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Towards a Synthetic Positive Energy District (PED) in İstanbul: Balancing Cost, Mobility, and Environmental Impact

Mine Sertsöz

Department of Railway Systems, Eskisehir Technical University, 26140 Eskisehir, Türkiye; msertsoz@eskisehir.edu.tr

Abstract: The influence of mobility modes within Positive Energy Districts (PEDs) has gained limited attention, despite their crucial role in reducing energy consumption and greenhouse gas emissions. Buildings in the European Union (EU) account for 40% of energy consumption and 36% of greenhouse gas emissions. In comparison, transport contributes 28% of energy use and 25% of emissions, with road transport responsible for 72% of these emissions. This study aims to design and optimize a synthetic PED in Istanbul that integrates renewable energy sources and public mobility systems to address these challenges. The renewable energy sources integrated into the synthetic PED model include solar energy, hydrogen energy, and regenerative braking energy from a tram system. Solar panels provided a substantial portion of the energy, while hydrogen energy contributed to additional electricity generation. Regenerative braking energy from the tram system was also utilized to further optimize energy production within the district. This system powers a middle school, 10 houses, a supermarket, and the tram itself. Optimization techniques, including Linear Programming (LP) for economic purposes and the Weighted Sum Method (WSM) for environmental goals, were applied to balance cost and CO_2 emissions. The LP method identified that the PED model can achieve cost competitiveness with conventional energy grids when hydrogen costs are below $93.16/MWh. Meanwhile, the WSM approach demonstrated that achieving a minimal CO_2 emission level of 5.74 tons requires hydrogen costs to be $32.55/MWh or lower. Compared to a conventional grid producing 97 tons of CO_2 annually, the PED model achieved reductions of up to 91.26 tons. This study contributes to the ongoing discourse on sustainable urban energy systems by addressing key research gaps related to the integration of mobility modes within PEDs and offering insights into the optimization of renewable energy sources for reducing emissions and energy consumption.

Keywords: Positive Energy Districts (PEDs); methods; planning tools; mobility in PEDs; smart cities; solar energy; hydrogen energy; CO_2 emission

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1. Introduction

The basic principle of Positive Energy Districts (PEDs) is to create an area within the city boundaries capable of generating more energy than consumed and agile/flexible enough to respond to the variation of the energy market because a PED should not only aim to achieve an annual surplus of net energy [1]. There is another notion named a "Net Zero District", this is an urban area or neighborhood where the total energy consumption is equal to the energy produced over a specified period, typically annually. The primary goal of a net-zero district is to balance energy use and production, resulting in a net-zero energy footprint. Unlike Positive Energy Districts (PEDs), which aim to generate more energy than consumed, Net Zero Districts focus on achieving equilibrium between the energy consumed and generated. This study focuses on PEDs.

Starting from a small scale (neighborhood or village) and then gradually expanding the area—all of Europe—urban living laboratories can be designed to emphasize the importance of mobility in PEDs. There are three basic platforms of PEDs:

Social: People can be encouraged to walk, bike, and use public transport. This incentive can be achieved by sharing with society how they contribute to the environment and economy with their mobility choice. This is just one example of incentives and examples can be multiplied.

Environmental: Existing and new laboratories can be used, the emission values of mobility modes can be determined, and research can be undertaken on how to reduce them.

Energy Economy: How to plan the most efficient mobility for both passenger car and public transportation users? What can countries gain financially thanks to these plans? The city-level indicators are used to show to what extent overall policy goals have been reached. These indicators are grouped under energy and environment, mobility, governance, and society and citizens domains [2].

The PED projects suggested for funding in the DUT Call 2022 will have a strong focus on making the energy transition an inclusive endeavor. They will embed technological solutions and practical tools into specific socio-cultural and socio-economic settings [3,4]. PEDs have been strongly encouraged by the scientific community and policy initiatives at the European level, but their implementation in cities is still limited [5].

Despite significant progress in PED research and implementation, several research gaps still exist:

Interdisciplinary Approach: Many PED projects focus primarily on technical solutions without fully integrating social, economic, and environmental considerations. There is a need for more interdisciplinary research that considers the complex interactions between technology, policy, and human behavior. This study aims to make environmental considerations of the PEDs.

Scalability and Replicability: While there are successful PED projects, there is a lack of research on how to scale up and replicate these initiatives in different urban contexts. Understanding the factors that influence the scalability and replicability of PEDs is crucial for widespread adoption.

Optimal Design and Integration: There is a need for research on the optimal design and integration of various renewable energy sources, energy storage systems, and smart grid technologies within PEDs. This includes identifying the most cost-effective and efficient combinations of technologies for different urban environments. This study aims to find the most cost-effective and efficient combinations of technologies of the PEDs.

Lifecycle Assessment: Assessing the environmental impact of PEDs throughout their lifecycle, including the production, operation, and end-of-life phases of infrastructure, is essential. More research is needed to quantify the environmental benefits and trade-offs associated with different PED designs and technologies. This study aims to make a trade-off between the cost and environmental effect of the PEDs. This trade-off is a part of the Lifecycle assessment.

