SUMP4Balkans

Supported by:
Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety
on the basis of a decision by the German Bundestag
European Climate Initiative EUKI

Feasibility Study: Integration of PV Systems into Electric Public Transport – Case Study: Umag



This project is part of the European Climate Initiative (EUKI) of the German Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN). It is the overarching goal of the EUKI to foster climate cooperation within the European Union (EU) in order to mitigate greenhouse gas emissions. The opinions put forward in this study are the sole responsibility of the author(s) and do not necessarily reflect the views of the German Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN).

Contents

List of figures 4
List of tables 5
1. Executive summary 6
2. Introduction 6
2.1. Project background 6
2.2. Objectives 7
2.2.1. Scope of the study 7
2.3. Methodology 8
2.3.1. Spatial assessment in QGIS and Electric public transport demand 9
2.3.2. Renewable energy availability and hourly balancing 9
2.3.3. GHG emissions assessment 9
2.3.4. Scenario development 10
2.3.5. Economic evaluation 10
2.3.6. Flexibility considerations 10
3. Policy and strategic context 10
3.1. European policy Framework 10
3.2. National policy context - Croatia 11
3.3. Regional and local policy context – Umag 12
3.4. Alignment with SUMP4Balkans Objectives 12
3.5. Barriers and Enabling Factors 12
4. Technical feasibility assessment 13
4.1. Transport system overview 13
4.2. Planned electrification of public transport – Electric buses 13
4.2.1. Electric Bus Energy Demand 14
4.2.2. Charging infrastructure and load profiles 14
4.2.3. Interaction with the local energy system 15
4.2.4. Key challenges and opportunities 15
5. Integration of PV in transport 15
5.1. PV potential in Umag 15
5.2. Methodology for PV potential assessment 17
5.3. Integration of PV 18
5.3.1. System architecture options 18

6. Scenario development 19
6.1. Purpose and construction of scenario analysis 19
6.1.1. Energy balancing 20
6.2. Baseline assumptions 21
6.2.1. Charging strategy and load curve development 22
6.2.2. Potential rooftop PV locations 25
6.3. Scenario definitions 25
6.3.1. Scenario 1 - Low PV integration 26
6.3.2. Scenario 2 - Partial PV integration 27
6.3.3. Scenario 3 - High PV generation 28
6.3.4. Scenario 4 - PV and BESS integration 29
6.3.5. Scenario comparison 31
7. Results 31
7.1. Scenario 1 results 31
7.2. Scenario 2 results 32
7.3. Scenario 3 results 33
7.4. Scenario 4 results 34
7.5. GHG emissions results 36
8. Economic and financial feasibility analysis 37
8.1. Baseline assumptions 37
8.2. Grid connection costs 38
8.3. Financing & Debt service 39
8.4. Financial performance & performance indicators 40
8.5. Available subsidy and grant instruments 41
9. Discussion and interpretation of results 41
10. Environmental and social impact 44
11. Implementation roadmap 46
11.1. Phase 1 – Initial Electrification and Distributed PV Deployment 46
11.2. Phase 2 – Expansion of PV Integration 46
11.3. Phase 3 – Utility-Scale Renewable Integration 46
11.4. Phase 4 – Advanced Flexibility and Storage Integration 47
11.5. Risk Assessment and Mitigation 47
12. Conclusions and recommendations 47

References 48

List of figures

Figure 1 *Methodological framework to evaluate the potential of integrating photovoltaic solar systems into the electric public transport infrastructure of Umag* 8
Figure 2 *Photovoltaic power potential of Croatia* 17
Figure 3 Schematic representation of the PV-integrated vehicle charging system infrastructure 20
Figure 4 Adding installed PV capacity and hourly profiles of production into EnergyPLAN 22
Figure 5 Main terminal and potential charging stations 23
Figure 6 Bus lines 1 & 2 24
Figure 7 Bus lines 3 & 4 24
Figure 8 Potential locations for rooftop PV installations in the city centre of Umag 26
Figure 9 Electricity demand profile for Scenario 1 27
Figure 10 Umag sports centre cadastral parcel and potential rooftop & canopy locations [30] 28
Figure 11 Donji Picudo location & cadastral units, potential location for PV powerplant [30] . 29
Figure 12 Hourly electricity Import, Export, and PV Generation in Scenario 1 32
Figure 13 Hourly electricity Import, Export, and PV Generation in Scenario 2 33
Figure 14 Hourly electricity Import, Export, and PV Generation in Scenario 3 34
Figure 15 Hourly electricity Import, Export, battery storage and PV Generation in Scenario 4 . 35
Figure 16 Hourly interaction between PV generation, storage and bus electricity demand in Scenario 4 36
Figure 17 Storage charging and discharging distribution in Scenario 4 36
Figure 18 Total CAPEX by scenario 39

List of tables

Table 1 Bus lines with their distances 21
Table 2 Bus Line 4 Schedule Provided by the City of Umag 22
Table 3 Potential locations with approximated installed capacities for rooftop PV installations 25
Table 4 Scenario comparison 31
Table 5 Annual CO2 emissions and savings by scenario 37
Table 6 CAPEX structure by scenario 38
Table 7 Illustrative loan amortisation schedule, Scenario 1 for selected years 39
Table 8 Key performance indicators by scenario 40

1. Executive summary

This feasibility study assesses the technical, economic, and environmental viability of integrating photovoltaic (PV) systems into the emerging electric public transport system in Umag. The study is conducted in the scope of the SUMP4Balkans EUKI project, which aims to accelerate sustainable urban mobility transitions in the Balkan region through the integration of renewable energy sources (RES).

