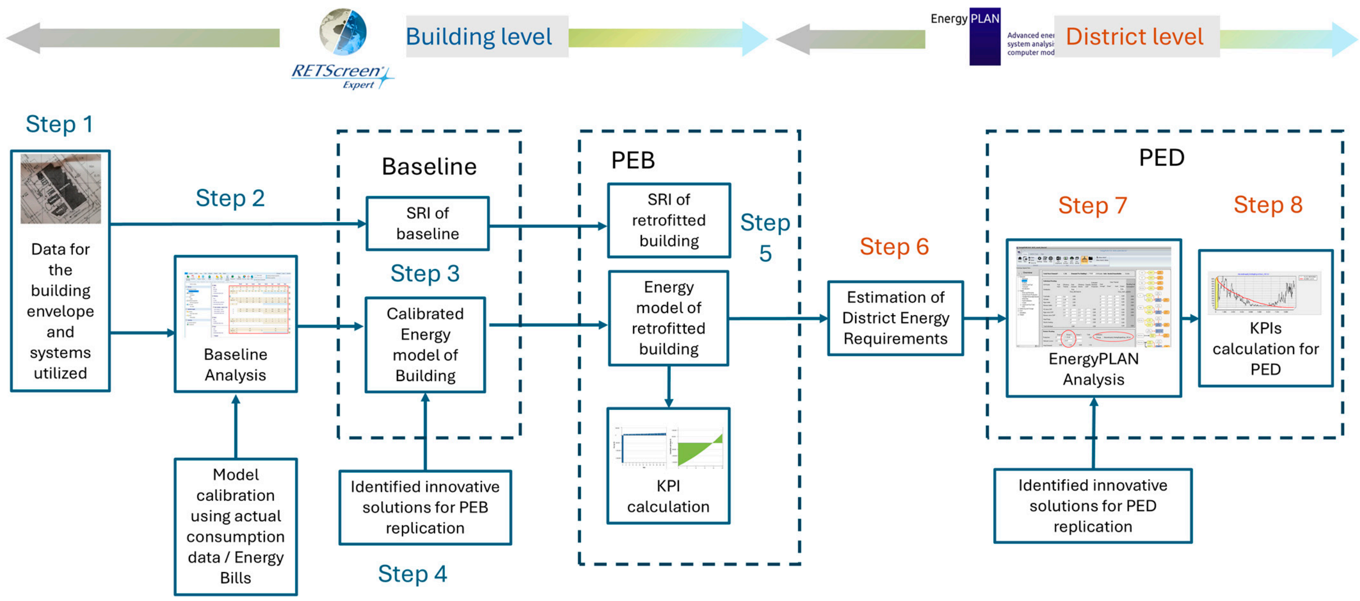

Figure 1. Flow chart of methodology for energy analysis at both the building and district levels.

2.2. Techno-Economic Assessment

Following the building and district-level processes aimed at achieving PEB and PEDs, respectively, a simplified techno-economic assessment is performed to evaluate the performance of the retrofit measures. The assessment incorporates three key indicators: the degree of energetic self-supply (DE) from renewable energy systems (RES), the payback period, and the reduction of CO_2 emissions. The degree of energetic self-supply through RES is measured by the ratio of on-site energy production from RES to the total energy consumption over a defined period [31].

$$DE_E = LPE_E/EE_C, \tag{1}$$

where

LPE_E = locally produced electrical energy (kWh/year),

EE_C = electrical energy consumption (kWh/month or kWh/year).

Following this, the static payback period (EPP) is defined as the energy-related investment cost over the difference between the total annual costs (TAC) after the energy-related investment (TAC_{after}) and the total annual costs before the investment (TAC_{before}).

$$EPP = ERI/m, \tag{2}$$

where

ERI = energy-related investment (EUR)

$m = TAC_{after} - TAC_{before}$ (EUR/year)

TAC_{after} = total annual costs (or revenues) after the energy-related investment (EUR/year). In the case of revenues, when energy exports exceed energy imports, the TAC_{after} receives a negative sign.

TAC_{before} = total annual costs before the energy-related investment (EUR/year).

The total annual cost is calculated by summing costs associated with heating, cooling, and electricity. These costs are calculated by multiplying each type of energy consumption by its corresponding energy vector price.

Finally, emissions reduction is defined as the difference between the amount of CO_2 emitted after the implementation of energy efficiency measures and the CO_2 emitted in the baseline scenario. The emissions are calculated by multiplying the energy consumption by national coefficients of carbon dioxide emissions per unit of energy, which can vary by country [32]. In this paper, the relevant coefficients for the Greek energy mix utilized are 0.347 kg CO_2 per kWh of thermal energy delivered by the district heating network and 0.989 kg CO_2 of electrical energy supplied from the grid [33].

3. Case Study in the Municipality of Eordaia

This section provides a detailed description of the application of the above methodology for the case study of the Municipality of Eordaia. The Municipality of Eordaia, located at the center of the lignite basin of Western Macedonia, has a population of 42,515 people (according to the 2021 census) [34]. Eordaia was the first municipality of Greece to join the Covenant of Mayors in 2008, and it approved its Sustainable Energy Action Plan (SEAP) in 2016. A recent revision, now termed Sustainable Energy and Climate Action Plan (SECAP), has been prepared to incorporate climate change adaptation measures. As one of four pilot projects under the Platform on Coal Regions in Transition, Western Macedonia is focusing on initiatives to facilitate a gradual transition to the meta-lignite era. The region has a continental climate, characterized by cold winters and hot summers, with an average annual air temperature of 12 °C. Additionally, a district heating network is operated within the municipality.

In the Municipality of Eordaia, several renovation measures were evaluated at the building and district levels. The municipality identified ten municipal buildings to assess the feasibility of implementing deep-energy renovations aimed at achieving nearly Zero Energy Building performance levels, two of which are included in the current study. In addition, a neighborhood in the city center was selected for achieving PED status by applying and evaluating energy upgrade measures. The selected municipal buildings and the PED area are illustrated in Figure 2.

3.1. Overview of the District's Building Characteristics

The selected PED area is in the city center and comprises 105 mixed-use privately owned (non-municipal) buildings, including residential and non-residential structures, as well as two municipal buildings: the Commercial Polycenter and the Municipal Library. An in situ inspection assessed the key characteristics of the non-residential building, including usage, useful area, number of floors, geometry, and age, to determine the energy requirements of the neighborhood in its baseline condition prior to any renovation measures examined.

Figure 2. Aerial view of Eordaia where the identified residential neighborhood (yellow box) with the two municipal buildings is presented.

Among the non-municipal buildings, eighty-eight are classified as residential, twelve as commercial (including shops and supermarkets), three as offices, one as a bank, and one as a hotel. Most buildings (60%) have three or more floors, while the rest have one to two floors. The total gross area of the PED was 68,617 m^2, which includes 46,284 m^2 of residential space, 15,913 m^2 for shops, 680 m^2 for supermarkets, 2592 m^2 for offices, 364 m^2 for the bank, and 1136 m^2 for the hotel. In addition, non-heated buildings, including abandoned structures, parking, and storage spaces, accounted for 2328 m^2.

