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Towards the Decarbonization of Urban Communities: Evaluation of Smart and Green Strategies to Reduce Gas Carbon Emissions

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Highlights

What are the main findings?

- NetLogo simulation results indicated that the implementation of intelligent traffic lights (ITS) can reduce fuel consumption by 5%, CO_2 emissions by 73 tonnes per year, and the average travel time by 20%. The landfill reconversion scenario (PV plant and electric buses) can save 38 tonnes of CO_2 per year and generate 117 Toe/y of renewable primary energy.
- A quantitative incidence matrix was used to compare these strategies against two others (library modernization and smart streetlights) based on multiple "smart axes" (energy, economy, community, etc.). The matrix analysis identified intelligent traffic lights as the optimal and highest-priority solution, while the landfill scenario ranked third, largely due to its high investment cost and long implementation time.

What is the implication of the main finding?

- The incidence matrix provides a holistic method for public administrations to create a priority ranking for diverse smart city interventions. It allows for the comparison of projects with different objectives and assesses their comprehensive impact beyond their primary addressed areas.
- The findings demonstrate the importance of selecting appropriate key performance indicators (KPIs) for evaluation. An intervention's overall benefit is not determined by the number of indicators it impacts but is critically influenced by its economic and temporal feasibility.

Abstract

One of the key aspects of a smart city is to reduce CO_2 emissions by adopting different strategies that can also improve the quality of life of citizens. Current metropolises present additional issues compared to traditional cities, such as extremely heavy traffic and abandoned spaces. This paper, therefore, proposes two interventions aimed at improving the smartness of the municipality of Rome: the implementation of a photovoltaic field in an abandoned space used to charge electric buses and the implementation of smart traffic lights that optimise the traffic flow. To measure the impact and effectiveness of those interventions, key performance indicators (KPI) were defined to point out the benefits of the analysed strategies, and a quantitative matrix approach was applied. The aim was to establish a correlation between the different scenarios proposed, assigning

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numerical indices to each of them that can comprehensively express their impact on the identified smart axes. The results obtained showed the importance of selecting appropriate performance indicators to assess the impact of interventions. Furthermore, the findings revealed that the scenarios with the greatest number of indicators are not necessarily the most advantageous. Overall, the simulations indicated that the proposed interventions could produce a significant reduction in emissions due to the implementation of renewable energy production.

Keywords: smart indicators; CO_2 emissions reduction; renewable energy; intelligent mobility

1. Introduction

Energy and environmental sustainability are crucial aspects in the context of today's global challenges. Sustainability aims to meet current energy needs without compromising the ability of future generations to meet their own [1]. It promotes the use of renewable energy sources, such as solar, wind [2], and hydroelectric energy [3] and sustainable development [4], while reducing greenhouse gas emissions [5–7]. In parallel, environmental sustainability focuses on preserving ecosystems, reducing pollution [8], managing natural resources responsibly, and promoting biodiversity. In this framework, the concept of smart cities emerges as an integrated solution to address sustainability challenges [9] in urban areas and to reach the Sustainable Development Goals (SDGs) [10].

The optimal management of energy resources represents an essential component of smart cities. Such management encompasses promoting renewable energy sources and distributed energy systems, including solar panels and microgrids. These cities invest in sustainable mobility [11], integrating green public transport [12], smart traffic lights [13], electric vehicles, and charging infrastructure [14,15] to reduce carbon emissions and improve air quality. The integrated approach of thinking, designing, and managing smart cities exemplifies the potential for innovative technologies [16,17] to be employed in the pursuit of energy and environmental sustainability objectives. This issue not only enhances the quality of life of citizens but also contributes to a more sustainable and resilient future [18]. Moreover, these cities serve as exemplars of sustainable urban development [19], offering practical and replicable solutions on a global scale. They demonstrate how the combination of advanced technologies and sustainable management practices can effectively address the challenges of urbanisation and climate change [20,21].

To evaluate the performance of the different actions within the integrated smart cities approach, several methods were proposed in the literature. Esteban-Narro et al. [22] defined a multidimensional tool to support the planning phase in evaluating the projects of transformation of the city; Bandeiras et al. [23] developed a multi-criteria model applicable to different policy scenarios to assess the sustainability of energy resources in their energy efficiency, energy supply, and storage technology. The ELECTRE system was realised to support the selection of the most appropriate technology for the smart city [24], and the BTOPSIS method was utilised for analysing the data coming from citizens' evaluation of urban factors that assess the quality of life within the city [25]. Some studies developed algorithms for different optimisation purposes: the scheduling for fuel dispatching, power generation [26], or for the optimal operation of a hydrogen hub [27], the functions of the smart street lighting [28], and the indication of the best parking solution. Other studies proposed models based on the finalised fuzzy logic to address the multiple urban issues [29], to rank the strategies related to business intelligence [30], to evaluate the sustainable energy systems [31], to select the smart transportation systems most suited for each city [32], to

define the optimal management of indoor systems in Nzebs [33], and to determine the location of service stations for electric vehicles [34].

To rank smart actions, it is essential to collect appropriate key performance indicators (KPIs). These indicators play a key role in measuring the impact of selected strategies on different fields and promoting energy sustainability. KPIs allow ongoing strategies to be adapted and optimised to ensure long-term benefits. This goal is currently relevant, as pointed out by the project "Fit for 55," aiming to reduce greenhouse gas emissions and promote a low-carbon economy [35].

There are several KPIs in the literature, such as GHG emission reduction, energy consumption, resource efficiency, and air quality, that can promote smart cities towards decarbonization goals [36]. In this context, smart energy system models are used to analyse how carbon pricing policies influence energy costs for users and the integration of renewable sources, which are key factors for decarbonization [37]. For instance, integrating green infrastructure [38], adopting energy-efficient technologies in buildings [39,40], and promoting low-emission transport can significantly contribute to improving the quality of the urban environment and reducing the overall carbon footprint. Incorporating targeted KPIs within a strategic framework, such as the "Fit for 55," allows them to dynamically adapt their strategies in response to achievements. The mentioned approach not only promotes transparency and accountability in the implementation of urban policies but also ensures more resilient urban systems.

The first list of KPIs was related to business administration, where they provide a means of measuring corporate performance in achieving broader objectives [41]. These indicators are quantifiable metrics that reflect an organisation's performance in the context of achieving its strategic objectives. Gradually, the use of KPIs has extended beyond business and industry to government administration. In general, indicators and, in particular, KPIs should express as accurately as possible the degree to which a target or standard has been met or exceeded. To assess progress towards a specific target, a variety of indicators are available [42]. It is of the utmost importance that the indicators identified are measurable, and preferably objectively so. For the majority of indicators within the people, governance, and propagation themes, quantitative measurability is limited. However, the social sciences offer approaches to deal with qualitative information in a semi-quantitative way [43]. To ensure reliability, the definitions of indicators must be clear and not open to different interpretations. In many cases, an existing set of indicators that meet this requirement can be relied upon. New indicators are defined in a meaningful manner in the context of existing policy objectives [44]. Furthermore, indicators within a system should not measure the same aspect of a sub-theme, as this would result in redundancy. Independence implies that minor alterations to the measurement of one indicator should not affect the preferences assigned to other indicators in the evaluation.