The City of Umag is currently undergoing a transition toward low-emission mobility by introducing electric bus lines. This transition presents a strategic opportunity to couple transport electrification with local renewable energy generation, particularly solar PV, as a significant share of the electricity demand can be met through locally generated solar energy due to the city's favourable geographic location and high solar irradiation levels.

The aim of this analysis is to evaluate different pathways for the integration of PV into the electric bus system by developing four scenarios:

1. **Low PV integration** – Electric buses are powered entirely by electricity from PV installed on available rooftops (e.g., public buildings and parking lots)
2. **Partial PV integration** – a portion of the bus fleet electricity demand is met through solar PV installed on available rooftops as well as Umag's sports centre
3. **High PV integration** – the majority of the demand is covered through a combination of rooftop PV and a moderately sized centralised PV power plant
4. **PV and BESS integration** – the total demand is supplied by a combination of rooftop and centralized PV, supported by an integrated battery energy storage system (BESS).

Integrating PV systems into electric public transport in Umag can substantially contribute to reduction of greenhouse gas emissions, increase of energy independence as well as long-term cost stability. Compared to the current diesel school bus fleet, the electric buses reduce CO2 emissions by 47% on grid electricity alone, and by 83-98% when supplied by PV.

2. Introduction

2.1. Project background

The transition toward climate-neutral and energy-efficient urban systems represents one of the central challenges facing European cities today. Urban transport, in particular, remains a major contributor to greenhouse gas (GHG) emissions, air pollution, and energy consumption. In response, the European Union has introduced a range of strategic initiatives aimed at decarbonizing the transport sector while increasing the share of renewable energy sources (RES) in final energy use.

Sustainable Urban Mobility Plan for the Balkans (SUMP4Balkans) project has been developed to support cities in Southeast Europe in designing and implementing integrated mobility solutions. The project places a strong emphasis on aligning transport electrification with renewable energy deployment, thereby addressing two critical pillars of the energy transition simultaneously.

The SUMP4Balkans project is supported under the EUKI (European Climate Initiative) framework and focuses on four pilot cities: Strumica, Ptuj, Cetinje, and Umag. These cities represent diverse urban contexts within the Balkan region, each facing specific challenges related to mobility, infrastructure, and energy systems.

A key component of the project is Activity A I.1, which involves conducting technical and economic feasibility studies for integrating photovoltaic (PV) systems into electric public transport fleets. These studies serve multiple purposes by providing evidence-based support for local decision-making, demonstrating the feasibility of integrated energy-transport solutions and enabling knowledge transfer and replication across the region.

This study focuses on the Croatian city of Umag, contributing to the broader objective of promoting sustainable, low-carbon mobility systems in the Balkans.

2.2. Objectives

The overarching objective of this feasibility study is to assess the potential for integrating photovoltaic (PV) systems into the electric public transport infrastructure of Umag. The study aims to provide a comprehensive evaluation of the technical, economic, and environmental implications of such integration, supporting strategic planning and investment decisions.

To achieve this objective, the study pursues several interrelated goals. It **assesses transport electrification needs** by estimating the and future electricity demand associated with the electric bus fleet, taking into account operational characteristics such as route length, frequency, and seasonal variations. It then evaluates the **solar energy potential** by analysing the availability of solar resources and identified suitable locations for PV installations within the urban area, including depots, public buildings and parking infrastructure.

Furthermore, the study develops and evaluates **multiple integration scenarios** representing different levels of PV integration and system configurations, enabling comparison of alternative development pathways, as well as a technical system analysis to assess the feasibility of integrating PV systems with charging infrastructure, including grid interaction, flexibility options, and energy management strategies.

The study also includes an economic and financial evaluation of the proposed solutions by analysing investment requirements, operational costs, and potential financial benefits, including cost savings and payback periods. Finally, the study assesses the environmental and societal impacts of the proposed integration by quantifying emission reductions and evaluate broader impacts such as employment generation.

Through these objectives, the study aims to provide a robust analytical foundation for the implementation of renewable energy-powered public transport systems.

2.2.1. Scope of the study

The scope of this feasibility study includes both the supply side (PV generation) and the demand side (electric bus charging), as well as their interaction within the local energy system. The

analysis considers planned deployment of electric buses across urban and peri-urban routes, as well as potential for both centralized PV powerplant production and decentralised rooftop PV installations on municipal and commercial buildings. It also examines the interaction between local electricity generation and the grid, alongside the temporal aspects of energy supply and demand, taking into account both daily and seasonal variations.

The study does not aim to provide detailed engineering design or procurement specifications. Instead, it focuses on strategic-level feasibility, identifying viable pathways and key parameters that influence system performance.

2.3. Methodology

The methodological approach adopted in this study is based on an integrated techno-economic framework, combining elements of energy system analysis, transport modelling, and scenario evaluation.

The methodological framework is comprised of four key components: mobility demand analysis, spatial assessment using geographic information systems (GIS), estimation of renewable energy potential, and hourly energy system modeling. The analysis has several distinct stages, as depicted in Figure 1.