Residential buildings were clustered into four groups, based on their year of construction, with a representative building selected from each group. These four representative buildings of each group align with typical building typologies for the region (Climatic Zone D) as defined by the TABULA Web Tool [35]. According to TABULA, buildings in Greece are grouped into four main categories based on the year of construction: (1) buildings constructed until 1980, (2) buildings from 1981 to 2000, (3) buildings from 2001 to 2010, and finally buildings constructed after 2011. The selected representative buildings from the PED are Building 27 (Tabula MFH-04), Building 57 (Tabula SFH-01), Building 59 (Tabula MFH-02), and Building 69 (Tabula MFH-03). The main characteristics of these buildings and the corresponding TABULA typologies are presented in Table 1. Data required for the simulations, including materials thermal transmittance, infiltration rate, typical shading coefficients, building element areas, and more, were obtained from the TABULA database.

Table 1. Main characteristics of the selected buildings in each group and corresponding typologies from the TABULA Webtool.

Group	Building	Type	Construction Year	Floors	Floor Area (m^2)	TABULA Building ID
Pre-1980	57	Single-family	1972	2	118	SFH.01
1981–2000	59	Multi-family	1995	5	212	MFH.02
2001–2010	69	Multi-family	2005	5	211	MFH.03
2011–	27	Multi-family	2020	4	118	MFH.04

The municipal buildings included in the assessment are as follows:

- Municipal Library (1953): This building has a total heated area of 288 m^2;
- Commercial Polycenter: A one-story building complex with a roof terrace and a total heated area of 872 m^2;

It is important to note that the assumptions used in the analysis were derived from the relevant national Technical Directive (TOTEE 20701-1:2017 [33]), with the exception of lighting gains, which in some cases were determined through a detailed inventory. In buildings where indoor access was not possible, reference data for the lighting gains were obtained from the Technical Directive. For residential buildings, the occupancy schedule is assumed to be 18 h per day, with internal gains at 4 W/m^2, lighting gains at 6.4 W/m^2, and appliance gains at 2 W/m^2. Lights operate for an average of 4 h per day (yearly average), while domestic hot water is supplied by district heating in winter and by an electric heater in summer, with consumption based on the number of bedrooms in each building at a rate of 27.38 m^3/year/bedroom [33].

Heating in the buildings is supplied by the district heating network of Eordaia, while cooling is provided through split-type air conditioning units. The thermostat settings are maintained at 20 °C during the heating season and 26 °C during the cooling season for all zones, except for corridors where the heating temperature is set to 18 °C.

By inserting all the data in the RETscreen, the consumption levels for electricity and thermal energy are calculated. In order to increase confidence in the simulations, results of the analysis of the two municipal buildings in RETScreen were compared against actual consumption data collected from the energy bills (Table 2). Deviations between the simulation and the actual consumption data for the Municipal Library were from 0.4% for the thermal and 21% for the electrical loads, while the respective deviations in the Municipal Commercial Polycenter were 9.9% and 18.8%, respectively. Such deviations are considered normal as it is common to encounter discrepancies between simulation models and actual building energy performance due to the use of standardized climatic data rather than actual conditions, assumptions regarding occupants, and approximations used in the simulations related to the building envelope and the HVAC systems [36]. A deviation of ±20% in the fuel and electricity consumption is considered a reasonable threshold for confirming that the model is calibrated and suitable for incorporating the innovative solutions discussed in the subsequent sections. Regarding the residential building typologies, due to the lack of actual monitored data, results from the RETScreen analysis were compared to the relevant calculation sheets obtained from the TABULA website [35]. Since the TABULA calculations estimated only the heating load of the buildings, the comparison of the results was based only on this parameter.

Table 2. Energy consumption from bills and simulation results from RETsrceen.

Building	Energy Consumption from Bills and TABULA (kWh/Year)		Simulation Results (kWh/Year)	
	Heat (District Heating)	Electricity	Heat (District Heating)	Electricity
Municipal Commercial Polycenter	365,914	43,308	329,734	51,444
Municipal Library	42,920	16,886	42,761	13,362
Building 27 (Tabula MFH-04)	32,742	-	25,745	-
Building 57 (Tabula SFH-01)	58,141	-	67,124	-
Building 59 (Tabula MFH-02)	143,670	-	147,929	-
Building 69 (Tabula MFH-03)	52,579	-	52,386	-

The baseline scenario is completed by calculating the Smart Readiness Indicator (SRI) for both municipal and residential buildings. SRI [37] is an EU scheme for rating the smart readiness of buildings. It is a key policy tool that will help the evaluation of the impacts of building smartification as well as support the decision-making and action planning as the EU building stock is modernized and becomes more sustainable and smarter. The SRI assesses the ability of a building to operate in such a way as to optimize its energy efficiency and overall performance, its ability to adapt to signals from the grid (energy flexibility), and respond to the needs of the building occupants [38]. The calculation of SRI as well as the methodology is described in detail in [39,40].

In the present analysis, the SRI estimations have been conducted by utilizing the SRI assessment package provided by the European Commission [41]. Method B, Expert SRI assessment, is chosen here for the non-residential municipal buildings as well as the residential buildings of the district. The SRI is calculated for the baseline scenario, i.e., the status of municipal buildings, using the default weighting factors for multicriteria evaluation.

Table 3 presents the total SRI scores for the baseline scenario of all categories of PED buildings. All buildings fall into the "lower than 20%" classification, with SRI scores ranging from 6 to 12%. Notably, the highest SRI score is found at the TABULA building 27, which is the most recently constructed residential building, while the lowest score is assigned to the Municipal Library. Buildings equipped with cooling devices generally exhibit higher SRI scores compared to those lacking such equipment. Overall, the buildings share similar characteristics leading to comparable low SRI results, with the notable exception being the presence of cooling systems, which influences significantly the total SRI score. Consequently, retrofit scenarios are necessary to improve the SRI score of all buildings, including newer ones, since despite having adequate thermal insulation and better heating systems, they still do not meet the criteria to be classified as smart buildings.

Table 3. Total SRI scores for the baseline scenario.

Building	Total SRI Score (%) and SRI Class
Municipal Commercial Polycenter	9.2 (<20%)
Municipal Library	5.5 (<20%)
Building 27 (Tabula MFH-04)	10.5 (<20%)
Building 57 (Tabula SFH-01)	6.3 (<20%)
Building 59 (Tabula MFH-02)	7.3 (<20%)
Building 69 (Tabula MFH-03)	8.3 (<20%)

The next step involves utilizing the previous analysis to facilitate the selection of the most appropriate retrofit scenarios for implementation, tailored to the specific requirements of each building. The following list presents selected retrofitting solutions for the analyzed buildings; however, users of this methodology are encouraged to select options that align with the individual requirements of the buildings under study.