Community Engagement and Behavior Change: Engaging local communities and fostering behavior change are critical for the success of PEDs. However, there is limited research on effective strategies for community engagement and behavior change interventions to promote energy efficiency and renewable energy adoption in PEDs.

Policy and Regulatory Frameworks: Policy and regulatory frameworks play a significant role in enabling the development of PEDs. Research is needed to identify the most effective policy instruments, incentives, and regulatory mechanisms to support the implementation of PEDs and overcome existing barriers.

Resilience and Adaptation: Climate change and other external factors can impact the performance and resilience of PEDs. Research is needed to enhance the resilience of PEDs to climate-related risks, such as extreme weather events, sea-level rise, and heat waves, and to develop adaptive strategies to ensure their long-term viability.

Addressing these research gaps will be crucial for advancing the development and implementation of Positive Energy Districts and accelerating the transition to more sustainable and resilient urban energy systems. The pillars of PEDs are optimized and flexible energy systems, a local/regional renewable energy supply, and lastly a high level of energy efficiency [6].The research objective of this study is a good example to fill three of these seven research gaps. These are the Interdisciplinary Approach, Optimal Design and Integration, and Lifecycle Assessment.

Section 2 will give more information about the mobility systems in the PEDs. The novelty impact of this study—evaluating trams as a mobility choice in the PEDs—can be understood after Section 2.

2. Status of Mobility in PEDs

2.1. Mobility Solutions in PED Frameworks, Programs

Here is an overview of the main frameworks and programs underpinning the Positive Energy District (PED) concept, with a focus on mobility considerations:

- European Union Horizon 2020 Program [7]:

Mobility Focus: Horizon 2020 supports research and innovation projects, including those related to Positive Energy Districts. Mobility considerations may involve sustainable transportation solutions within and around the district, such as electric mobility, shared mobility services, and integration with public transportation.

- ICLEI—Local Governments for Sustainability [8]:

Mobility Focus: ICLEI provides frameworks for local governments to achieve sustainability goals, including Positive Energy Districts. Mobility considerations may involve promoting active transportation, developing efficient public transit systems, and incorporating smart mobility solutions to reduce carbon emissions.

- Covenant of Mayors for Climate and Energy [9]:

Mobility Focus: The Covenant of Mayors encourages local authorities to commit to climate and energy objectives. Mobility strategies within Positive Energy Districts may include the promotion of walking, cycling, and electric vehicles, as well as the integration of renewable energy sources for charging infrastructure.

- Smart Cities and Communities European Innovation Partnership (EIP-SCC) [10]:

Mobility Focus: EIP-SCC promotes smart and sustainable urban development. Within Positive Energy Districts, mobility solutions may include smart grid technologies, energy-efficient buildings, and intelligent transportation systems to optimize the use of renewable energy and reduce carbon emissions.

- District Energy in Cities Initiative (UN Environment and Danfoss) [11]:

Mobility Focus: This initiative aims to support cities in transitioning to sustainable, low-carbon, and climate-resilient energy systems. Mobility considerations may involve the integration of renewable energy sources into transportation infrastructure, such as electric vehicle charging stations powered by local renewable energy.

- European Innovation Partnership on Smart Cities and Communities (EIP-SCC)—Sustainable Urban Mobility Action Cluster [12]:

Mobility Focus: EIP-SCC's Sustainable Urban Mobility Action Cluster focuses on innovative solutions for urban mobility. In Positive Energy Districts, mobility programs may involve the development of sustainable transport infrastructure, shared mobility services, and the incorporation of renewable energy into transportation systems.

In Positive Energy Districts, mobility considerations are integral to achieving sustainability goals, and planning often emphasizes energy-efficient transportation, the use of renewable energy in mobility infrastructure, and the integration of smart and sustainable mobility solutions. Local and regional authorities collaborate with various programs and frameworks to implement these strategies effectively.

2.2. Mobility Solutions in PED Applications

There are three main applications for PEDs in the World. The mobility features designed in these projects are shared below:

HIKARI Block [13] is the first example of a performed positive energy district. It is in in the district La Confluence in Lyon, France, and was built in 2015. The architect is Kengo Kuma (Japan). The Hikari Block is an urban block composed of buildings with residential, commercial, and tertiary use. The mobility system of Hakari Block is as follows:

- Vehicles for car-sharing using on-site renewable energy production.
- Integrated urban data platform collecting data and service on the mobility system.
- The tram line connects 'La Confluence' to the other Lyon neighborhoods.

Hunziker Areal [14] is an ex-industrial district in the northern part of Zurich. It has redesigned the neighborhood for space where people can both live and carry out their jobs according to sustainability considerations. It was completed in 2015. The mobility system of Hunziker Areal is as follows:

- Car parking is a few and limited time (2 h. maximum).
- Car parking with e-charging is available.
- Public transportation—i.e., railway service, buses, e-mobility (bike sharing, scooters, etc.) towards the center with efficiency.
- Safe cycle lanes towards the city center.