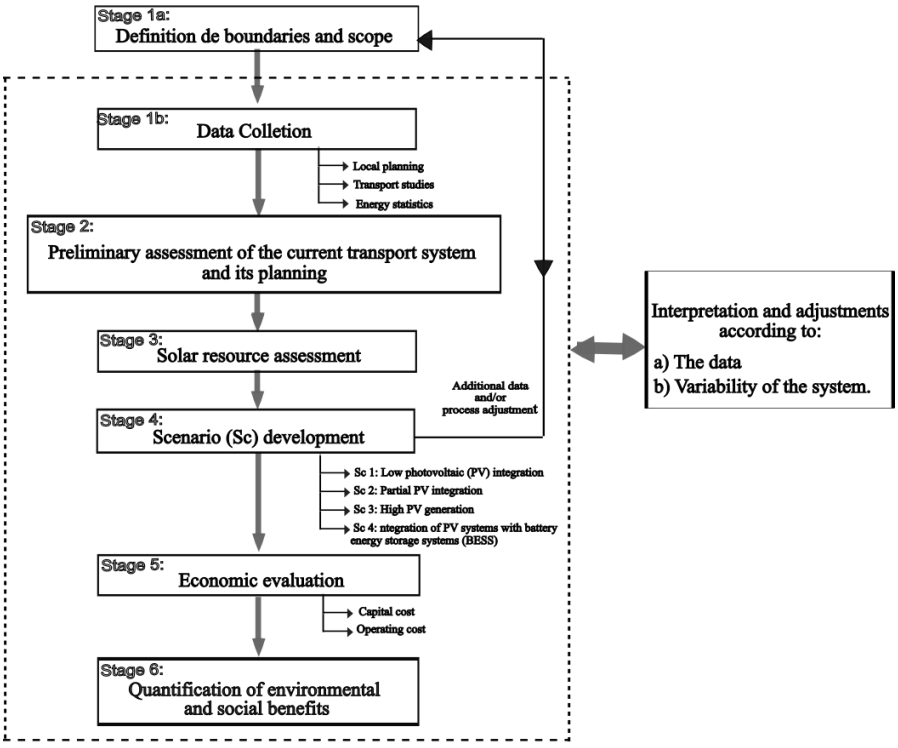


Figure 1 *Methodological framework to evaluate the potential of integrating photovoltaic solar systems into the electric public transport infrastructure of Umag*

2.3.1. Spatial assessment in QGIS and Electric public transport demand

The spatial component of the framework identifies the physical relationship between electric bus routes, charging points, depots, terminal locations and potential renewable energy sites. QGIS is used to map the transport network and candidate PV locations, including municipal rooftops, commercial buildings, parking areas and ground-mounted sites. The spatial assessment supports two planning questions: where renewable generation can be installed, and how close this generation is to the charging infrastructure and operational nodes of the public transport system. The use of QGIS ensures that the analysis can be replicated using open-source geospatial tools [26].

The electricity demand of the bus fleet is calculated from route length, daily mileage, number of vehicles, operating calendar and specific energy consumption. The feasibility study assumes electric bus operation with pronounced seasonal variations. Depot charging is treated as the dominant initial charging strategy, while the possibility of shifting charging to periods of high PV production is analysed as a flexibility measure. The hourly charging profile is constructed by distributing the daily fleet electricity demand across feasible charging windows, taking into account vehicle availability and operational constraints.

2.3.2. Renewable energy availability and hourly balancing

PV output is estimated from installed capacity and specific yield. For the Istrian region, the feasibility study uses favorable solar conditions, with global horizontal irradiation in the range of approximately 1400-1600 kWh/m2 per year and typical PV yields of about 1100 -1400 kWh/kWp per year. Hourly PV generation profiles are then compared with demand profiles in EnergyPLAN program. [27] The model calculates grid imports, exports, direct RES use, surplus generation and storage operation. The assessment focuses on indicators that are directly useful for SUMP decision-making: the RES share in transport electricity consumption, grid dependency, self-consumption of local PV, exported electricity, storage utilisation and the temporal coincidence between RES availability and charging demand.

2.3.3. GHG emissions assessment

The greenhouse gas (GHG) effect of each scenario is quantified using energy balances obtained through EnergyPLAN program. [27] Emissions of the electric buses are calculated as the grid electricity drawn by the buses multiplies by the grid emission factor, while PV electricity supplied to the buses is treated as zero emission. The reference case used is the existing diesel-powered school transport which uses approximately 30 L/100km.

The diesel emission factor used is 2.68 $kgCO_2/L$ which is also 0.8 $kgCO_2/km$. That means that yearly the current diesel bus fleet drives 79,935 km emitting around 64.3 tCO_2. The Croatian grid emission The Croatian grid emission factor used is 0.164 tCO2/MWh, which is the mean of the latest published yearly values which are 151 g/kWh for 2022 [31], 179 g/kWh for 2024 [32] and 161 g/kWh for 2025 [33]. The same factor is used to express avoided emissions which are PV electricity exported to the grid as well as the PV electricity self-consumed in public buildings. The CO_2 emissions caused by the manufacture of vehicles and PV systems are excluded. The transport savings and the grid credit are reported separately as they have different system boundaries.