1. **Pergola with bi-facial PVs and conventional rooftop PVs:** Bi-facial photovoltaic (PVs) panels integrated into pergolas, along with conventional rooftop PVs, are proposed as an alternative when exterior space is limited. The BIPV pergolas utilize double-laminated glass with embedded bi-facial cell technology, which helps to minimize roof load and reduce shading on the PV arrays.
2. **Predictive Thermostats:** Predictive thermostats incorporate advanced capabilities featuring a display interface and a data platform [29]. They collect energy data to perform daily consumption calculations using machine learning techniques, allowing for predictive estimates for the remainder of the year. This type of thermostat is estimated to reduce annual heating energy consumption by 7–25% and cooling demand by 15–40% [42]. For the purposes of this analysis, it is conservatively assumed that energy requirements for heating and cooling will be reduced by 15% and 25%, respectively.
3. **Nano-coated four-glazing windows**: Nano-coated four-glazing windows offer exceptional energy efficiency with performance levels 75% better than existing windows. The four-glazing modern nanocoatings on the windowpanes block the radiative heat transfer from the clear sky, with technical specifications that include a U-value of 0.55 W/m^2K and an infiltration rate of 0.5 $m^3/h\ m^2$ according to the Greek Building Code.
4. **LED lights:** Replacing traditional light bulbs with LED lights is a common yet critical retrofit measure that significantly impacts the energy efficiency of buildings.
5. **Conventional retrofit:** A typical yet important intervention is the conventional retrofit, which includes adding insulation to walls, roofs, and floors. Furthermore, older windows are replaced with newer double-glazed windows featuring more insulated frames.

The costs associated with these interventions are presented in Section 3.3.

3.2. Calculating the Baseline Energy Consumption of the District

The energy consumption of the district under study encompasses the aggregated energy consumption of both the municipal and the non-municipal buildings. Energy consumption for non-municipal buildings was estimated separately for residential and non-residential buildings.

The analysis to estimate the energy requirements of each building, including space heating (district heating demand), electricity for cooling, lighting, appliances, and district heating demand for domestic hot water (DHW), was conducted using RETScreen following the methodology outlined in Section 2. The results are presented in Table 4 in terms of specific heat (kWh/m^2) and were subsequently multiplied by the total area of the buildings in each group to calculate the total consumption for the 88 residential buildings (Table 5).

Table 4. Specific energy demand of the four building typologies.

Building	District Heating (Space Heating) (kWh/m^2)	Electricity (Cooling) (kWh/m^2)	Electricity (Appli-ances/Lights) (kWh/m^2)	District Heating (DHW) (kWh/m^2)	Electricity (DHW) (kWh/m^2)	Total Area (m^2)
57	567.6	20.1	22.5	9.9	3.9	29,755
59	237.1	18.7	22.5	14.2	5.6	11,316
69	127.5	11.2	22.5	21.5	8.4	4859
27	57.2	11.6	22.5	15.7	6.2	354

Table 5. Total energy demand of the residential buildings.

Building	Total District Heating Demand (kWh)	Total Electricity Demand (kWh)
57	17,183,301	1,381,161
59	2,842,673	529,023
69	724,020	204,802
27	25,800	14,241
Total	20,775,794	2,129,227

The calculation of the energy required for non-residential buildings followed a different methodology due to the absence of typical building typologies for comparison (as utilized for residential buildings with TABULA data). Instead, the specific energy demand for each type of use was derived from statistical data obtained from Energy Performance Certificates issued in the city for the period 2011 to 2023 [43]. The following assumptions relevant to Eordaia were applied to convert these values to final energy:

- 100% of space heating demand is covered by the District Heating network.
- 100% of cooling demand is met by Air-Source Heat Pumps.
- The District Heating Network Cover Domestic Hot Water needs from October to May, while electrical heaters cover the remaining DHW demand in the summer. It is assumed that the DH network provides 75% of the annual DHW demand, while the remaining 25% is covered by electrical heaters.
- The primary energy conversion factors were 0.7 for the district heating network and 2.9 for electricity [33].

The resulting final energy demand per category, i.e., heating, cooling, lighting, and DHW is presented in Table 6.

Table 6. Specific final energy demand for the non-residential building uses.

	Final Energy Demand (kWh/m^2/Year)			
Building Use	**Heating**	**Cooling**	**Lighting**	**DHW**
Shops	340.31	23.41	55.31	3.58
Super Markets	143.51	29.04	62.47	0.35
Offices	192.89	15.68	54.37	3.82
Bank	154.71	12.45	48.03	13.44
Hotel	145.57	28.29	97.07	16.68

The final energy consumption for the non-residential buildings, based on the above assumptions and the total area for each building use, is provided in Table 7.

Table 7. Total final energy demand of the non-residential buildings.

	Final Energy Demand (kWh/Year)				
Building Use	**District Heating (Space Heating)**	**Electricity (Cooling)**	**Electricity (Appliances/Lighting)**	**District Heating (DHW)**	**Electricity (DHW)**
Shops	5,184,007	356,609	927,944	40,946	13,648
Super Markets	97,589	19,745	48,884	179	59
Offices	499,959	40,649	171,586	7418	2472
Bank	56,316	4531	17,941	3669	1223
Hotel	165,369	32,141	125,197	14,211	4737
TOTAL	**6,003,242**	**453,677**	**1,291,554**	**66,424**	**22,141**

The total final energy consumption of the district is calculated as the sum of the demands for space heating, cooling, electricity for appliances lighting, and DHW for the 105 neighborhood buildings, comprising both residential (Table 5) and non-residential structures (Table 7), as well as the two municipal buildings (Table 2). The total energy demand of the PED area was determined at 27,217,955 kWh of thermal energy supplied by the district heating network (covering space heating and DHW) and 3,961,409 kWh of electricity (for cooling, lighting, appliances, and DHW).

3.3. Results

This section presents the results of the retrofitting measures for the individual buildings and the overall district. The renovation measures for each building, as well as those within the district, were selected based on their technical suitability and cost-effectiveness. A parametric analysis was performed to identify the most economically viable solutions for each building. Each renovation measure was assessed in isolation, allowing the calculation of the resulting thermal energy savings (from heating and DHW supplied from the district heating network) and electricity savings, along with the associated annual cost savings and payback period for each solution. A summary of the results is presented in Table 8. To estimate the payback period of the technologies examined, the following assumptions were made regarding the cost of the renovation measures and the energy prices:

- **Insulation costs:** Estimated at EUR 50–55/m^2 for the external walls, roofs, and floors based on information provided by installers
- **Window replacement costs:** Set at EUR 250/m^2 (based on information provided by installers)
- **Cost of nano-coated four-glazing windows:** Estimated at EUR 380/m^2 based on manufacturer's data
- **Photovoltaic (PV) system Cost:** Estimated at EUR 1100/kW (a conservative value for Greece) for conventional systems [44,45], and at EUR 1250/kW for the bi-facial PVs installed in pergolas/canopies [46]
- **Cost of LED lights:** Priced at EUR 3 per 10 W lightbulb, based on market data
- **Cost of predictive thermostats:** Ranging from EUR 4000 to EUR 40,000, depending on the size of the building and based on market data
- **Cost of thermal energy:** EUR 0.04/kWh [47]

- **Cost of electricity purchase:** EUR 0.18/kWh, according to billing

Table 8. Payback period (years) of each renovation measure when examined individually in each building.