Evora City Centre [15] is one of the pilot areas of the 'POCITYF' project, funded by the European Commission under the Horizon Programme 2020. This is the only example which is built in a historical city center. This project is ongoing. The mobility system of Hunziker Areal is as follows:

- Electric vehicle sharing programs to reduce the density of cars in the city center.
- Energy management platform to control the charging of electric vehicles.

2.3. Mobility Literature Review for PED Applications

While many studies focus on buildings in Positive Energy Districts (PEDs), few explore the mobility systems of the residents living within these districts. Balancing energy requirements with the design of buildings, transportation systems, and public spaces is essential to optimizing energy efficiency and creating a livable environment [16].

There are a few mobility studies in the literature. Mobility studies have generally been made on the charging of Electrical vehicles. Tony Castillo-Calzadilla's [17] PED might provide as much as about 7 million green kilometers, which can be turned into 545 EVs in the best scenario. Another study from the same author [18] analyzed the possibility of achieving a Positive Energy District (PED), i.e., a district that generates more energy than it consumes. The paper presents a simulation-based analysis (MATLAB-Simulink environment) of an urban unit that consists of six buildings, six streetlights, and an electric vehicle (EV) charger. Pignatta and Balazadeh [19] aimed to quantify the exhaust emissions of six conventional and two fully hybrid vehicles using a portable emission measurement system (PEMS) in real driving conditions. The fuel consumption and exhaust pollutants of the conventional and hybrid vehicles were compared on four different urban and highway driving routes during the autumn of 2019 in Iran. The results showed that hybrid vehicles had lower fuel consumption and produced slight exhaust emissions. This paper also [20] looks at the five cities of Maia, Reykjavik, Kifissia, Kladno, and Lviv that are part of an ongoing Horizon 2020 project. They transition towards PEDs. In another study [21], key pathways forward for a rapid, far-reaching translation of the ambitious PEDs agenda into multi-sited, district-scale beacons of sustainable energy transition are highlighted. The study in [22] aims to investigate these issues, providing a critical overview of the PED situation using a systematic literature review based on the use of open-access bibliometric software supplemented with content analysis. There are two examples of the Integration of Electric Railways in Positive Energy Districts (PEDs). The first one is the European Commission's Strategic Energy Technology Plan which includes the creation of 100 Positive

Energy Districts (PEDs) by 2025, which emphasizes energy efficiency and renewable energy production. These districts often integrate sustainable transportation systems, such as electric railways, to enhance overall energy efficiency and sustainability. By utilizing renewable energy sources to power electric trains, PEDs contribute to reducing carbon emissions and achieving their energy-positive goals [23]. The second one is for Hydrogen-Electricity Hybrid Energy Pipelines in Railway Transportation. There are explorations into the use of hydrogen-electricity hybrid energy pipelines for railway transportation within PEDs. This approach supports the energy needs of electric railways while contributing to the district's renewable energy goals. Integrating these technologies helps balance energy supply and demand, enhancing the sustainability of both the PEDs and the transportation systems [24].

CO_2 emissions per passenger differ greatly by transport mode. Trams are evaluated not only for their energy consumption but also for CO_2 emissions and have been considered for mobility systems. Although trams already produce very little CO_2 emissions per passenger compared to a vehicle powered by an internal combustion engine [25], they also produce less than electric vehicles which are the only vehicles considered in PEDs. This study has two novel aspects compared to previous studies. Firstly, the study focuses not only on examining the mobility in PEDs, which few studies have undertaken, but also on finding a solution to public mobility in PEDs, which is a subject that has never been touched upon, with the tram, one of the cleanest public mobility vehicles. Secondly, while reducing CO_2 emissions by using renewable energy sources, the optimum investment cost conditions considering the environment using two different optimization methods are found. This study addresses the limited attention given to the influence of mobility modes in Positive Energy Districts as integrating a tram into a PED.

3. Renewable Energy Potential of Turkey

Turkey, with an electric power generation capacity of approximately 105 GW, is Europe's sixth-largest electricity market and the 14th-largest in the world. Approximately 56% of Turkey's electric power generation capacity consists of renewable energy, including hydroelectric, wind, solar, geothermal, and biomass power plants, making Turkey the fifth-largest generator of renewable energy in Europe and the 11th-largest in the world.

Turkey currently has a capacity of approximately 31.6 GW of hydroelectric, 25.75 GW of natural gas (NG), 21.3 GW of coal, 11.45 GW of wind, 9.93 GW of solar, 1.7 GW of geothermal, and 2 GW of biomass power installed.