2.3.4. Scenario development

Four scenarios are developed to represent different levels of renewable energy integration and system complexity. They are constructed by varying installed PV capacity, the spatial distribution of PV systems, the inclusion of commercial and public building demand, and the use of battery energy storage. The scenarios are not intended as final engineering designs, but as planning alternatives that reveal how system performance changes when SUMP electrification measures are coupled with local RES availability and flexibility options.

2.3.5. Economic evaluation

The economic feasibility of the system is evaluated using several key indicators. To determine long-term profitability, metrics such as Net Present Value (NPV) and Internal Rate of Return (IRR) are calculated to asses discounted future cash flows against initial capital expenditures (CAPEX). The benefit-cost ratio (BCR) measures overall cost-efficiency, while both Simple and Discounted Payback Periods establish the exact timeframe required to fully recover the project's initial investments under varying risk scenarios. To evaluate debt sustainability and ensure bankability, the Debt Service Coverage Ratio (DSCR) is analysed to verify that operational revenues sufficiently cover ongoing principal and interest obligations.

Cost savings are primarily achieved through reduced electricity purchases from the grid, avoided fossil fuel consumption due to electrification of transport, and reduced exposure to fluctuations in energy prices. These factors together improve the long-term financial attractiveness of PV-integrated electric bus systems.

2.3.6. Flexibility considerations

Flexibility is represented through two main options. The first is smart charging, which shifts charging toward hours with high local PV production when vehicle operation allows. The second is battery energy storage, which decouples electricity generation from charging demand by storing excess midday PV generation for later use. In the context of public transport planning, these flexibility options are important because they determine whether electric buses act as passive consumers or as controllable loads that support the local energy transition.

3. Policy and strategic context

3.1. European policy Framework

The transition toward sustainable and low-carbon transport systems is a central pillar of European climate and energy policy. The European Union has established a comprehensive legislative and strategic framework aimed at achieving climate neutrality by 2050. Transport plays a particularly important role in this transition, as it accounts for approximately 29% of total EU greenhouse gas emissions.

A cornerstone of this framework is the **European Green Deal**, which sets the overarching objective of transforming the EU into a climate-neutral economy. Within this strategy, The Fit for 55 legislative package sets binding targets, including a reduction of net GHG emissions by at least 55 % by 2030 compared to 1990 levels. In the transport sector this translates into strengthening emission standards for vehicles, promoting the deployment of alternative fuels infrastructure and increasing the use of renewable energy.

The Renewable Energy Directive (RED II and its revision RED III) further reinforces these objectives by setting binding targets for renewable energy consumption, including through the electrification of transport supported by renewable energy sources such as solar PV Complementing this, the Sustainable and Smart Mobility Strategy outlines the roadmap toward a modernised transport system based on zero-emission vehicles, smart charging infrastructure and integration of renewable energy into transport systems.

Urban mobility is specifically addressed through the promotion of **Sustainable Urban Mobility Plans (SUMPs)**, which provide a strategic framework for cities to plan and implement integrated mobility solutions. The coupling of electric mobility with renewable energy sources, such as photovoltaic systems, represents a key measure promoted within these plans.

Overall, the European policy framework strongly supports the type of integrated solution analysed in this study, namely the combination of PV generation with electric public transport systems.

3.2. National policy context - Croatia

Croatia's national energy and climate policy framework is closely aligned with EU objectives and provides a clear direction toward decarbonisation and renewable energy expansion.

The **Integrated National Energy and Climate Plan (NECP)** outlines Croatia's targets up to 2030, including an increased share of renewable energy in gross final consumption, reduced greenhouse gas emissions in line with EU commitments, and improved energy efficiency across sectors. In the transport sector the NECP places particular emphasis on electrification, the deployment of alternative fuels infrastructure and the promotion of sustainable urban mobility.

These priorities are further expanded in the **Low-Carbon Development Strategy**, which outlines long-term pathways toward climate neutrality. A key element of this strategy is the integration of renewable energy into transport systems, where electric transport powered by locally generated renewable electricity is identified as an important measure for emissions reduction and improved urban air quality.

Croatia has also implemented support mechanisms for renewable energy deployment, including **incentives** for PV installations, funding schemes for energy efficiency and sustainable mobility projects, and access to **EU structural and investment funds**. In addition, national legislation supports the development of distributed energy systems, enabling municipalities and local stakeholders to take a more active role in energy generation and management. Together these elements create a supportive environment for PV-integrated transport solutions.

3.3. Regional and local policy context – Umag

At the local level, the City of Umag has increasingly prioritised sustainability across mobility, energy, and environmental policy domains. As a coastal city with a tourism-based economy, it faces pronounced seasonal fluctuations in transport demand, congestion during peak periods, and associated environmental pressures from transport emissions.

In response, the city has initiated measures aimed at decarbonising its transport system. These include the introduction of electric bus lines, the promotion of low-emission mobility solutions, and alignment with regional and EU mobility initiatives. The development of a Sustainable Urban Mobility Plan (SUMP) provides the strategic foundation for these efforts, with objectives focused on reducing dependence on fossil fuels, improving public transport efficiency, and enhancing overall urban air quality and liveability.

Within this framework, the integration of photovoltaic systems into the electric bus infrastructure emerges as a logical next step. It enables reductions in transport-related emissions, increases local energy self-sufficiency, and contributes to greater long-term stability of energy costs.

3.4. Alignment with SUMP4Balkans Objectives

The proposed integration of PV systems into Umag's electric public transport system is strongly aligned with the objectives of the SUMP4Balkans project.