In this framework, this study proposes a smart evaluation of selected strategies to reduce gas emissions and increase the spread of renewable sources in an urban district. The role of the selected KPIs in the study is crucial to calculate the impact of strategies on different fields, such as environmental, community, and economic aspects. The smart methodology was previously defined by the authors [45] and it is essential to aggregate the KPIs into a unique value that reflects the overall impact of the strategies considered. The main output of the work is to evaluate the final score per strategy, drafted in a priority ranking. The ranking gives a list of priorities that can guide policies and designers during the realisation processes.

Two scenarios are used for the integration of renewable energy sources into urban infrastructure. The first scenario involves the installation of a photovoltaic (PV) field on the roof of an abandoned building to power an electric bus line. The second scenario considers

the deployment of smart traffic lights. The proposed interventions foresee an increase in the produced and self-consumed renewable share and a substantial reduction in CO_2 emissions. This reduction is linked to the diminished use of energy produced from fossil fuels and to an improvement in the management of motorised traffic, with the consequent lowering of the related consumption. Although the two proposed interventions were developed by analysing specific data from a particular urban context, the measures proposed can be generalised and applied in other cities.

Moreover, the work proposes to employ a quantitative approach to identify a priority among the proposed interventions. The analysis, therefore, initially focuses on the identification of key performance indicators (KPIs) that are useful for characterising the interventions; then, an overall numerical value was attributed to each scenario, representing the impact of each scenario on the identified smart axes. This process enabled the identification of the most effective and pressing strategies, which were then ranked in order of priority. The presented work aims to evaluate the effectiveness of integrated smart city initiatives by defining and monitoring key performance indicators (KPIs), ensuring alignment with long-term sustainability goals, and contributing to reducing environmental impact.

The paper is structured as follows: Section 2 delineates the methodology employed, including the tools utilised and the input required for the different actions. Section 3 presents a detailed account of the primary findings, followed by the discussion (Section 4), while Section 5 offers a synthesis of the key insights. The presented work aims to evaluate the effectiveness of integrated smart city initiatives by defining and monitoring key performance indicators (KPIs), ensuring alignment with long-term sustainability goals, and contributing to reducing environmental impact.

2. Materials and Methods

The preliminary stage of the investigation entailed a comprehensive analysis of the case study to identify the principal weaknesses and potential solutions. In order to identify the priority actions, a survey was carried out among citizens to evaluate the solutions they prefer: the most rated interventions were considered in this study. The initial proposal involved the redevelopment of the former landfill site; this entailed the conversion of the principal structure into a depot for electric buses, with a photovoltaic system installed on the roof of the building itself. The structure was modelled using AutoCAD 3D software (Version 2025) to obtain a suitable model for subsequent simulations. The photovoltaic field was thus modelled using PvSyst 8; once the CAD model was imported into PvSyst, the system components (inverters and panels) were selected, and the orientation of the structure and project parameters (inclination and orientation) were defined. This enabled the calculation of the system's annual production to be made. The proposed solution entails virtual self-consumption, grid-connected operation, and a year-long energy balance based on the total energy produced and consumed. In particular, the energy is employed to recharge a fleet of electric buses that operate on a local public transport route. By selecting the bus model and assuming a charging strategy that optimises battery life and maximises the number of daily routes, the reduction in pollutant emissions due to reduced fuel consumption resulting from a shift from private to public transport was estimated. This estimation can be made based on the assumption that the selected bus model is representative of the average bus model in terms of battery life and daily routes.

The second proposed action is the Intelligent Traffic Lights (ITS) scenario. The behaviour and effects of the ITS were simulated using NetLogo 7, a programming language and integrated development environment (IDE) for agent-based modelling. The software was selected for its capacity to provide a granular representation of the system, encompassing individual vehicles and their distinctive characteristics. Furthermore, the system

enables the monitoring of parameters that are of interest for the study, including CO_2 reduction, idling time, reduction in average travel time, average speed, and average consumption, as well as the number of stops. The simulation results were then compared with empirical data, both to refine the model in the initial phase and to highlight the effectiveness of the tool in describing this type of phenomenon. The final results of the smart traffic light simulations were compared with those of the traditional traffic light simulations.

Subsequently, to prioritise the different proposed strategies, a quantitative incidence matrix was developed [45] to compare the different scenarios to the smart axes. To define the matrix properly, it is necessary to propose more than two solutions. Therefore, this study not only analyses the two central strategies of intelligent traffic lights and landfill reconversion but also includes a scenario involving the modernisation of a municipal library and the replacement of traditional streetlamps with intelligent lamps. Firstly, the KPIs were defined, and for each one, the relevance to the proposed scenario was assessed. A numerical value was then assigned to each scenario, thereby providing a comprehensive representation of the impact of each scenario on the identified smart axes. The obtained score of the interventions is then adjusted by two coefficients representing the economic-financial feasibility and the temporal feasibility of the interventions themselves to obtain a final ranking. The following subsections provide detailed explanations of the smart method's steps as well as the case study employed.

2.1. Case Study

The proposed interventions have been designed for the third municipality of Rome. The characteristics of the municipality do not significantly affect the applicability of these solutions in other contexts. The implementation of a photovoltaic field and an electric bus route represents a viable measure for most urban centres, assuming the availability of adequate space for the installation of the PV plant. However, the variation in the performance of the panels depending on the location must be taken into account. Similarly, the values associated with the bus route indicators depend on specific estimates of use in the context studied. It is also worth noting that the use of electric buses is limited in terms of route length or duration unless intermediate charging stations are installed, which are unnecessary in this case.

In total, the structure occupies an area of approximately 40,000 square metres with a perimeter of 1027 m. The total area can be divided into three zones of interest:

- The area currently used as a parking area and workshop for landfill vehicles, with an area of 11,238 square metres and a length of 334 m.
- The first unused structure of the plant, with an area of 18,445 square metres and a perimeter of 529 m.
- The second structure, which is currently not in use, has an area of 7175 square metres and a perimeter of 374 m.