According to Turkey's 2020–2035 National Energy Plan, Turkey's power generation capacity will reach 189.7 GW in 2035 (a 79% increase from 2023). Turkey's share of renewable energy will increase to 64.7% with solar power capacity increasing 432% and wind capacity increasing 158%. The market's hydroelectric capacity will increase to 11% while NG will see a 38% increase. In addition, a nuclear power plant is currently being built by Russian company Rosatom at a capacity of 4.6 GW (1.2 GW × 4 units).

Turkey has a large and growing manufacturing base which requires an increasing amount of power generation. The annual growth rate in additional power generation capacity has been around 5% due to growing economic activity and a rising population in Turkey.

Turkey has committed to achieving net-zero emissions by 2053. As a result, Turkey plans to continue supporting renewable energy investments including nuclear energy projects on a BOT or build-own-operate (BOO) basis. Turkey is also open to public-owned partnerships. The government provides power purchase guarantees with a high feed-in tariff until the debt is recovered. There are many leading sub-sectors: Solar energy power generation, Wind turbines and generators, Energy storage systems, Small Modular Reactors (SMRs), Smart grid systems (SCADA, GIS, AMR, AMI, Automated Demand Side Management, PLC, and other communication systems, Volt-VAR control systems, OT, CIS, Control Centers, etc.), Grid modernization and voltage and frequency regulation systems, Geothermal power plant equipment, Waste-to-energy systems, Smart LED Lighting Systems, Fuel cells, Hydroelectric turbines, coal gasification systems, and Micro Grid Systems [26].

There is a connection between renewable energy sources and PEDs in Turkey. Because Turkey's rich renewable energy potential can be effectively utilized within PEDs to generate clean, local energy. Solar panels on buildings, wind turbines, and geothermal systems can be integrated into the district's energy infrastructure. And, by leveraging local renewable resources, PEDs can reduce reliance on imported fossil fuels, enhancing energy security and independence. Positive Energy Districts promote economic development through job creation in the renewable energy sector and improve environmental quality by reducing greenhouse gas emissions. Implementing PEDs involves smart grids, energy storage solutions, and advanced energy management systems, fostering technological innovation. PEDs support sustainable urban development, creating livable communities with lower energy costs and reduced environmental impact.

In summary, Turkey's abundant renewable energy resources provide a strong foundation for developing Positive Energy Districts. These districts can capitalize on local renewable energy, enhance energy efficiency, and contribute to Turkey's goals of sustainability, energy independence, and economic growth.

4. Methods

4.1. Optimization

There are different types of optimizations according to classification based on a Decision Maker (DM):

1. No preference method: no DM.
2. Priori methods: a DM gives preferences before optimization.
3. Posteriori methods: Firstly, the best Pareto optimal solutions are found, and then a DM chooses the best one between them.
4. Progressive methods: a DM guides the optimization process by giving preferences during optimization.

In this study, linear programming as the Priori method and the weighted sum method as the No preference method are used. Optimization was also performed using an evolutionary algorithm (genetic algorithm) as the posterior method. However, the genetic algorithm (GA) method did not produce results that differed from linear programming and weighted sum methods for this problem. To avoid repetition, the numerical results found by linear programming and the weighted sum method were not shared again for GA. Therefore, only the results of the two methods are given.

It is possible to explain why the selected methods were chosen for this problem as follows:

- The first aim is to find the most economical way to provide electrical energy for the designed PED. Linear programming was chosen because the objective function and the constraint functions do not contain convexity and concavity.
- The second aim is to find the most environmentally friendly way of providing electrical energy for the designed PED. The objective function is the same; however, coefficients in the objective function should be revised by considering the CO_2 emission values produced by different energy sources and the constraint functions do not contain convexity and concavity. One of the most suitable methods for this is the weighted sum method.

In this study, linear programming (LP) and the weighted sum method (WSM) were used to optimize the energy management of the synthetic Positive Energy District (PED). The primary goal of the LP method was to minimize the overall cost of energy production, while the WSM method was focused on minimizing CO_2 emissions while considering economic factors.

4.1.1. Linear Programming (LP)

There is an objective function, and the aim is to minimize or maximize this function (z). Linear programming can be illustrated by the equation below:

Objective function:

$$\min z = c_1x_1 + c_2x_2 + \ldots\ldots\ldots + c_nx_n \tag{1}$$

Constraints:

$$a_{11}x_1 + a_{12}x_2 + \cdots\ldots\ldots\ldots a_{1n}x_{2n} \geq b_1$$
$$a_{21}x_1 + a_{22}x_2 + \cdots\ldots\ldots\ldots a_{2n}x_{2n} \geq b_2$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$a_{m1}x_1 + a_{m2}x_2 + \cdots\ldots\ldots\ldots a_{mn}x_{mn} \geq b_m \tag{2}$$
$$x_1,\ x_2 + \cdots\ldots\ldots\ldots x_n \geq 0 \tag{3}$$

In Equations (1)–(3):
$c_1, c_2, \ldots, c_n$ are cost coefficients,
$x_1, x_2, \ldots, x_n$ are decision variables,
$a_{11}, a_{12}, \ldots, a_{m1}$ are coefficients of the objective function.