The project emphasises the integration of renewable energy into urban mobility systems, the development of replicable solutions for cities in the Balkan region and the strengthening of institutional capacity and stakeholder engagement.

In this context, this feasibility study provides both a practical decision-support tool for local authorities and a demonstration of the technical and operational viability of integrated energy-transport systems, while also supporting knowledge transfer to other municipalities in the region.

3.5. Barriers and Enabling Factors

Despite a generally supportive policy environment, several barriers may influence the implementation of PV-integrated electric transport systems. These include regulatory complexity related to grid congestion and energy management in Croatia, high upfront investment costs for both PV and charging infrastructure, limited local technical capacity for integrated system planning, and potential grid constraints, particularly in coastal and tourism- intensive areas where demand is highly seasonal.

At the same time, several enabling factors support the implementation of such systems. These include the availability of EU and national funding mechanisms which can significantly reduce initial investment costs, strong policy support for renewable energy and electrification at both European and national level, and rapid technological progress combined with continuously decreasing costs of PV systems. In addition, increasing public awareness and acceptance of sustainable solutions further supports their implementation and long-term success.

4. Technical feasibility assessment

4.1. Transport system overview

The City of Umag is a coastal municipality in the north-western part of the Istrian peninsula, made up of the urban centre and a number of smaller settlements spread across its hinterland and coastline. Mobility needs in Umag are shaped first and foremost by its residents: daily trips to schools, workplaces, healthcare, public services and shops, many of which are concentrated in the town centre. These needs are present throughout the year, and they are especially pronounced for residents of the outlying settlements, for whom the distances to central facilities are longest. Tourism, an important sector of the local economy, adds a further seasonal layer of demand during the summer months, concentrated along the coast and around key visitor destinations. Transport planning, infrastructure sizing and energy system integration must therefore serve a stable, year-round base demand while remaining flexible enough to accommodate summer peaks.

At present, the public transport system in Umag is relatively limited in scale and coverage, reflecting the city's size and dispersed settlement pattern. Daily mobility relies predominantly on private cars, complemented by organised school transport and a small number of structured public transport routes. For residents of the outlying settlements, and particularly for groups without access to a car, such as schoolchildren, older residents and people with limited mobility, this means fewer options and greater dependence on family members or contracted services. The current configuration also leads to higher emissions from conventional internal combustion engine vehicles and to congestion that intensifies during the summer season. Strengthening a reliable, year-round public transport offer, starting with school transport, which already forms the backbone of daily demand, is therefore a key step in aligning Umag's mobility system with long-term objectives of social inclusion, sustainability, energy efficiency and decarbonisation.

4.2. Planned electrification of public transport – Electric buses

As part of its transition toward sustainable mobility, the City of Umag is introducing electric bus lines alongside the development of necessary charging infrastructure and integration within the broader Sustainable Urban Mobility Plan (SUMP) framework. This represents a significant shift in both transport and energy system dynamics.

Electric buses offer several advantages in terms of zero emissions, reduced noise pollution, and higher energy efficiency compared to diesel vehicles. However, their implementation also introduces new operational requirements, particularly in relation to electricity demand management, charging infrastructure planning, and integration with the local power system.

Energy demand and operational performance are influenced by factors such as route characteristics, driving patterns, service frequency and fleet size, which vary between peak and off-peak periods, as well as the need to maintain reserve capacity to account for maintenance activities and fluctuations in demand.

Given Umag's tourism-driven dynamics, one would normally expect higher system utilization during the summer season and lower utilization during the winter months. However, since the

proposed electric bus system is primarily intended for use as school transport, this seasonal variability is largely mitigated. As a result, the buses are expected to operate consistently throughout the year, ensuring stable demand and utilization regardless of seasonal tourism fluctuations.

4.2.1. Electric Bus Energy Demand

The introduction of electric buses creates a new electricity demand component within the local energy system. This demand depends on specific energy consumption, which typically ranges between 1.0 and 2.5 kWh/km depending on vehicle type, driving patterns, ambient temperature and passenger load.

Assuming an average daily operational distance of approximately 60 km per bus, the estimated daily energy demand ranges from 60 to 150 kWh per vehicle, depending on vehicle characteristics and operating conditions. Actual energy consumption may vary due to tourism-driven route extensions during the summer season, increased air-conditioning demand, and additional energy required for heating during the winter months.

On an annual level, total electricity demand depends on fleet size, operational mileage, and seasonal utilisation patterns, and can be generally expressed as the product of daily demand, number of busses and operational days. This estimation provides a basis for photovoltaic system sizing, scenario development, and subsequent economic analysis.

4.2.2. Charging infrastructure and load profiles

Charging infrastructure design plays a key role in shaping electricity demand profiles and determining the overall technical requirements of electric bus systems. Two main charging strategies are typically considered: depot charging, where buses are charged during night time or off-peak hours and which requires larger onboard batteries but simpler infrastructure, and opportunity charging, where charging takes place during operation at selected stops, reducing battery size requirements but increasing infrastructure complexity.

These strategies result in distinct load profiles. Depot charging typically leads to concentrated demand peaks during night time hours, while opportunity charging introduces additional daytime loads. This temporal behaviour is particularly important for photovoltaic integration, as it can create a mismatch between solar generation peaks during the day and electricity demand patterns, which is addressed in later sections of the analysis.