The photovoltaic plant was installed on the existing but currently unused structure. The plant occupies an area of 5397 square metres and consists of 2656 Trinasolar TSM-DE15M-(II)-400 modules [46], each with a nominal power of 400 Wp, for a total of 1062 kWp (Table 1). The modules are inclined at 30° to the horizontal surface. The DC/AC converter employed is an Emerson SPV 1800 [47], which has a rated power of 1060 kW and an AC/DC ratio of 1 (Table 2). The electric bus selected is the basic 3-door Mercedes eCitaro [48]. The estimated range of the vehicle is approximately 320 km when using the entire battery pack, which consists of 12 modules. Each module is composed of a package of 12 NMC2 batteries of 33 kWh, for a total capacity of 396 kWh.

Table 1. Photovoltaic panel datasheet. Source: Ref. [46].

Parameter	Value
Solar Cells	Monocrystalline, 144 cells (6 × 24)
Maximum Efficiency	20.70%
Module Dimensions	2015 × 996 × 35 mm
Peak Power Watts-P_{MAX} STC	400 Wp
Power Output Tolerance-P_{MAX}	0/+5 W
Maximum Power Voltage-U_{MPP} STC	40.3 V
Maximum Power Current-I_{MPP} STC	9.92 A
Open Circuit Voltage-U_{OC} STC	49 V
Short Circuit Current-I_{SC} STC	10.45 A
Module Efficiency η_m	19.90%
NMOT (Nominal Module Operating Temperature)	41 °C (±3K)
Maximum Power-P_{MAX} NMOT	302 Wp
Maximum Power Voltage-U_{MPP} NMOT	38 V
Maximum Power Current-I_{MPP} NMOT	7.95 A
Open Circuit Voltage-U_{OC} NMOT	46.2 V
Short Circuit Current-I_{SC} NMOT	8.42 A
Temperature Coefficient of P_{MAX}	−0.36%/K
Temperature Coefficient of U_{OC}	−0.26%/K
Temperature Coefficient of I_{SC}	0.04%/K

Table 2. DC/AC converter datasheet. Source: Ref. [47].

Parameter	Value
DC INPUT	
MPPT Range (@ 340 Vac)	510–800 Vdc
Maximum Voltage	830/1000 Vdc
Maximum Current	2100 A (Idc)
Maximum Power Point Trackers	1
AC OUTPUT	
Apparent Power (@ 340 Vac)	1060 kVA/kW
Nominal Output Voltage	3-Phase 260 V to 400 V ± 10%
Rated Current	1800 A (Iac)
Grid Nominal Frequency	50/60 Hz
Current Distortion (THID)	2.30%
SYSTEM DATA	
Inverter Topology	Multimaster with fault tolerance
Night Time Power Consumption	<0.1 kW
Ambient Operating Temperature	0–50 Â°C

AutoCAD 3D was initially employed to generate the three-dimensional model of the structure that would house the photovoltaic plant. The CAD project was then imported into the PVsyst software, which enabled the modelling of the installation.

The proposed circular route of buses is approximately 28 km long with an estimated journey time of approximately 90 min, taking into account potential city traffic, the need for passenger stops, and the final stop at the terminal. The strategy for managing charge cycles and bus use is as follows: assuming an average consumption of 1.5 kWh/km [49], each route consumes a total of 42 kWh. To optimise battery life, it is assumed that the consumption is evenly distributed across the twelve modules, resulting in a reduction of 3.5 kWh per module after each complete route. This strategy exploits partial cycle operation to ensure that the residual capacity threshold of 16.5 kWh [50] is not breached. Therefore, with a consumption of 3.5 kWh per route, each bus can complete four routes before recharging.

For recharging, a system capable of delivering 360 kW has been assumed, with a duration of 28 min (approximately 30 min). Two charging stations have been purchased

to circumvent potential issues that may arise when multiple buses require simultaneous charging. It is assumed that four buses are used, with the first leaving at 7:00 in the morning and subsequent buses leaving every thirty minutes, with the last bus returning to the station at 22:00. Furthermore, it is essential to connect the charging stations to the grid to guarantee the availability of charging for the vehicles even when the photovoltaic plant is not generating power.

It can be assumed that for every 100 people using electric buses, there is a reduction of approximately 70 cars on the road [51]. Subsequently, the average fuel consumption was estimated to be 7 litres per 100 km, and the daily result was extrapolated to reflect the annual consumption. Moreover, the conversion factor from kg to tonne of oil equivalent (Toe), which is equivalent to 1.051 Toe/kg [52], the density of petrol, which is 0.76 kg/dm^3 [31], and the primary energy conversion factor of 0.086 Toe/MWh [53] have been employed to assess the results obtained and to facilitate comparison with the outcomes of alternative actions.

For the economic analysis, a unit cost of EUR 250,000 was assumed for each bus [54], EUR 4000 for each charging station, and EUR 1500 per kWp for the photovoltaic system. It was assumed that operating and maintenance costs would be equal to 4% [55], 2% [56], and 2% [57], respectively. Given the considerable total investment foreseen for this scenario, a financial structure of 70% debt and 30% equity was assumed. The investment period was assumed to be thirty years. The reference price for electricity sold is 0.25 EUR/kWh [58]. Furthermore, the "renovation bonus" incentive, which guarantees a 50% reduction in IRPEF (Italian personal income tax) up to a maximum expenditure limit of EUR 96,000, divided into ten equal annual instalments, has also been applied.

2.2. NetLogo Intelligent Traffic Light Simulations

The traffic light system model was created using the two-dimensional version of NetLogo. It provides researchers with a flexible environment to create simulations where autonomous agents interact with each other and their environment. NetLogo supports the development of models that incorporate dynamic behaviours, rules, and emergent properties, making it suitable for exploring phenomena such as traffic dynamics. In traffic modelling, NetLogo allows for the representation of vehicles as agents that follow personalised rules for acceleration, deceleration, and lane changing. This enables the simulation and analysis of traffic flow dynamics, congestion patterns, and the impact of different traffic management strategies (including smart traffic lights). Researchers can adjust parameters such as vehicle density, road network topology, and signal timing algorithms to investigate their influence on traffic efficiency and safety within simulated environments.

The environment in which the agents (cars) operate is defined by "tiles," which are built-in agents that represent floor tiles. The NetLogo environment employs a built-in variable, "ticks," to track the passage of time: each time a command sequence is executed, a tick is added to the elapsed time. In the analysed model, a tick is equivalent to one second.

In this project, the spatial domain of the model was represented by a rectangular brown frame measuring 400 × 200 "tiles" or "patches" (see Figure 1). In the model, cars are represented by the length of a single patch. Therefore, assuming an average car length of 4 m, the unit area of the model, i.e., the patch, corresponds to a square of 4 × 4 m, describing an area of 1.6 × 0.8 km.