4.1.2. Weighted Sum Method (WSM)

A weighted sum is a mathematical operation that involves multiplying each element in a set of values by a corresponding weight and then summing up the results. The equation for a weighted sum can be represented as follows in Equation (4):

$$Weighted\ Sum = w_1x_1 + w_2x_2 + \cdots w_nx_n \tag{4}$$

In this equation:

- $w_1, w_2, \ldots, w_n$ are the weights assigned to the corresponding values.
- $x_1, x_2, \ldots, x_n$ are the values being multiplied by their respective weights.

The weighted sum is a way to combine multiple variables, giving more or less importance to each variable based on its associated weight. It is a common operation in various fields, including optimization problems, machine learning, and signal processing. Adjusting the weights allows for the modulation of the impact of each input on the final result.

5. Case Study

In this study, a synthetic PED was designed in which the producers are Solar and Hydrogen Energy, and the consumers are homes, supermarkets, and middle schools. Here is a general overview of the distribution and use of different energy sources in buildings:

In residential buildings, electricity is used for lighting, heating, cooling, appliances, and electronic devices. Renewable energy is increasing the use of solar panels as in this study and sometimes small wind turbines.

In commercial buildings, electricity is mostly used in lighting, HVAC (Heating, Ventilation, and Air Conditioning) systems, office equipment, and elevators. Renewable energy is growing via the adoption of solar panels, especially in large office buildings and shopping centers as in this study.

In Public Buildings (schools and hospitals), electricity is used for lighting, HVAC systems, medical equipment, computers, and other electronic devices. Renewable energy is becoming more common via solar panels, especially in schools and hospitals as in this study.

In addition to buildings, there is a tram that both consumes and provides energy with its regenerative braking energy.

Apart from solar energy, the use of hydrogen energy and regenerative braking energy is one of the aspects that make this study innovative.

Firstly, the electrical energy consumption of the houses [27], schools [28], supermarkets [29], and trams were calculated. While calculating the energy consumption of the tram, the traction consumption per person was taken from a tram operating on the T1 metro line in Istanbul. It was assumed that the tram carried 1000 people daily. The energy production was then calculated. The regenerative braking energy of the tram is accepted as 20% [30] by the studies in the literature. To find the energy production of solar panels, a 120 kWp medium-sized commercial unit from Global Solar Atlas [31] used in the Istanbul region was chosen as the sample model. Finally, the hydrogen energy production values were calculated by taking them from the IEA [32].

Two optimization methods (linear programming) were then used to ensure energy consumption was used most economically by utilizing solar, hydrogen, and the regenerative braking energy of the tram. Combined with the expected drop in the cost of renewable energy, this can bring the cost of green hydrogen down to a range of \$1.3/kg to \$4.5/kg of H_2 (equivalent to \$39–135/MWh) [33] and the solar energy cost was \$32.78 per MWh [34]. In this study, the solar energy cost was constant, \$32.78, and the hydrogen energy cost ranged from \$39/MWh to \$135/MWh.

In Figure 1, the synthetic PED model used in this study is illustrated. Figure 1a is Solar panels, Figure 1b is Hydrogen energy; these two are the energy production part of the PED. Figure 1c is ten houses, Figure 1d is one middle school and one supermarket, and Figure 1e is a tram. The tram is both a source of energy production with regenerative braking energy and consumption. The energy consumption for each type of building (houses, middle schools, supermarkets) was derived from reliable sources. The household energy consumption of 49.92 MWh is based on average residential energy use reported in Turkey [27]. Similarly, the consumption of the middle school (18 MWh) [28] and supermarket (148 MWh) [29] was calculated using energy intensity data from studies on educational and commercial buildings.

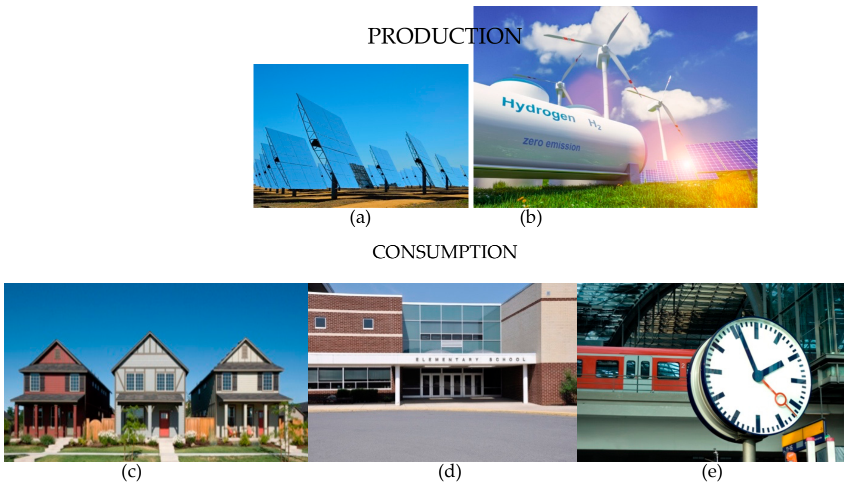

Figure 1. General view of the synthetic PED model.