From a technical perspective, typical charging power requirements range from 50–150 kW per bus for depot charging systems and 150–450 kW for fast or opportunity charging systems.

In the case of Umag, depot charging is expected to be the dominant charging strategy during the initial phase of transport electrification. This is primarily due to the current operating schedule of the school bus service. The busses spend less than five minutes at intermediate stops, which is insufficient for opportunity charging. On the other hand, busses remain parked for extended period of time at the main terminal, between the morning and afternoon school services, as well as

overnight. The long idle periods provide sufficient time for both daytime and night time charging, making depot charging the most practical and cost-effective solution. This however implies concentrated electricity demand during specific time periods and the potential occurrence of peak load issues.

Accordingly, the electrification of public transport requires adequate charging infrastructure and careful consideration of grid integration aspects. Key requirements include sufficient capacity of the local distribution network, potential upgrades of transformers, and the implementation of load management strategies to avoid peak demand penalties. These constraints may become increasingly relevant as both fleet size and PV capacity increase, making coordinated planning of charging infrastructure and energy systems essential.

4.2.3. Interaction with the local energy system

The introduction of electric buses represents a new demand segment within Umag's local electricity system. This raises considerations related to distribution grid capacity, the ability to accommodate high-power charging loads, and the potential need for grid reinforcement.

At the same time, the integration of PV systems offers presents an opportunity to partially offset this new demand through local generation, thereby reducing reliance on the grid and improving overall system efficiency. This interaction between transport electrification and distributed energy generation is a central aspect of the system under study.

4.2.4. Key challenges and opportunities

The main challenges associated with this transition include variability in transport demand, temporal mismatches between solar generation and charging needs, infrastructure investment requirements, and potential constraints in grid capacity.

However, these challenges are offset by several important opportunities. Umag benefits from a high solar energy potential, creating favorable conditions for local photovoltaic (PV) electricity generation. Moreover, the daytime idle period between morning and afternoon school services coincides with periods of high solar irradiance, enabling a strong synergy between PV electricity production and bus charging demand. Additional opportunities arise from the implementation of smart charging strategies and energy management systems, which can optimize charging schedules, reduce peak loads, and maximize the utilization of locally generated renewable electricity. These technical advantages are further reinforced by strong national and policy support for both transport electrification and the deployment of renewable energy systems.

5. Integration of PV in transport

5.1. PV potential in Umag

The City of Umag is located in the north-western part of the Istrian peninsula along the Adriatic coast, a region characterised by favourable solar conditions for photovoltaic (PV) energy generation.

Based on regional solar resource data, the area receives a global horizontal irradiation (GHI) of approximately 1400-1600 kWh/m^2 per year, and benefits from a high number of sunshine hours, particularly during the summer season. In addition, it exhibits relatively low seasonal variability compared to continental regions, ensuring stable solar availability throughout the year.

These conditions position Umag among the more suitable locations in Croatia for solar PV deployment, particularly for applications that benefit from **seasonal alignment between energy production and demand**, such as tourism-driven transport systems.

A key advantage in this context is the **coincidence of peak solar generation with peak transport demand**. This alignment enhances the potential for high self-consumption of locally generated electricity.