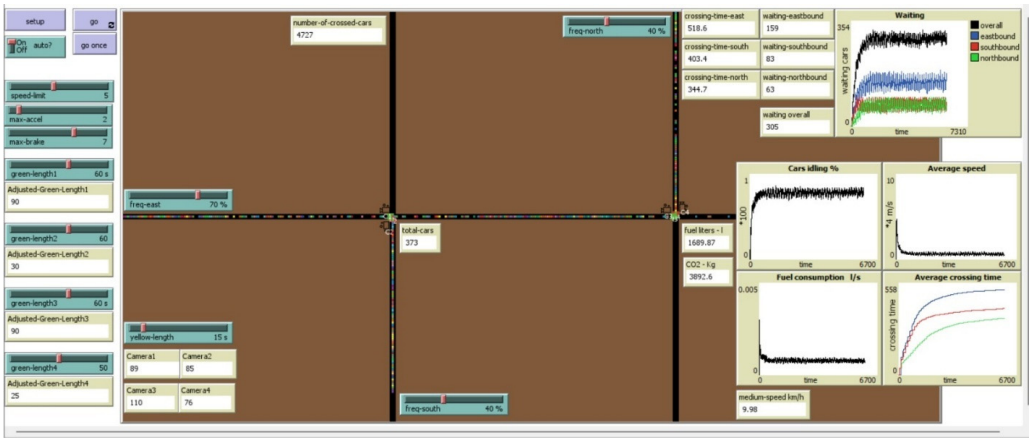


Figure 1. NetLogo interface simulation.

The model depicts a principal road intersecting with two perpendicular side roads. All roads in the model are single-lane and one-way. The associated flows may be adjusted using the freq-north, freq-south, and freq-east sliders. A value of 70 means that there is a 70% probability that a car will be generated at each "tick", another built-in temporal variable. Both intersections are equipped with intelligent traffic lights. The outcomes are then compared with those of simulations conducted using traditional traffic lights. The behaviour of the traffic lights is based on the detection of vehicles in the previous sections of the road. The traffic light adjusts the duration of the green light to favour the lane with the greater number of vehicles.

The green length sliders, specific to each traffic light, define the duration of the green time for that traffic light. The initial settings for the secondary roads are 60 s, while the main roads are set to 50 s. In the simulation with the switch on, i.e., with the intelligent traffic lights, the green length is the starting variable from which the adjusted green length is obtained. This is the optimised green time based on the incoming traffic. At each iteration of the script, the number of vehicles on the road segments ahead of the traffic lights is counted. For each pair of traffic lights, the green lengths are scaled by the same amount, either positively or negatively, depending on the road segment with the highest number of vehicles. The adjusted green length may vary by up to 30% of the initial green length, with increments of 0.1% per tick.

The number of vehicles generated is determined by the sliders visible in the graphical user interface. Each car is controlled by a few simple rules. These include adjusting their speed according to the behaviour of the car in front and striving to reach the optimal speed while avoiding collisions. The acceleration and braking values can be set using the corresponding sliders. The speed of each car is updated based on the distance from the preceding vehicle and the maximum acceleration and maximum braking values. Due to the unavailability of sufficient data, the simulations have been conducted with predetermined values for the acceleration, braking, and fuel consumption of the vehicles. It would be preferable to assign these values based on probabilistic distributions, thus better representing the variability in drivers' behaviour. The fuel consumption is calculated based on the speed, which determines the gear used. This allows for the monitoring of fuel consumption for stationary cars.

The maximum acceleration, maximum braking, and speed limit sliders define the behaviour of the vehicles, adjusting their speed based on the distance to the preceding vehicle. It can be assumed that vehicles will always attempt to reach the speed limit if conditions allow. All three sliders have been set to values that are realistic and representative of the

typical behaviour of vehicles. Based on the speeds, five distinct consumption classes have been delineated:

- Idle consumption (0 km/h—0.00055 L/s);
- First gear consumption (0–10 km/h—0.0043 L/s);
- Second gear consumption (10–30 Km/h—0.0028 L/s);
- Third gear consumption (30–50 Km/h—0.0019 L/s);
- Fourth gear consumption (50–70 Km/h—0.0013 L/s).

The absence of a fifth gear is logical, given that the model describes an urban context with a speed limit of approximately 70 km/h.

The road section where the results were applied consists of eight traffic lights distributed over a length of approximately 2.5 km. Based on empirical observations, it can be estimated that approximately four hours of heavy traffic are recorded daily. The observed traffic flow under these conditions was estimated to be 2000 vehicles per hour or a total of eight thousand vehicles per day. Furthermore, given that Rome is one of the most congested cities in the world [59], it has been estimated that four hours of traffic congestion per day occur on this route for at least 200 days per year. A value of 2.34 kg of CO_2 per litre of fuel consumed has been assumed in accordance with the findings of (Touring Club, Domande frequenti sul CO_2, n.d.), along with a social cost associated with carbon dioxide emissions of EUR 185 per ton. Additionally, an average social cost per capita per hour of congestion of EUR 12 has been assumed [60]. For the economic analysis, a unit cost of EUR 30,000 per intelligent traffic signal and an operating cost of 6% of the investment cost were assumed. Considering the intersections of the road section under analysis, it is necessary to replace eight traffic lights, resulting in a total expenditure of EUR 240,000 [61]. Given that this represents an acceptable amount for the municipality of Rome, a debt-free financing structure was established.

2.3. Photovoltaic System Simulations and Software

PvSyst is a specialised software application developed by the University of Geneva, which is widely employed in the solar energy industry and research to simulate and analyse photovoltaic (PV) systems. It provides robust capabilities for the design, optimisation, and assessment of PV installations across a range of scales and configurations. The detailed component modelling of PVsyst enables users to specify crucial parameters, including those pertaining to the characteristics of photovoltaic (PV) modules, the efficiencies of inverters, and the effects of shading. Engineers and researchers can then generate precise energy production predictions tailored to the PV system's design, accounting for factors such as tilt, orientation, and shading conditions. Additionally, PVsyst includes robust financial analysis tools that are essential for the assessment of the economic viability of PV projects. The software is capable of calculating metrics such as the levelized cost of electricity (LCOE), payback periods, and financial returns [62].

The initial step in the software is to import the weather data from Meteonorm 8.0, NASA, or PVGIS, depending on the project site. For this case study, the input data was limited to the indication of the panels' orientation, the definition of the generation system (building structure, photovoltaic panels, and inverters), the module layout, and the electrical load due to the charging of electric buses. Once the modelling was complete, a simulation was executed to provide as an output the energy productivity of the system, the annual energy supplied to the user from the photovoltaic plant, and the share that needs to be supplied from the grid. The efficacy of the simulation is ensured by the mathematical models that describe the behaviour of the photovoltaic modules, the solar radiation incident on the photovoltaic system, and the energy conversion.

2.4. Simulations of Library Occupancy and Smart Street Lighting

Two additional possible solutions were simulated to correctly apply the matrix: the monitoring of the seat occupancy within the municipal library and the substitution of the traditional street lighting with a smart system. Both solutions were simulated with MATLAB Simulink R2025a.