Solar energy and hydrogen energy were chosen as renewable resources based on their availability and relevance in the context of Istanbul, Turkey. Solar energy is abundant in this region, making it a viable option, while hydrogen energy was included due to its potential for future scalability. The use of regenerative braking from the tram system (0.92 MWh) is also included as it provides an additional sustainable energy source. Table 1 shows the energy consumption and production for this PED Model:

Table 1. Energy consumption and installed energy for a synthetic PED model.

Consumption Types	Consumption (MWh in a Year)	Production Types	Installed Energy (MWh)
Houses	49.92 [27]	Solar	159.97
1 Middle School	18 [28]	Green Hydrogen	100
1 Supermarket	148 [29]	Regenerative Braking	0.92
Tram	4.6 [35]		

5.1. The Mathematical Expression of the Problem

The tables below were used to build the optimization problem mathematically. This system is more environmentally friendly; however, the aim was to find the cheapest way to install such a system compared with the conventional grid. There is one objective function and two methods. LP focuses only on economic solutions; however, WSM focuses firstly on environmental and secondly on economic solutions. WSM has its weights in the objective function. In this study, the solar energy cost was constant, $32.78, and the hydrogen energy cost ranged from $39/MWh to $135/MWh.

The costs per MWh for solar energy and hydrogen energy were estimated using current market prices. The solar energy cost was assumed to be constant at $32.78/MWh, derived from regional solar energy data [34]. Hydrogen energy costs, however, vary depending on production technologies, and the range provided ($39–135/MWh) reflects this uncertainty [33].

The upper limits on energy production were set based on the available capacity of each energy source. For example, solar energy production is capped at 159.97 MWh based on local solar irradiance data [31], while hydrogen energy was limited to 100 MWh, which is considered sufficient for this study. In Table 2, g is the ID, C is the cost, and E is the installation capacity of the energy sources.

Table 2. Cost and constraints of the energy sources.

	g	C ($)/MWh	E (MWh)
Solar	0	32.78	159.97
Hydrogen	1	39–135	100
Regenerative Braking	2	0	0.92

Energy demand for each consumer was estimated using standard consumption patterns. The values for houses (49.92 MWh), the middle school (18 MWh), the supermarket (148 MWh), and the tram (4.6 MWh) were calculated from studies on energy consumption in similar buildings and transportation systems. The tram's energy consumption, for instance, was modeled using data from the T1 metro line in Istanbul [35]. In Table 3, d is the ID, and E is the energy requirement of the energy consumers in the PED.

Table 3. The demand of the energy consumers.

	d	E (MWh)
Houses	0	49.92
Middle School	1	18
Supermarket	2	148
Tram	3	4.6

5.2. Economical Cost for the Best Economical Solutions

The objective function of the problem with the linear programming method:

$$min\sum_{g=0}^{g=2} CgEg \tag{5}$$

5.3. Economical Cost for the Best Environmental Solution

The objective function of the problem with the weighted sum method:

$$min\sum_{g=0}^{g=2} 3\left(0.542C_0 + 0.453\ C_1 + 0.417 \times 10^{-3}C_2\right)Eg \tag{6}$$

In Equation (6), these weights are found with the CO_2 emission values of energy sources. While adjusting the coefficients in the WSM, the amount of CO_2 they produce per unit of energy was taken into account, it was assumed that all the hydrogen and regenerative braking energies with the lowest CO_2 emissions were used, and then the remaining requirement was met from solar energy. As a result, the energy producer with the lowest CO_2 emissions had the highest coefficient, considering the constraints.

General constraints of the problems:

$$\boldsymbol{\sum_{g=0}^{g=2} E_g = \sum_{d=0}^{d=3} E_d} \tag{7}$$

$$\boldsymbol{E_{g2} = 0.2xE_{d3}} \tag{8}$$

$$\boldsymbol{E_g \geq 0} \tag{9}$$

$$\boldsymbol{E_g \leq E_{g\_lim}} \tag{10}$$

$$\boldsymbol{E_{g0} \leq 159.97} \tag{11}$$

$$\boldsymbol{E_{g1} \leq 100} \tag{12}$$

$$\boldsymbol{E_{g2} \leq 0.92} \tag{13}$$

The constraints in Equations (7)–(13) are based on the energy balance requirements and operational capacities of the energy systems modeled in the Positive Energy District (PED). The capacity constraints for solar, hydrogen, and regenerative braking were estimated using data from energy production and consumption patterns cited from the relevant literature and operational data from similar systems. Specifically, the regenerative braking constraint (Equation (8)) was derived from studies on energy recovery systems in trams, which typically recover 20% of traction energy [30].