Building	Conventional Retrofit	LED Lights	Nano Coated 4-Glazed Windows	Predictive Thermostats	PV Canopies	Rooftop PV
Commercial Polycenter	42.3	5.4	65.0	5.1	7.1	-
Municipal Library	21.3	2.7	39.3	15.2	-	4.4
Building 27 (Tabula MFH-04)	50.6	3.8	47.2	8.8	-	4.2
Building 57 (Tabula SFH-01)	10.2	4.2	22.7	5.4	-	4.2
Building 59 (Tabula MFH-02)	17.4	4.1	28.3	8	-	4.2
Building 69 (Tabula MFH-03)	31.6	4.2	28.4	20.5	-	4.2

Based on the results presented in Table 8, the most cost-effective solutions were selected for each building examined for each renovation scenario. In some cases, additional technologies were also selected from the pool of the RESPONSE Innovative Solutions (IS) (even though they were not the most financially attractive) for alternative purposes, such as exploring innovative solutions or due to their suitability when conventional technologies were not technically feasible for installation. A summary of the selected measures applied to each building is provided in Table 9.

Table 9. Selection of measures considered for the renovation in each building ("X" indicates the technology has been implemented to the building, whereas "-" indicates that it has not).

Building	Conventional Retrofit	LED Lights	Nano Coated Four-Glazed Windows	Predictive Thermostats	PV Canopies	Rooftop PV
Commercial Polycenter	-	X	-	X	X	-
Municipal Library	X	X	-	X	-	X
Building 27 (Tabula MFH-04)	-	X	-	-	-	X
Building 57 (Tabula SFH-01)	X	X	-	X	-	X
Building 59 (Tabula MFH-02)	X	X	-	X	-	X
Building 69 (Tabula MFH-03)	X	X	-	-	-	X

The amount of savings in thermal energy and electricity varies considerably depending on the selected measures at each building. The two municipal buildings incorporated photovoltaic (PV) systems, either conventional rooftop panels (Library) or those installed on pergolas/canopies (Commercial Polycenter), to meet all electricity needs. Consequently, the buildings achieved electricity savings of over 100%, resulting in a positive electricity balance where the electricity produced exceeded the net electricity demand on an annual basis (considering net metering). Savings in district heating consumption ranged from modest to substantial, with a reduction from 15% in the Municipal Commercial Polycenter to over 90% in the Municipal Library, depending on the baseline condition and the measures implemented. The thermal and electrical consumption of the two municipal buildings and the four typical buildings (when examined individually) prior to and post renovation are illustrated in Figure 3 below.

A summary of the technical and economic KPIs for all PED building typologies is presented in Table 10.

The smart readiness indicator (SRI) for all the examined buildings was recalculated following the methodology outlined in Section 2. The renovation Scenario aims to retrofit the building towards the Nearly Zero Energy Building (NZEB) standard [48], as introduced by the Energy Performance of Buildings Directive (EPBD). The interventions include the installation of a photovoltaic (PV) system (BAPV/BIPV) and a building management system (BMS) for controlling HVAC systems, lighting, and renewable electricity loads in all residential and municipal buildings. The cost of the BMS is estimated at 25–80 EUR/m^2.

Additionally, a solar thermal system is installed in the residential buildings SFH.01 (57), MFH.02 (59), and MFH.03 (69), with costs ranging from EUR 150 to EUR 500 per person depending on the installation location. The renovation scenario primarily emphasizes the smartification of the buildings rather than an extensive retrofit of the energy systems. Given that there is district heating utilized in Eordaia, significant changes to the heating system are not feasible, except for minor HVAC automation such as occupant detection sensors.

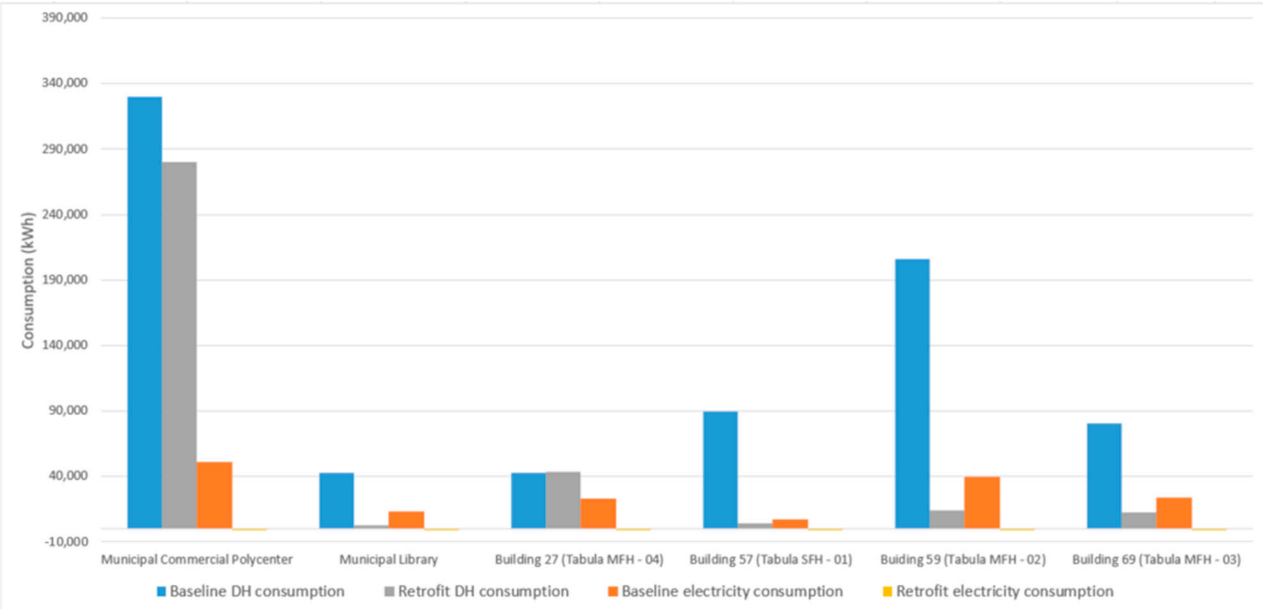

Figure 3. Reduction in thermal and electrical energy consumption in the two municipal buildings and the four residential building typologies.

Table 10. Summary of the technical and economic KPIs.