To address the problem of the limited number of seatings in the public library, a MATLAB code was developed to simulate the functioning of a pressure sensor installed on the seat that detects the person's weight. This sensor communicates with a display on the desk through which the person can indicate the hours of permanence in the library; this information will then be reported to an online database accessible to people who want to go to the library. The Simulink system is based on two "if" cycles: the first to set the display on and the second to show the message on the display. The display has two operating modes: on and off, corresponding to the values 1 and 0 exiting from the first "if" cycle. The message "Please insert the number of occupied hours" appears on the display when the input signal is 1, which occurs when the pressure sensor on the seat detects a weight higher than 45 kg; otherwise, if the pressure sensor detects a weight lower than 45 kg, the input signal to the display is 0 and the number of occupied hours will result in zero.

A new system of outdoor lighting for public parks was simulated in which the luminous intensity of the lamps is regulated by the users; this lighting system has the aim of reducing energy consumption when no people are in the area. The lighting system turns on when the environmental illuminance is below 10 lux, and the luminous flux of the lamps is set to the minimum by default, but people in the park can select the preferred illuminance level. The MATLAB Simulink structure is based on two "if cycles": one manages the on-off condition of the lamps, and the other represents the interaction with people. A photocell detects the environmental luminous condition and sends the signal to the system: above 10 lux, the signal is 0, and the system is off, while under 10 lux, the signal is 1, and the system is on at the minimum level. The second "if system" reproduces the action of people who can regulate the luminous intensities of the lamps by means of a knob installed on the poles. The luminous intensity corresponds to the x variable in MATLAB: it can be set between 6.67% (corresponding to 10 lux and 400 lm) and 100% (corresponding to 150 lux and 6000 lm).

2.5. Incidence Matrix

The incidence matrix enables a quantitative analysis of the proposed strategies. To define the incidence matrix, the smart axes that guide the study's approach to the problem were defined, followed by the definition of smart indicators that specifically characterise these smart axes (Table 3). The following smart axes were established in the project: energy, for the analysis of different aspects of the energy balance; economy, for the study of the economic structure; community, referring to the benefits that the community will obtain from the implementation of the proposed strategies; environment, to analyse the impact on the environment; and mobility, to study changes in transport. Except for the energy and economy axes, at least one indicator has been assigned for the other smart axes. The energy axes involve different indicators as follows:

- Non-renewable primary energy saved [Toe/year]. The calculation was based on a factor that takes into account network losses based on voltage level and consumption/exchange regime [63]. For the landfill, this factor was medium voltage (0.918), while the average efficiency of the Italian thermal power plant fleet was used as a reference (0.422) [64].
- Renewable primary energy produced [Toe/yr].
- Fuel savings [l/yr].

The common economic indicators are employed to evaluate the actions proposed in the study, such as

- Investment costs [EUR/yr]. The total investment cost was calculated by estimating the costs required to implement the proposed scenario.
- Economic savings [EUR/yr]. The potential economic savings guaranteed by the implementation of the scenario were evaluated.
- Investment payback period [yr]. It was evaluated using the following Formula (1):

$$PBP_d = \frac{-\ln\left[1 - \frac{WACC \times INV}{UCF}\right]}{\ln(1 + WACC)} \quad (1)$$

where

PBP_d is the compound payback period.
WACC is the weighted average cost of capital, expressed as a percentage:

$$\text{WACC} = (\text{D} \times \text{kd}) + (\text{E} \times \text{ke}) \quad (2)$$

where

D is the percentage of investment financed by debt.
kd is the rate of return on debt.
E is the percentage of investment financed by equity.
ke is the rate of return on equity.
INV is the investment cost required to implement the scenario.
UCF is the unlevered cash flow, which represents the actual cash flow generated by the financial structure. It is calculated by subtracting operating and maintenance costs from the sum of annual savings and any incentives.

Moving to the community axis, the following indicators were used:

- Approval rate [%]. It is based on the direct involvement of citizens in the choice of solutions.
- Time saved [min]. It is defined to assess the impact of the proposed solutions on the daily lives of citizens directly affected by the implementation of the action.
- Reduction in social costs [EUR/year]. The social cost of one tonne of CO_2 is set at 185 EUR/tonne [65], while the social cost of congestion is estimated at 12 EUR/h [66].

For the environmental study:

- Reduction in tonnes of CO_2 emitted [t CO_2/year]. This indicator is used to assess the environmental impact resulting from the implementation of the proposed solutions. The emission factor utilised in this analysis is 348 kg CO_2/MWh.

For mobility:

- Reduction in travel time [min].

The following formula is used to calculate the correction factor, which takes into account economic and time feasibility.

$$F_j = 1 - \left(\frac{a_j}{\max\limits_{1<j<n} a_j}\right) \quad (3)$$

where

Fj is the value of the economic or time feasibility assumed for the j-th solution.
aj is the value of the investment cost or implementation time assumed for the j-th solution.

Table 3. Indicators of smart axes.

Indicator	Units of Measurement
En 1 (Primary non-renewable energy saved)	Toe/yr
En 2 (Renewable primary energy produced)	Toe/yr
En 3 (Fuel savings)	l/yr
Ec 1 (Investment cost)	EUR/yr
Ec 2 (Economic savings)	EUR/yr
Ec 3 (Investment payback time)	yrs
Co 1 (Satisfaction index)	%
Co 2 (Time saved)	min
Co 3 (Social cost reduction)	EUR/yr
Ev 1 (Tonnes of CO_2 saved)	t CO_2/yr
Mo 1 (Travel time reduction)	min

Referring to Table 1, the mean value of each proposal is calculated for each smart indicator:

$$M_i = \frac{1}{n}\sum_{j=1}^{n} s_{i,j} \quad (4)$$

where

Mi is the mean of the i-th indicator.
n is the number of proposed solutions.
$\mathbf{s_{i,j}}$ is the value assumed by the j-th proposed solution for the i-th smart indicator.

A scaling procedure (normalisation of the numerical data) is then performed to evaluate the distance from the mean:

$$D_{i,j} = \left(\frac{s_{i,j} - M_i}{M_i}\right) \times 100 \quad (5)$$

where

$\mathbf{D_{i,j}}$ is the deviation of the i-th smart indicator from the mean of the j-th strategy.

The raw KPI data were normalised to a −5 to +5 scale for each indicator, allowing for direct comparison across different units of measurement. A positive score indicates a performance above the mean of all four scenarios, while a negative score indicates performance below the mean. A detailed description of the scaling procedure is reported in Appendix A.