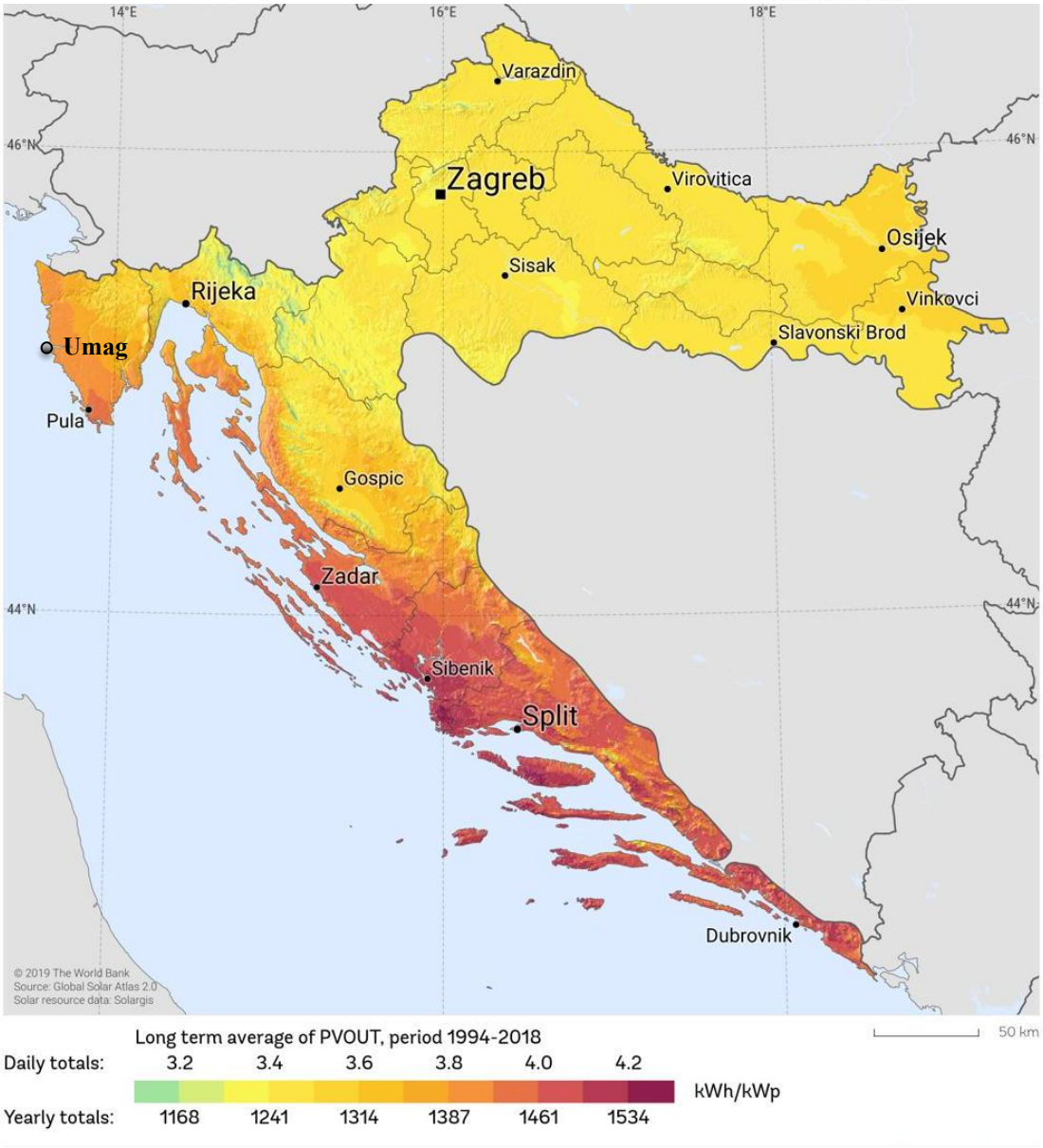


Figure 2 *Photovoltaic power potential of Croatia*

5.2. Methodology for PV potential assessment

The estimation of photovoltaic potential in this study is based on a simplified yet robust methodological approach, suitable for feasibility-level analysis.

The assessment begins with the identification of suitable installation surfaces, followed by the estimation of installable PV capacity and the calculation of expected annual electricity generation.

The annual PV electricity generation can be estimated using the general relationship:

Annual PV output = Installed capacity × Specific yield,

where installed capacity is expressed in kWp, and the specific yield (kWh/kWp/year) depends on location, orientation and system performance. For the Istrian region, typical specific yields range between 1100 and 1500 kWh/kWp/year. This range accounts for common system losses, including inverter and wiring losses, temperature effects, variation in orientation and tilt as well as general operational inefficiencies.

The methodology is consistent with standard practices in energy system analysis and compatible with tools such as EnergyPLAN.

5.3. Integration of PV

The potential for PV deployment in Umag is primarily determined by the availability of suitable urban surfaces, which can be grouped into rooftop and ground-mounted options. Rooftop PV potential is mainly associated with bus depots, public and municipal buildings such as schools, administrative facilities, public parking lot canopies and sports centres, where systems can be integrated relatively easily and support direct consumption within the transport system. Ground-mounted PV potential is linked to underutilised city-owned land, including areas such as depots, marginal urban zones, or similar available sites suitable for larger installations.

PV generation follows a highly variable temporal pattern, with peak output during midday hours and no production during night time. Seasonally, generation is highest in summer and lowest in winter.

Based on a simplified estimation using typical installation densities (approximately 5–7 m² per kWp), the combined rooftop and ground-mounted potential could support PV deployment ranging from several hundred kWp to multi-MWp scale, depending on the selected development strategy and level of system ambition.

The effectiveness of PV integration is largely determined by the extent of local self-consumption. This depends on the temporal alignment between generation and demand, the spatial configuration of PV systems (centralised vs distributed), and the flexibility of the charging strategy, including options such as smart charging or energy storage. Higher levels of self-consumption improve economic performance, reduce reliance on the electricity grid, and enhance overall system efficiency. These factors are therefore central to the scenario analysis presented in the following chapters.

5.3.1. System architecture options

The integration of PV systems with electric bus operations can be implemented through several technical configurations that differ in terms of complexity, flexibility and cost.

The simplest approach is a **grid-connected PV system with depot charging**, where PV installations are located at bus depots and connected to the distribution grid. In this configuration, PV electricity is used locally when available, while any surplus is exported to the grid. This option

is characterized by low system complexity, minimal additional infrastructure requirements, and limited control over energy flows.

A more advanced approach is **distributed PV combined with smart charging**. PV systems are installed across multiple urban locations, including depots, public buildings, and parking canopies, or a remotely located PV powerplant. Smart charging plays a key role by shifting charging activities toward period of high PV generation, thereby reducing peak loads and increasing the share of locally consumed solar energy. In addition, load management techniques such as staggered charging schedules, temporary power limitation during peak periods, and integration with local energy management systems further support the efficient use of available infrastructure and grid capacity. This results in higher self-consumption of PV electricity and improved system efficiency, albeit with a moderate increase in system complexity. This configuration is applicable to both partial and high PV integration scenarios.

The most advanced configuration includes **PV integration combined with battery energy storage systems (BESS)**. This approach involves large-scale PV deployment supported by batteries which provide additional flexibility by storing excess PV generation for later use, particularly during nighttime charging periods. This improves the alignment between production and demand and enhances overall system flexibility. Advanced control systems are required to manage energy flows effectively. While this configuration significantly increases flexibility and reduces grid dependency, it also leads to higher investment costs due to BESS increasing overall system costs.