Building	Total Cost of Measures (EUR)	Total Emission Savings (kg CO_2)	Annual Savings (EUR)	Payback Period (Years)	DE_E
Commercial Polycenter	71,926	68,154	11,259	6.4	100.28%
Municipal Library	48,788	27,892	4147	11.8	106.73%
Building 27 (Tabula MFH-04)	17,932	23,483	4293	4.2	102.20%
Building 57 (Tabula SFH-01)	39,204	37,180	4783	8.2	101.83%
Building 59 (Tabula MFH-02)	161,326	106,171	12,069	13.4	100.50%
Building 69 (Tabula MFH-03)	98,022	47,768	2766	35.4	101.08%

Results for the SRI calculation for municipal and residential buildings are presented in Table 11, including the total SRI score (%), achieved SRI improvement (%), total intervention cost (in EUR), and relative SRI improvement (%) per EUR 5000 invested. Overall, the application of the SRI methodology across the 10 different buildings indicates that all buildings achieve similar SRI scores after the interventions, regardless of their initial status, with scores ranging from 25.7 to 30.8%.

The highest performance in terms of cost-effectiveness is observed in residential buildings 27, 59, 69, and the Municipal Library, which have smaller floor areas and therefore achieve higher value increases from the renovation scenario interventions. Conversely, larger buildings exhibit lower SRI improvements (%) per EUR 5000 invested. The remaining differences among buildings can be attributed to the presence of cooling systems and their associated higher baseline scores.

Table 11. SRI score, class, and cost analysis for renovation scenario.

Building	Scenario (%) and SRI Class	SRI Improvement (%)	SRI Improvement (%/5000 EUR Invested)
Commercial Polycenter	27.1 (between 20% and 35%)	17.9	1.3
Municipal Library	27.1 (between 20% and 35%)	21.6	7
Building 27 (Tabula MFH-04)	30.8 (between 20% and 35%)	20.3	2.3
Building 57 (Tabula SFH-01)	27.4 (between 20% and 35%)	21.1	9.8
Building 59 (Tabula MFH-02)	30.8 (between 20% and 35%)	23.5	1.4
Building 69 (Tabula MFH-03)	30.8 (between 20% and 35%)	22.5	1.5

The investigation into the development of a Near Zero/Positive Energy District involved a parametric analysis that explored various cases that involved different configurations for a range of potential renovation measures. Some of these measures were assessed in individual buildings, while additional measures were also considered to collectively reduce energy consumption in the neighborhood. In total, eight different cases were examined. The specific configurations of these technologies for each case (Cases 1–8) are presented in Table 12 below. The measures evaluated include the following:

- Insulation of the building envelope
- Replacement of old inefficient windows with more efficient options
- Upgrading old inefficient lights with LED lighting
- Installation of rooftop photovoltaic (PV) systems for the generation of renewable electricity
- Implementation of solar thermal systems to produce domestic hot water (DHW), thereby decreasing electrical loads for DHW during the summer months
- Integration of battery energy storage systems, including both conventional and second-life batteries

Table 12. Summary of cases examined in the PED.

Case	Conventional Retrofit	PV (kWp)	BESS (kWh)	Solar Thermal (Units)
Case 1	Building envelope insulation—windows replacement—LED lights	957.35 (30% of available roof area)	0	144
Case 2		1500.19 (45% of available roof area)	0	144
Case 3		2043.03 (60% of available roof area)	0	144
Case 4		2043.03 (60% of available roof area)	1000	144
Case 5		2043.03 (60% of available roof area)	2000	144
Case 6		1137.34 (45% of available roof area)	0	552
Case 7		1680.18 (60% of available roof area)	1000	552
Case 8		1680.18 (60% of available roof area)	2000	552

Conventional retrofit measures, including insulation, window replacement, and the installation of LED lighting to replace the old inefficient lightbulbs, were considered in all cases. In contrast, the capacity of the photovoltaic (PV) systems, the amount of installed solar thermal systems, and the capacity of the battery varied among the different scenarios. The assumptions made to determine the system configuration for each case include:

- Solar thermal systems are already installed in 26% of the neighborhood apartments; the total number of neighborhood apartments is estimated at approximately 552 apartments based on an average dwelling size of 84 m^2 [49] in Greece, with 144 of them already having a solar thermal system installed. Cases 1 to 5 focus only on existing solar thermal system installations, while Cases 6 to 8 include new solar thermal systems. The solar thermal system has a flat plate glazed collector with an area of 2.5 m^2 and a 160-liter storage capacity, typical for Greek dwellings [50]. In all cases, solar thermal systems were covering all thermal needs of the DHW during the mid-May to mid-October period when the district heating network was not operating. Dwellings with no solar thermal systems were using electrical heaters for the provision of DHW during the summer months. During autumn-winter, the DHW was covered solely by the district heating network.

- In certain cases, collective battery systems were implemented to enhance electrical self-consumption. Collective battery energy storage systems (BESS) with a total capacity of 1000 kWh were considered in Cases 4 and 7, while a capacity of 2000 kWh was evaluated in Cases 5 and 8.
- The total available roof space of the neighborhood's buildings, excluding the area occupied by existing solar thermal systems, is 20,338 m^2. To account for factors such as roof orientations and required spacing to avoid self-shading, the maximum area suitable for installing photovoltaic (PV) panels and/or additional solar thermal systems is limited to 60% of the total available space. Additional PV capacities were examined, with 30% of the available free space considered in Case 1 and 45% in Cases 2 and 6. In scenarios with solar thermal systems (Cases 6–8), the total available roof area was adjusted accordingly, maintaining the 60% limit for PV installation while accounting for the space taken by new solar thermal systems. A standard monocrystalline PV panel, approximately 2.3 m^2 in size with a nominal capacity of 410 Wp, was used as a reference for these PV systems.

The district heating demand for the neighborhood, which includes both space heating and DHW, was estimated at 1,674,064 kWh, while the total electricity consumption amounted to 3,623,677 kWh for Cases 1–5. In Cases 6–8, which included additional solar thermal systems, the DHW demand in the summer months decreased, resulting in a reduction of overall electricity demand to 3,431,053 kWh. These collective thermal energy and electricity demands were then used as inputs in the EnergyPlan software to derive the annual energy balance of the district on an hourly basis. After determining the annual energy balances for the various cases, the technical and economic KPIs were calculated and are presented in Table 13. To estimate the basic economic indicators, additional assumptions were made regarding the costs of renovation measures and electricity prices, including the following:

- Battery system cost: EUR 800/kWh based on information provided from installers
- Solar thermal system cost: EUR 800/unit, based on market data
- Selling price of electricity: EUR 0.06887/kWh [51]

Table 13. Main technical and economic indicators for the cases examined.