In the event that a scenario is not described by a smart indicator, the value assumed for the indicator in the occurrence matrix is set to zero. This calculation must be performed for each smart indicator. The final ranking is thus obtained by summing all the values for each scenario, with the correction factor that takes into account the economic and temporal feasibility being applied. This represents the correlation value that is representative of each proposal.

3. Results

3.1. Smart Traffic Lights Results

The analysis and the simulations conducted show that the installation of intelligent traffic lights instead of traditional ones can result in a 5% reduction in fuel consumption, which is accompanied by a corresponding 5% reduction in CO_2 emissions associated with vehicular traffic. The results are derived from the specific application to our case study and a comparison with applications in comparable contexts [13]. It should be noted that the aforementioned simulation was carried out under conditions of considerable

traffic intensity. Simulations conducted under conditions of more fluid traffic flow yielded smaller reductions.

The NetLogo simulations yielded a total of 3120 litres of fuel consumed per day on the section in question, with 8000 vehicles in circulation. A 5% reduction would result in a daily saving of 156 litres of fuel and an annual saving of 31,200 litres. For the sake of simplicity, all vehicles were considered to be internal combustion and petrol cars.

The total carbon dioxide emission in the case of traditional traffic lights is 7.3 tonnes of CO_2 per day, equivalent to 1460 tonnes of CO_2 per year. This can be reduced to 1387 tonnes with the use of intelligent traffic lights, with a total reduction equal to 73 t CO_2/y (5%). In consideration of the social cost associated with carbon dioxide emissions, it is possible to achieve a saving of EUR 13,505 per year.

Figure 2 illustrates the reduction in travel time on the route and speed change. The results of the simulation demonstrate an increase in average vehicle speed of 3.35 km/h. In particular, in the simulation with traditional traffic lights, the average speed was 16.19 km/h, corresponding to a crossing time of 9.26 min. The use of smart traffic lights results in an average speed increase of 19.54 km/h, which reduces the average crossing time to 7.58 min. This represents a 20% reduction in travel time for the case study. Furthermore, assuming an average social cost per capita per hour of congestion of EUR 12, it is possible to save EUR 484,979 per year.

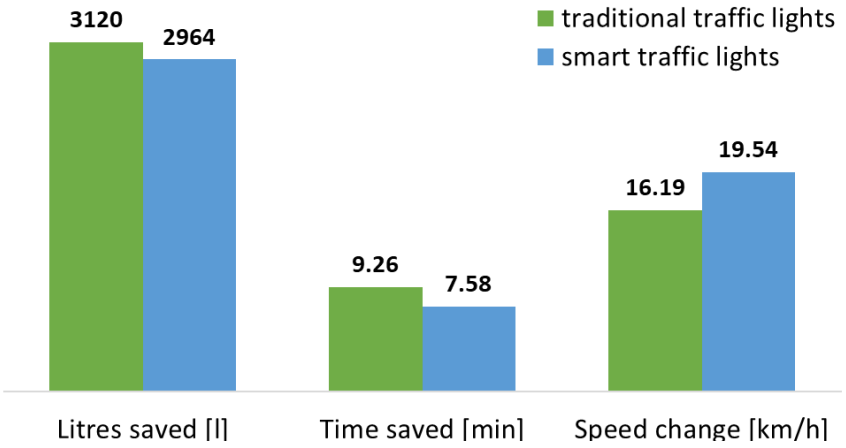


Figure 2. Results of simulation: traditional vs. smart traffic light.

The annual economic savings amount to EUR 498,484, guaranteed by the reduction in social costs associated with CO_2 emissions and traffic congestion (Figure 3).

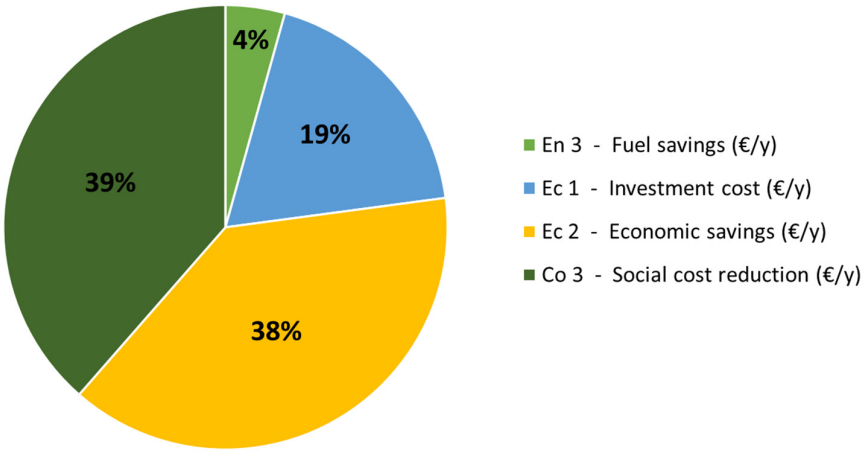


Figure 3. Results obtained from interventions on the traffic lights.

It should be noted that the management of intelligent traffic lights in most prominent applications involves integration with AI and some of its branches, such as deep learning and neural networks.

3.2. Landfill Results

The analysis of the photovoltaic system and the strategy of the electric bus service has led to the conclusion that the reduction in CO_2 emissions is 36 tonnes per year. This result was obtained by assuming that for every 100 people using electric buses, there is a reduction of approximately 70 cars on the road. Assuming an average fuel consumption of 7 litres per 100 km and replicating the daily result for the entire year, it was possible to observe a saving of 33,982 litres of fuel per year, which corresponds to 80 tonnes of CO_2 emissions saved. However, not all the energy used to recharge the electric fleet can be counted as self-consumption; the share of CO_2 produced due to the generation of energy through the Italian thermoelectric park must be subtracted from the CO_2 saved. In this scenario, the energy withdrawn from the grid is 183 MWh/y. Given that the share of energy produced from non-renewable sources in the Italian grid is 64% of the energy mix this share must be subtracted from the non-renewable primary energy savings produced by the reduced circulation of cars. The total non-renewable primary energy saved is then equal to 2 Toe/y. With regard to the generation of renewable primary energy by the photovoltaic system, if the 1377 GWh (see Figure 4) of electricity generated is converted to Toe, and further converted to primary energy, the result obtained is equal to 117 Toe/y. In the proposed scenario, a proportion of the energy, amounting to 307 MWh/y, is consumed on-site for the purposes of recharging electric buses during daylight hours (i.e., during the hours of production of the photovoltaic system). The remaining portion is then sold to the grid (1043 MWh/y, once system losses have been taken into account).