6. Results

In this study, two different optimization methods are used. These are linear programming (LP) and the weighted sum method (WSM) for finding the best solution for economic and environmental. In the designed synthetic PED, all energy sources are renewable energy. LP is focused on economic optimization, aiming for the lowest-cost solution while still utilizing renewable energy sources. While LP's priority is economical energy management, WSM's priority is environmental impact, aiming to reduce CO_2 emissions, even if it means accepting higher costs.

6.1. Calculation of Cost

In March 2023 the energy cost for 1 kWh of electricity was calculated as $0.048 for a household, and $0.118 for a commercial enterprise in Turkey [31]. Cost of energy consumption of houses, schools, and supermarkets used from the household enterprise and tram uses from the commercial enterprise. Regenerative braking does not use either. The total approximate cost was found to be $10,798 per year with such a system.

In this study, the most appropriate value was calculated according to the system's variable hydrogen energy prices. Table 4 summarizes the results for LP and WSM, respectively. The cost changes because of variable hydrogen energy costs.

Table 4. Production, rate, and cost of energy for LP and WSM.

LP	Production (MWh)	Rate (%)	Cost ($)
Solar	159.97	100	
Green Hydrogen	59.62	59.62	7569.34–13,293.25
Regenerative Brak.	0.92	100	
WSM			
Solar	119.6	74.7	
Green Hydrogen	100	100	11,674.82–19,465.69
Regenerative Brak.	0.92	100	

The investment gave reasonable results compared to the conventional network for all times when the price of hydrogen was below 93.16 $/MWh with LP.

In WSM, where the coefficients of the objective function are produced for the best environmentally friendly solution when the hydrogen energy is 32.55 $/MWh and below, the investment becomes logical compared to the conventional grid, but since the cheapest hydrogen energy price is currently 39 $/MWh, the investment does not seem reasonable with hydrogen costs.

In the calculations made with the hydrogen costs given in Table 5, electricity production costs are the same as the conventional grid. It is assumed that all these scenarios are carried out after the system has amortized investment costs. Table 5 summarizes these results:

Table 5. Hydrogen cost for LP and WSM for optimum cost.

	Hydrogen Cost ($/MWh)
LP	93.16
WSM	32.55

6.2. Determination of CO_2 Emissions

Solar panels produce 48 g CO_2/kWh according to the sixth assessment report which was published by the IPCC in March 2023 [36]. Hydrogen energy has no emissions because it is a clean fuel source. It was also assumed in this study that regenerative braking energy has no emissions.

On the other hand, an average of 0.440 tons of CO_2 emissions are released for every 1 MWh (unit) of net electricity produced throughout Turkey according to the Republic of Turkey Ministry of Energy and Natural Resources [37].

As a result, the synthetic PED model, powered by solar, hydrogen, and regenerative braking energy, achieved a significant reduction in CO_2 emissions compared to a conventional grid. While the conventional grid produces approximately 97 tons of CO_2 annually, the PED model reduced emissions to 7.285 tons using LP and to 5.74 tons with the WSM. This equates to an annual reduction of up to 91.26 tons of CO_2.

In Figure 2, there is a comparison graph between LP, WSM, and the Conventional Grid both for cost and CO_2 emission. The hydrogen energy cost is assumed as 87 $/MWh, (average of 39 $/MWh and 135 $/MWh).

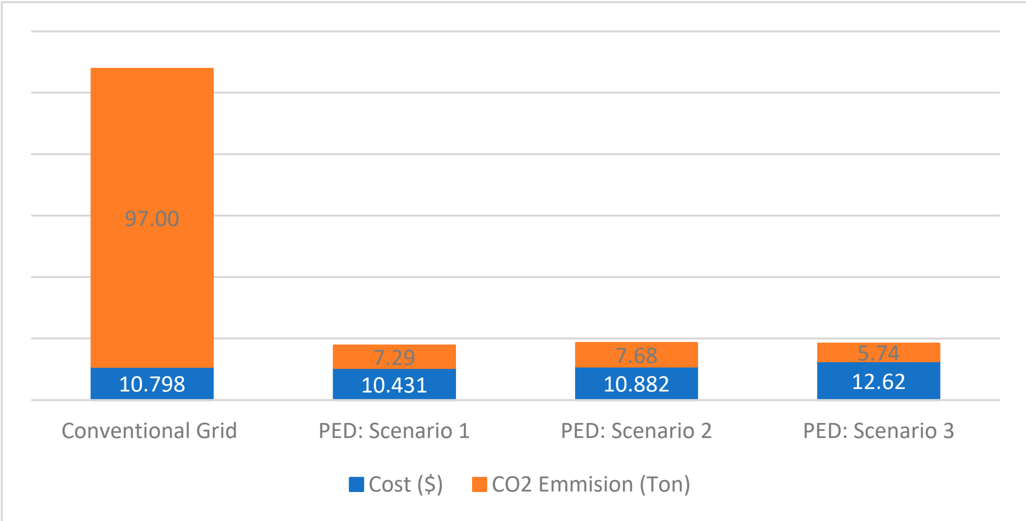

Figure 2. A comparison between different scenarios for cost ($) and CO_2 emission.