Case	Cost (EUR)	Total Cost Savings (EUR/Year)	Payback Period (Years)	CO_2 Reduction (Tons CO_2)	DEE (%)
Case 1	12,389,365	1,383,429	9.0	11,373	30.3%
Case 2	12,932,205	1,470,251	8.8	12,253	36.6%
Case 3	13,475,045	1,544,934	8.7	13,133	39.9%
Case 4	14,275,045	1,573,569	9.1	13,054	48.2%
Case 5	15,075,045	1,598,746	9.4	12,994	55.4%
Case 6	12,895,755	1,443,567	8.9	11,857	33.4%
Case 7	14,238,595	1,551,196	9.2	12,668	46.8%
Case 8	15,038,595	1,573,873	9.6	12,609	53.5%

In all scenarios, the payback periods are notably similar, ranging from 8.7 to 9.6 years, indicating that no case stands out significantly from a financial perspective. In terms of CO_2 emissions reduction, Cases 3–5 demonstrate the most significant reductions, totaling approximately 13,000 tonnes of CO_2 per year, followed by cases 7 and 8. Additionally, cases 5 and 8 exhibit the highest degree of energetic self-supply, achieving 55.4% and 53.5%, respectively.

It is important to note that since all thermal energy is supplied by the Eordaia district heating network, the Degree of Energetic Delf-Supply Thermal (DE_T) is 0% across all cases. To increase DE_T and achieve near-zero energy performance for the district, RES needs to be integrated into the network. A photovoltaic (PV) system providing the required electricity to the boilers has been proposed. With an assumed boiler efficiency of 99% efficiency [52], the estimated annual electricity demand that needs to be met by the PV systems totals 1,809,358 kWh. A 1.3 MW PV power plant is considered sufficient to meet this demand when connected to the grid (utilizing virtual net metering) with a total cost of approximately EUR 1,300,000.

4. Discussion

This study's detailed analysis of renovation measures across individual buildings and the entire Eordaia district underscores the potential of PED strategies, offering a systematic approach to achieve NZED standards. The renovation measures for each building were selected based on their technical suitability and cost-effectiveness, aligning with a broader district-level strategy that emphasizes not only thermal and energy efficiency but also financial viability. The analysis conducted enabled the identification of economically viable solutions for individual buildings by isolating each renovation measure to calculate respective thermal and electrical energy savings, annual cost savings, and payback periods. Such an approach illustrates the importance of evaluating solutions on a per-building basis to achieve optimal outcomes across varied building conditions within a district.

Key findings reveal that the most cost-effective measures were achieved through conventional retrofits, such as insulation upgrades, window replacement, and LED lighting installation, alongside renewable technologies like PV systems. Notably, two municipal buildings achieved electricity savings exceeding 100% due to PV installations, with systems like rooftop panels at the library and PV pergolas at the Commercial Polycenter allowing these structures to achieve a positive energy balance. This demonstrates the effectiveness of renewable integration in urban settings, supporting broader PED goals by showcasing substantial savings and a positive electricity surplus.

Thermal energy savings varied significantly across buildings depending on the existing baseline conditions and renovation measures implemented. For example, district heating savings ranged from modest reductions of 15% in the Commercial Polycenter to over 90% in the library, highlighting how baseline thermal efficiency and targeted retrofits affect energy savings. To capture the added benefits of modernization, this study recalculated the SRI for each building, revealing SRI scores ranging from 25.7% to 30.8% following the interventions. Smaller residential buildings exhibited the highest cost-effectiveness in SRI improvements per investment unit, indicating that floor area plays a crucial role in maximizing SRI value in smaller structures compared to larger buildings.

The case analysis for eight different renovation scenarios within the district revealed that conventional retrofitting measures, such as insulation and efficient lighting, were consistently effective across cases, while the capacity and configuration of PV systems, solar thermal units, and battery storage varied. Collective battery storage was introduced in certain cases to increase self-consumption, achieving a degree of energetic self-supply of over 55% in Cases 5 and 8, which maximized the district's energy independence. Despite similar payback periods across cases (8.7 to 9.6 years), significant differences were observed in CO_2 emissions reduction, with Cases 3–5 showing the highest impact at roughly 13,000 tonnes per year. These findings highlight that while financial feasibility may be consistent, environmental benefits vary substantially depending on technology configuration.

This study also points to district-level limitations, particularly in the degree of energetic self-supply thermal, which remained at 0% across cases due to the district's reliance on an external heating network. This finding suggests that for districts like Eordaia to attain near-zero energy performance, further integration of RES within the district's heating infrastructure is essential. As a proposed solution, a 1.3 MW PV power plant connected through virtual net metering would provide sufficient electricity to offset boiler demands, thus supporting the district's heating needs sustainably. The feasibility of this measure, estimated at approximately EUR 1,300,000, could provide a model for integrating renewables into urban district heating networks in similar European regions, aiding in achieving broader EU sustainability goals.

Overall, this study emphasizes that district-level energy strategies, combined with building-specific parametric analyses, offer valuable insights into optimizing PED designs, suggesting that such frameworks can effectively guide urban planners and policymakers in achieving financially viable, energy-efficient districts. Future research should expand this framework to diverse urban and rural environments, particularly in varying climatic regions, to assess the transferability of these results across the EU and beyond.

5. Conclusions

This study offers a valuable blueprint for urban planners and policymakers working toward the EU's 2050 net-zero emissions target by developing a replicable framework for PEDs. The results demonstrate the economic and environmental benefits of district-wide energy interventions, including advanced insulation, renewable energy sources, and predictive energy management systems.

The analysis shows that, with payback periods of 8.7 to 9.6 years, these interventions present a financially viable path toward sustainability. Moreover, achieving a degree of energetic self-supply above 55% in optimal scenarios highlights the potential for positive energy communities to enhance urban energy resilience and independence.

While the Eordaia case provides a practical benchmark for transitioning urban areas, future studies should explore the adaptability of these findings in various climates, building typologies, and policy contexts. Expanding the framework to include a range of urban and rural settings as well as diverse economic conditions would provide a more comprehensive understanding of the feasibility of positive energy communities across Europe.

Longitudinal studies examining the long-term effectiveness and adaptability of these energy strategies under evolving technological, economic, and policy conditions would further refine this approach. By advancing district-level strategies for Positive Energy Districts, this research supports sustainable urban development and provides a critical pathway toward meeting ambitious climate goals.

Author Contributions: Conceptualization, V.S., A.T. and G.M.; methodology, V.S. and G.M.; software, V.S. and A.T.; validation, V.S. and A.T.; formal analysis, V.S., G.M. and A.T.; investigation, P.D.; resources, V.S. and P.D.; data curation, V.S. and P.D.; writing—original draft preparation G.M., A.T., V.S. and P.D.; writing—review and editing, V.S., G.M., A.T., K.A. and P.G.; visualization, V.S. and A.T.; supervision, G.M. and N.N.; project administration, G.M. and N.N.; funding acquisition, N.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union's H2020 program as part of the RESPONSE project (integRatEd Solutions for POsitive eNergy and reSilient CitiEs), Grant Agreement ID 957751.