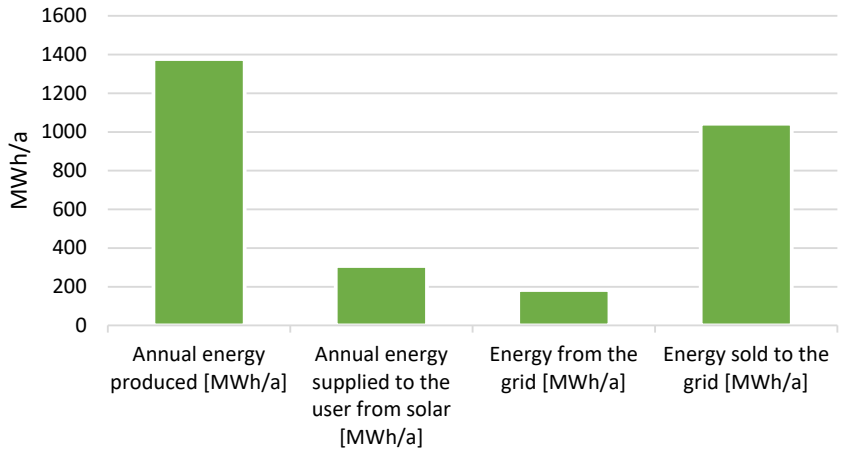


Figure 4. Landfill results: annual energy distribution.

The economic analysis (see Figure 5) revealed that the investment amounts to EUR 2,601,000, with an estimated economic saving of EUR 276,298 per year. In order to obtain this result, it was first necessary to calculate the revenue from the sale of the electricity produced, minus the cost of the electricity from the grid. Secondly, the savings resulting from the avoidance of 36 tonnes of CO_2 per year must be included. This final value is equivalent to EUR 6698 per year, with a cost of EUR 185 per tonne of CO_2. The investment is projected to yield a 19-year payback period.

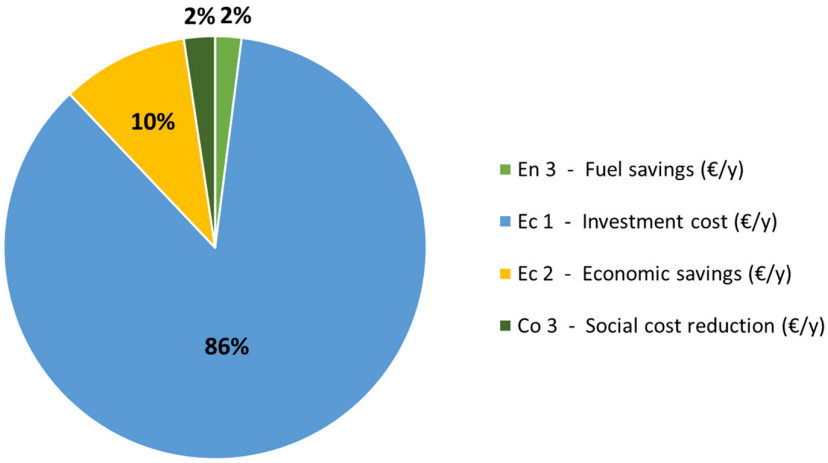


Figure 5. Results obtained from interventions on the landfill.

3.3. Matrix Ranking

The incidence matrix allows for a quantitative assessment of the proposed strategies. To properly define the matrix, more than two solutions were considered: in addition to the two main strategies of intelligent traffic lights and landfill remediation, a scenario involving the modernisation of a municipal library and the replacement of traditional streetlamps with intelligent lamps was included. The smart axes guiding the study's approach to the problem are outlined, followed by the identification of smart indicators that specifically characterise these axes. Subsequently, the proposed interventions are subjected to a quantitative analysis based on the aforementioned indicators. Table 4 provides a quantitative description of the proposals, categorised according to the smart axes.

Table 4. Summary of scenario evaluation across smart axes.

	Scenarios				
Indicator	**Smart Traffic Lights**	**Landfill**	**Library**	**Smart Streetlights**	**Mean**
En 1	25	2	0	2	19
En 2	0	117	0	0	29
En 3	31,200	33,982	0	0	22,730
Ec 1	240,000	2,601,000	4420	5000	712,605
Ec 2	498,484	276,298	0	4007	287,640
Ec 3	0.5	19	0	5	7.96
Co 1	0.5	0.7	1	0.4	0.65
Co 2	1.58	0	0	0	0.4
Co 3	498,484	6698	0	596	231,384
Ev 1 (Tonnes of CO_2 saved)	73	36	0	3	55
Mo 1 (Travel time reduction)	1.58	0	0	0	0.4

To estimate the economic and time feasibility of each strategy and to define the correction factors [67], the following implementation times were assumed:

- Intelligent traffic lights: 6 months for implementation, 4464 h;
- Landfill: 36 months for implementation, 26,784 h;
- Library: 1 month for implementation, 744 h;
- Smart street lights: 3 months for implementation, 2232 h.

Table 5 shows the economic and time feasibility of the four considered strategies.

Table 5. Summary of economic and time feasibility.

	Smart Traffic Lights	Landfill	Library	Smart Streetlights
Investment cost (EUR/yr)	240,000	2,601,000	4420	5000
Economic feasibility (%)	0.91	0.000	0.99	0.99
Time required (hours)	4464	26,784	744	2232
Time feasibility (%)	0.83	0.00	0.97	0.92

To compare all the data, a scaling method is required, as explained in the methodology overview, and shown in Appendix A. The resulting evaluation matrix across all the smart axes is reported in Table 6.

Table 6. Scenario evaluation matrix across smart axes.

		Scenarios			
Axes	**Indicator**	**Smart Traffic Lights**	**Landfill**	**Library**	**Smart Streetlights**
Energy	En 1	5.00	−2.87	0.00	−2.88
	En 2	0.00	5.00	0.00	0.00
	En 3	4.10	5.00	0.00	0.00
Economy	Ec 1	2.92	−5.00	5.00	5.00
	Ec 2	5.00	2.34	0.00	−3.51
	Ec 3	3.88	−5.00	0.00	−3.19
Community	Co 1	−2.87	1.13	5.00	−5.00
	Co 2	5.00	0.00	0.00	0.00
	Co 3	5.00	−3.81	0.00	−5.00
Environment	Ev 1 (Tonnes of CO_2 saved)	5.00	1.03	0.00	−3.91
Mobility	Mo 1 (Travel time reduction)	5.00	0.00	0.00	0.00
Economic feasibility		0.91	0.00	0.99	0.99
Time feasibility		0.83	0.00	0.97	0.92
Sum		39.77	−2.17	11.97	−16.58

The final ranking, showing the final score obtained for each strategy developed and the order of priority, is presented in Table 7.

Table 7. Final ranking of the proposed strategy.

Scenarios	Final Ranking
Smart traffic lights	39.77
Library	11.97
Landfill	−2.17
Smart streetlights	−16.58

4. Discussion

A comparison of the results of the different scenarios allows us to conclude the effectiveness of the interventions, the ability of the matrix to represent them correctly, and the suitability of the indicators employed.