7. Discussion

The outputs of this study highlight the complicated relationship between economic costs and environmental benefits in the background of Positive Energy Districts. The application of linear programming (LP) revealed that the PED model could achieve cost competitiveness with conventional energy grids when hydrogen costs are below a specific threshold ($93.16/MWh). However, the weighted sum method (WSM), which integrates environmental considerations into the optimization process, demonstrated that achieving the most environmentally friendly outcomes might require higher initial costs, especially under current hydrogen pricing.

The high variability in both the economic and environmental performance of the PEDs is largely attributed to the fluctuating costs of hydrogen energy. Although solar energy provides a relatively stable and low-cost option compared with other renewable energy sources, its environmental benefits are lower than hydrogen. Because hydrogen produces no CO_2 emissions directly. However, the economic usefulness of hydrogen is currently restricted by its higher costs, which may challenge the adoption of PEDs to use hydrogen in the near term easily.

Furthermore, this study features integrating regenerative braking systems within urban mobility solutions as a cause to increase energy efficiency and decrease emissions. However, the relative proportion of regenerative braking to whole energy production is minimal, it represents a novelty step towards more sustainable urban energy systems and also highlights not wasting any energy, even a little.

This research also points to the need for further studies on the scalability of PEDs and the integration of emerging renewable energy technologies. As PEDs are relatively new and still in the experimental phase, understanding the long-term impacts and potential for large-scale implementation remains critical. Additionally, this study intends to balance environmental and economic goals through optimization methods that could present a scheme exploring the combining of multi-renewable energy sources within PEDs for future studies.

Also, for a more comprehensive optimization, additional variables must be considered to capture the full complexity of energy systems. Factors such as transport demand, photovoltaic material selection, the strategic placement of solar panels [38], shading [39], and building orientation have been shown to significantly influence both energy efficiency and overall system performance. Integrating these variables into future analyses would provide a more holistic approach, enabling better alignment between energy production, consumption, and the environmental impact of PEDs. By considering these factors, future research could not only improve optimization outcomes but also enhance the scalability and replicability of PEDs in diverse urban contexts.

8. Conclusions

Positive Energy Districts (PEDs) are an emerging concept in urban sustainability, aiming to generate more energy than they consume and supply energy to the local grid or neighborhood. Several research gaps still exist although significant progress is being made in PED research and its application. These research gaps are scalability and replicability, optimal design and integration, lifecycle assessment, interdisciplinary approach, community engagement and behavior change, policy and regulatory frameworks, and resilience and adaptation. This study focuses on the interdisciplinary approach, optimal Design and integration, and lifecycle assessment.

Also, unlike the other studies, this study uses a tram which is a form of public transportation instead of electric cars in the created synthetic PED. The pillars of PEDs are optimized and flexible energy systems, a local/regional renewable energy supply, and lastly a high level of energy efficiency. Also, this article focuses on these three pillars together.

To summarize, this study has three basic novel findings. The first is Economic Viability. In this study, two hydrogen cost thresholds were identified using linear programming (LP) and weighted sum methods (WSM) to achieve cost competitiveness and minimal CO_2 emissions. The LP method identified that investment in such a system is economically reasonable when hydrogen energy costs are below $93.16/MWh. However, the WSM which considers firstly environmental factors, showed that the investment becomes economically sensible when hydrogen costs are equal to or below $32.55/MWh. However, with current hydrogen costs starting at $39/MWh, the investment does not yet seem economical. The second is Environmental Impact. The LP method found CO_2 emissions of 7.285 tons per year, while the WSM method reduced emissions even further to 5.74 tons per year. However, the conventional grid produces approximately 97 tons of CO_2 annually. Lastly, the third is Energy Production and Consumption. The study demonstrated that the synthetic PED, which includes energy production from solar panels (159.97 MWh) and green hydrogen (up to 100 MWh), is capable of meeting the energy demands of residential buildings, schools, supermarkets, and public transportation as trams. In this study, thanks to the optimization methods, synthetic PED managed its energy logically considering both the environmental and economic factors; 40.37 MWh can be given to the local grid.

This study represents a preliminary analysis that highlights the key variables crucial for designing a sustainable Positive Energy District (PED). By examining economic and environmental trade-offs through optimization methods such as LP and the WSM, this work identifies important considerations for future PED implementations. However, further research is needed to refine these variables and explore more advanced models. Future studies should focus on incorporating real-time data, scalability, and integration of emerging technologies such as energy storage systems and smart grid solutions. Additionally, future research could explore the social and regulatory frameworks necessary for large-scale deployment, aiming to enhance both economic feasibility and environmental impact.

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