Data Availability Statement: Data are available upon request.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of this study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Renewable Energy Targets—European Commission. Available online: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en (accessed on 29 August 2024).
2. Greenhouse Gas Emissions from Energy Use in Buildings in Europe | European Environment Agency's Home Page. Available online: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-energy (accessed on 29 August 2024).
3. Luqman, M.; Rayner, P.J.; Gurney, K.R. On the Impact of Urbanisation on CO_2 Emissions. *NPJ Urban Sustain.* **2023**, *3*, 6. [CrossRef]
4. European Commission; Directorate-General for Research and Innovation. *The Human-Centred City: Opportunities for Citizens Through Research and Innovation*; Publications Office of the European Union: Berlin/Heidelberg, Germany, 2019.
5. Komninos, N. Net Zero Energy Districts: Connected Intelligence for Carbon-Neutral Cities. *Land* **2022**, *11*, 210. [CrossRef]

6. Delmastro, C.; Gargiulo, M. Capturing the Long-Term Interdependencies Between Building Thermal Energy Supply and Demand in Urban Planning Strategies. *Appl. Energy* **2020**, *268*, 114774. [CrossRef]
7. Murray, P.; Marquant, J.; Niffeler, M.; Mavromatidis, G.; Orehounig, K. Optimal Transformation Strategies for Buildings, Neighbourhoods and Districts to Reach CO_2 Emission Reduction Targets. *Energy Build.* **2020**, *207*, 109569. [CrossRef]
8. Becchio, C.; Bottero, M.C.; Corgnati, S.P.; Dell'Anna, F. Decision Making for Sustainable Urban Energy Planning: An Integrated Evaluation Framework of Alternative Solutions for a NZED (Net Zero-Energy District) in Turin. *Land Use Policy* **2018**, *78*, 803–817. [CrossRef]
9. Synnefa, A.; Laskari, M.; Gupta, R.; Pisello, A.L.; Santamouris, M. Development of Net Zero Energy Settlements Using Advanced Energy Technologies. *Procedia Eng.* **2017**, *180*, 1388–1401. [CrossRef]
10. Hachem, C. Impact of Neighborhood Design on Energy Performance and GHG Emissions. *Appl. Energy* **2016**, *177*, 422–434. [CrossRef]
11. Hachem-Vermette, C.; Grewal, K.S. Investigation of the Impact of Residential Mixture on Energy and Environmental Performance of Mixed Use Neighborhoods. *Appl. Energy* **2019**, *241*, 362–379. [CrossRef]
12. Isaac, S.; Shubin, S.; Rabinowitz, G. Cost-Optimal Net Zero Energy Communities. *Sustainability* **2020**, *12*, 2432. [CrossRef]
13. Paduos, S.; Corrado, V. Cost-Optimal Approach to Transform the Public Buildings into NZEBs: An European Cross-Country Comparison. *Energy Procedia* **2017**, *140*, 314–324. [CrossRef]
14. Evins, R. A Review of Computational Optimisation Methods Applied to Sustainable Building Design. *Renew. Sustain. Energy Rev.* **2013**, *22*, 230–245. [CrossRef]
15. Allegrini, J.; Orehounig, K.; Mavromatidis, G.; Ruesch, F.; Dorer, V.; Evins, R. A Review of Modelling Approaches and Tools for the Simulation of District-Scale Energy Systems. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1391–1404. [CrossRef]
16. Ala-Juusela, M.; Crosbie, T.; Hukkalainen, M. Defining and Operationalising the Concept of an Energy Positive Neighbourhood. *Energy Convers. Manag.* **2016**, *125*, 133–140. [CrossRef]
17. Rehman, H.u.; Reda, F.; Paiho, S.; Hasan, A. Towards Positive Energy Communities at High Latitudes. *Energy Convers. Manag.* **2019**, *196*, 175–195. [CrossRef]
18. Saarloos, B.A.; Quinn, J.C. Net-Zero Energy Districts and the Grid: An Energy-Economic Feasibility Case-Study of the National Western Center in Denver, CO, USA. *Buildings* **2021**, *11*, 638. [CrossRef]
19. Iturriaga, E.; Campos-Celador, Á.; Terés-Zubiaga, J.; Aldasoro, U.; Álvarez-Sanz, M. A MILP Optimization Method for Energy Renovation of Residential Urban Areas: Towards Zero Energy Districts. *Sustain. Cities Soc.* **2021**, *68*, 102787. [CrossRef]
20. Sougkakis, V.; Lymperopoulos, K.; Nikolopoulos, N.; Margaritis, N.; Giourka, P.; Angelakoglou, K. An Investigation on the Feasibility of Near-Zero and Positive Energy Communities in the Greek Context. *Smart Cities* **2020**, *3*, 362–384. [CrossRef]
21. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Revision of the Strategic Energy Technology (SET) Plan. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023DC0634 (accessed on 4 November 2024).
22. RESPONSE—IntegRatEd Solutions for POsitive ENergy and ReSilient CitiEs. Available online: https://h2020response.eu/ (accessed on 29 August 2024).
23. Owolabi, A.B.; Emmanuel Kigha Nsafon, B.; Wook Roh, J.; Suh, D.; Huh, J.S. Measurement and Verification Analysis on the Energy Performance of a Retrofit Residential Building after Energy Efficiency Measures Using RETScreen Expert. *Alex. Eng. J.* **2020**, *59*, 4643–4657. [CrossRef]
24. Natural Resources Canada RETScreen Software Online User Manual. Available online: https://publications.gc.ca/collections/Collection/M39-114-2005E.pdf (accessed on 1 November 2024).
25. Psomopoulos, C.S.; Ioannidis, G.C.; Kaminaris, S.D.; Mardikis, K.D.; Katsikas, N.G. A Comparative Evaluation of Photovoltaic Electricity Production Assessment Software (PVGIS, PVWatts and RETScreen). *Environ. Process.* **2015**, *2*, S175–S189. [CrossRef]
26. Mukhtar, M.; Ameyaw, B.; Yimen, N.; Zhang, Q.; Bamisile, O.; Adun, H.; Dagbasi, M. Building Retrofit and Energy Conservation/Efficiency Review: A Techno-Environ-Economic Assessment of Heat Pump System Retrofit in Housing Stock. *Sustainability* **2021**, *13*, 983. [CrossRef]
27. Augustowski, Ł.; Kułyk, P. The Economic Profitability of Photovoltaic Installations in Households in Poland from a New Policy Perspective. *Energies* **2023**, *16*, 7595. [CrossRef]
28. Smart Readiness Indicator—European Commission. Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator_en (accessed on 29 August 2024).
29. Shemeikka, J. D1.3 "Master City Plans for TA#1 Positive Energy Building Systems" 2021. pp. 1–131. Available online: https://h2020response.eu/wp-content/uploads/2022/05/D1.3-Master-City-Plans-for-TA1-Positive-Energy-Building-Systems.pdf (accessed on 29 August 2024).
30. Lund, H.; Thellufsen, J.Z.; Østergaard, P.A.; Sorknæs, P.; Skov, I.R.; Mathiesen, B.V. EnergyPLAN—Advanced Analysis of Smart Energy Systems. *Smart Energy* **2021**, *1*, 100007. [CrossRef]
31. Tryferidis, A.; Pramangioulis, D.; Kakaras, E.; Tsarchopoulos, P.; Nikolopoulos, N.; Salanova, J.M.; Chrysostomou, K.; Nooij, T.; Crombie, D. D1.1-"Report on the List of Selected KPIs for Each Transition Track". Project Deliverable IRIS. 2018. Available online: https://irissmartcities.eu/wp-content/uploads/2022/01/d1.1_report_on_the_list_of_selected_kpis_for_each_transition_track.pdf (accessed on 29 August 2024).
32. Ministry of Finance, Ministry of Environment Energy and Climate Change Regulation for the Energy Efficiency in Buildings. *Greek Off. Gov. Gaz.* **2017**, *B2367*, 23905–23924. Available online: https://ypen.gov.gr/wp-content/uploads/2020/11/KENAK_FEK_B2367_2017.pdf (accessed on 29 August 2024). (In Greek).