The scenarios that have the greatest impact on the problems identified in the third municipality of Rome are landfill rehabilitation and intelligent traffic lights. These scenarios are described by 10 out of a total of 11 indicators. Nevertheless, the landfill scenario ranks third. The presented analysis shows that an intervention that is beneficial for the municipality in terms of energy and environmental impact can still be evaluated negatively based on the values assigned to certain selected indicators. It is evident that the greatest impact on the landfill rehabilitation scenario is the significant economic expenditure required to implement the scenario itself.

Conversely, the implementation of intelligent traffic lights is a solution that is readily achievable in terms of both cost and time. Furthermore, it ensures superior outcomes for the majority of indicators. It is also noteworthy that the implementation of this solution can have a positive impact on the mobility of areas that are geographically distant from the application area. By extending the simulation to neighbouring areas, it is possible to observe a positive influence on a number of the indicators related to the scenario.

Furthermore, the implementation of this solution would result in a reduction in emissions from one of the most significant sources of pollution in Europe. In fact, in 2019, the transport sector was the primary source of greenhouse gas emissions on European territory, responsible for 28.6% of total greenhouse gas emissions. Of these emissions, 72.6% originated from private road vehicles such as cars (60.6%), motorcycles (1.3%), and light commercial vehicles (11.0%) [68].

The reuse of the landfill site and its conversion into a sustainable energy production facility are fully aligned with European sustainability goals, such as the 2030 Agenda. Furthermore, there is also the potential of obtaining incentives for the reclamation and redevelopment of abandoned sites. For instance, Italy has allocated EUR 500 million for such objectives as part of the National Recovery and Resilience Plan [69].

Several considerations also need to be made regarding the matrix and the indicators chosen to represent it. Firstly, it should be emphasised that, as the scaling process is based on assigning minimum and maximum scores (in our case, 5.5) to interventions that take the extreme values of a given indicator, it is mandatory to compare at least three interventions.

It should be further observed that the matrix may be constructed without including certain indicators, which may then be subsequently incorporated. For instance, the economic indicator representing the total investment of a given intervention is most effective when comparing solutions to the same problem. In the context of evaluating alternative solutions, it may be more appropriate to exclude this indicator from the matrix and consider it at a later stage in relation to the rankings obtained. This approach allows for an evaluation based on scores and the estimated impact of the interventions.

5. Conclusions

This paper presents two scenarios for the integration of renewable energy sources and smart solutions into urban infrastructure, focusing on the implementation of intelligent traffic lights and the deployment of a photovoltaic system coupled with an electric bus service. The two scenarios were analysed through simulation tools and evaluated using a KPI-based incidence matrix to support a comparative assessment of heterogeneous smart city interventions and identify priority actions for public administrations.

The results show that both scenarios can contribute to urban decarbonization, although with different impacts across the considered smart axes. The intelligent traffic lights scenario emerged as the most effective solution in terms of overall priority, due to its favourable balance between environmental benefits, economic feasibility, and implementation time. Conversely, the landfill reconversion scenario demonstrated a strong contribution to renewable energy production and CO_2 emission reduction, but its higher investment costs and longer implementation time affected its final ranking. These findings highlight that the effectiveness of smart city interventions should be evaluated through integrated approaches that consider not only environmental performance but also economic and temporal aspects.

The adoption of an incidence matrix proved to be a useful tool for comparing interventions with different objectives and scales, allowing a holistic evaluation of their impacts beyond the primary sector addressed. By aggregating multiple key performance indicators

into a single ranking, the proposed methodology supports strategic decision-making and helps identify interventions that are both impactful and feasible within an urban context.

Some limitations of the study should nevertheless be acknowledged. The analysis is based on a single urban case study, and the quantitative results are influenced by local conditions, such as traffic demand, energy mix, and socio-economic characteristics. In addition, the simulation models rely on representative and simplified assumptions regarding traffic behaviour, modal shift, and energy use due to the limited availability of detailed real-world data. For these reasons, the results should be interpreted mainly in terms of relative comparison and priority ranking rather than as directly generalizable outcomes.

Future research could extend the proposed framework by validating the methodology with real operational data, applying it to different urban contexts, and performing sensitivity analyses on indicator selection and feasibility assumptions. These developments would further enhance the robustness of the approach and strengthen its applicability as a decision-support tool for smart and sustainable urban planning.

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Abbreviations

The following abbreviations are used in this manuscript:

ITS	Intelligent Traffic Lights
PV	Directory of open access journals
CO	Carbon Oxide
KPI	Key Performance Indicator
SDGs	Sustainable Development Goals
GHG	Greenhouse Gas
IDE	Integrated Development Environment
LCOE	Levelized Cost Of Electricity
PBP	Payback Period
WACC	Weighted Average Cost of Capital
UCF	Unlevered Cash Flow

Appendix A

The scaling procedure of the matrix is explained in the following.

The maximum and minimum values of the distance from the average for each strategy were evaluated for each indicator, and the scaling procedure was initiated. The range between the maximum and minimum values of the deviation from the mean was divided

into regular sub-intervals. It was assumed that the range would be divided into 10 sub-intervals, with the lower and upper limits set at −5 and 5, respectively, corresponding to the minimum and maximum values of the deviation from the average of the analysed smart indicator. A linear approximation was then performed between the aforementioned intervals (−5;0) and (0;5). For this reason, the effectiveness of the matrix in comparing the different interventions benefits from a larger number of proposals. Specifically, the following calculation was performed to determine the width of each sub-interval (in this context, the symbol "k" represents the number of sub-intervals):

- For 1 < k < 6

$$I_{k+1,min} = I_{k,max} \tag{A1}$$

$$I_{k+1,max} = I_{k+1,min} + \frac{|D_{min}|}{5} \tag{A2}$$

- For 6 < k < 10

$$I_{k+1,min} = I_{k,max} \tag{A3}$$

$$I_{k+1,max} = I_{k+1,min} + \frac{|D_{max}|}{4} \tag{A4}$$

where

$\mathbf{I_{k+1,min}}$ is the lower limit of the (k + 1)th subinterval, given by the upper limit of the previous subinterval, the kth interval.

$\mathbf{I_{k+1,max}}$ is the upper limit of the (k + 1)th sub-interval, given in the first interval by the lower limit of the (k + 1)th interval plus the minimum value of the deviation from the mean divided by five, and in the second interval by the lower limit of the (k + 1)th interval plus the maximum value of the deviation from the mean divided by four.

With reference to the mean deviation, the sub-intervals within which the calculated mean deviation values for each scenario fall are evaluated. Each scenario is then assigned a value between −5 and 5. This value is then multiplied by the correction factor, which is equal to 1 if an increase in the absolute value of the indicator under consideration is favourable for the analysis or −1 if the opposite is true.

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