33. Technical Chamber of Greece Technical Directive 20701-1/2017—Analytical National Specifications of Parameters for the Calculation of the Energy Efficiency of Building and the Issuance of Energy Efficiency Certificate, 1st Ed. Available online: https://web.tee.gr/wp-content/uploads/%CE%95%CE%93%CE%9A%CE%A1%CE%99%CE%A3%CE%97-TOTEE-1.pdf (accessed on 29 August 2024). (In Greek).
34. Hellenic Statistical Authority, Census Results of Population and Housing; 2023. Available online: https://www.statistics.gr/documents/20181/18019778/census_results_2022_en.pdf/7c52ff55-9de3-d0d0-d9ea-73d6e908468b?version=1.0&t=1679057363566&download=true (accessed on 29 August 2024).
35. Loga, T.; Stein, B.; Diefenbach, N. TABULA Building Typologies in 20 European Countries—Making Energy-Related Features of Residential Building Stocks Comparable. *Energy Build.* **2016**, *132*, 4–12. [CrossRef]
36. Hensen, J.L.M.; Radošević, M. Teaching Building Performance Simulation—Some Quality Assurance Issues and Experiences. In Proceedings of the 21th Conference on Passive and Low Energy Architecture, Eindhoven, The Netherlands, 19 September 2004; pp. 19–22.
37. Directive-2018/844-EN-EUR-Lex. Available online: https://eur-lex.europa.eu/eli/dir/2018/844/oj (accessed on 29 August 2024).
38. European Commission Smart Readiness Indicator (SRI). Training Slide Deck; Version 2.0; European Commission Smart Readiness Indicator (SRI). Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator/implementation-tools_en (accessed on 29 August 2024).
39. Directorate-General for Energy; Verbeke, S.; Aerts, D.; Reynders, G.; Ma, Y.; Waide, P. *Final Report on the Technical Support to the Development of a Smart Readiness Indicator for Buildings—Final Report*; Publications Office of the European Union: Berlin/Heidelberg, Germany, 2020.
40. Apostolopoulos, V.; Giourka, P.; Martinopoulos, G.; Angelakoglou, K.; Kourtzanidis, K.; Nikolopoulos, N. Smart Readiness Indicator Evaluation and Cost Estimation of Smart Retrofitting Scenarios—A Comparative Case-Study in European Residential Buildings. *Sustain. Cities Soc.* **2022**, *82*, 103921. [CrossRef]
41. SRI. Implementation Tools. Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator/implementation-tools_en (accessed on 29 August 2024).
42. Luo, M.; Zheng, Q.; Zhao, Y.; Zhao, F.; Zhou, X. Developing Occupant-Centric Smart Home Thermostats with Energy-Saving and Comfort-Improving Goals. *Energy Build.* **2023**, *299*, 113579. [CrossRef]
43. Ministry for the Environment and Energy. Statistical Results for the Energy Efficiency of Buildings in the Residential, Tertiary and Public Sector. Available online: https://bpes.ypeka.gr/?page_id=21&stat=222 (accessed on 29 August 2024). (In Greek).
44. Hyperion Energy Community. The First Solar Energy Community in Greece, Powered by Citizens. Available online: https://2022.prizes.new-european-bauhaus.eu/sites/default/files/uploaded-reports/_Hyperion%20Summary%20Report%20Members%20(3).pdf (accessed on 29 August 2024).
45. Bellos, E.; Iliadis, P.; Papalexis, C.; Rotas, R.; Mamounakis, I.; Sougkakis, V.; Nikolopoulos, N.; Kosmatopoulos, E. Holistic Renovation of a Multi-Family Building in Greece Based on Dynamic Simulation Analysis. *J. Clean. Prod.* **2022**, *381*, 135202. [CrossRef]
46. A Guide to Bifacial Solar Panels. Available online: https://www.marketwatch.com/guides/solar/bifacial-solar-panels/ (accessed on 23 April 2024).
47. District Heating Municipal Company of Ptolemaida Pricelist. Available online: https://tpt.gr/%CE%98%CE%95%CE%9C%CE%91%CE%A4%CE%91-%CE%9A%CE%91%CE%A4%CE%91%CE%9D%CE%91%CE%9B%CE%A9%CE%A4%CE%A9%CE%9D/%CE%A0%CE%9B%CE%97%CE%A1%CE%9F%CE%A6%CE%9F%CE%A1%CE%99%CE%95%CE%A3-%CE%A4%CE%99%CE%9C%CE%9F%CE%9B%CE%9F%CE%93%CE%99%CE%91-%CE%A3%CE%A5%CE%9D%CE%94%CE%95%CE%A3%CE%97%CE%A3-%CE%9A%CE%91%CE%99-%CE%9A (accessed on 21 November 2023).
48. BPIE—Buildings Performance Institute Europe. Principles for Nearly Zero-Energy Buildings. Available online: https://www.bpie.eu/publication/principles-for-nearly-zero-energy-buildings/# (accessed on 24 April 2024).
49. Average Size of Dwelling. Available online: https://entranze.enerdata.net/average-size-of-dwelling.html (accessed on 29 August 2024).
50. Tsilingiridis, G.; Martinopoulos, G. Thirty Years of Domestic Solar Hot Water Systems Use in Greece—Energy and Environmental Benefits—Future Perspectives. *Renew. Energy* **2010**, *35*, 490–497. [CrossRef]
51. Guide to PV Investment | Solarway. Available online: https://solarway.gr/guides/odigos-stin-ependysi-fwtovoltaikwn/ (accessed on 24 April 2024).
52. Schoeneberger, C.; Zhang, J.; McMillan, C.; Dunn, J.B.; Masanet, E. Electrification Potential of U.S. Industrial Boilers and Assessment of the GHG Emissions Impact. *Adv. Appl. Energy* **2022**, *5*, 100089. [CrossRef]