6. Scenario development

6.1. Purpose and construction of scenario analysis

The integration of photovoltaic (PV) systems into electric public transport in Umag involves multiple uncertainties and interdependent variables, including transport demand, available PV capacity, charging strategies, and grid interaction. To address these complexities, a scenario-based approach is applied.

This approach allows for the exploration of different development pathways for integrating PV into the electric bus system, while also assessing how various system configuration affect energy performance, economic viability and environmental outcomes. In addition, it supports decision-making under uncertainty, which is particularly important in early stages of planning. By comparing multiple scenarios, it becomes possible to identify solutions that achieve an appropriate balance between technical feasibility, cost-effectiveness, and decarbonization potential.

The aim of this analysis is to examine different system architecture options for coupling PV generation with electric bus charging, the associated infrastructure requirements and operational strategies, as well as the investment and operational costs for each scenario. It also considers the trade-offs between system complexity, cost, and performance.

The scenarios are constructed by varying a set of critical parameters that define both the transport system and the energy system. On the transport side, the scenarios are defined by a number of electric buses in operation, the average daily distance per bus (km/day), the specific energy consumption (kWh/km) and the seasonal variation in service demand. These parameters determine the overall electricity demand profile of the fleet. On the energy systems side, the main variables include installed PV capacity (kWp), the spatial distribution of PV systems (centralised vs distributed), and the specific PV yield (kWh/kWP/year), which reflects local solar conditions and system performance.

In addition, operational and flexibility-related parameters are considered, such as the timing of charging (daytime vs. nigh time), the potential inclusion of BESS, and the level of interaction with the electricity grid, including import and export dynamics. Together, these parameters define the structure of each scenario and strongly influence overall system performance.

6.1.1. Energy balancing

Each scenario is assessed through an energy balance framework that includes total electricity demand of the electric bus fleet, PV electricity generation, the share of directly self-consumed PV energy, and the interaction with the grid in terms of imports and exports.

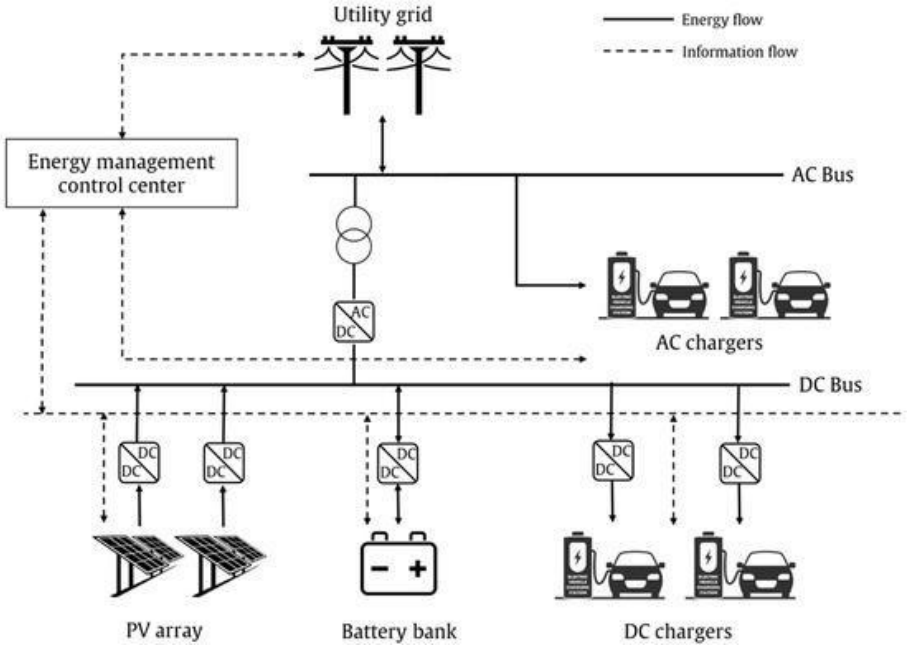


Figure 3 Schematic representation of the PV-integrated vehicle charging system infrastructure

A central aspect of the analysis is the temporal relationship between PV generation and electricity demand. PV systems produce electricity primarily during daytime hours, which partially coincides with the bus charging hours during the school operating huours, but remains a challenge for nighttime bus charging. Without appropriate system adjustments, a portion of PV generation is expected to be exported to the grid. This mismatch can be partially mitigated through smart

charging strategies that shift demand towards periods of high solar availability, while battery storage offers an additional option for aligning generation and consumption over a 24-hour cycle.

6.2. Baseline assumptions

To ensure consistency across scenarios, a set of baseline assumptions is defined.

In the initial deployment phase, a school bus fleet consisting of 4 school busses is electrified. The proposed electrification project includes four existing school bus routes with a combined daily travel distance of 219 km.

Table 1 Bus lines with their distances

Bus line	Daily distance [km/day]
Line 1	44
Line 2	60
Line 3	73
Line 4	42
Total	**219**

Considering the expected passenger capacity requirements and available electric bus technologies suitable for school transport applications, an average electricity consumption of 2 kWh/km was adopted. Since this value does not include additional auxiliary loads such as cabin heating, cooling, ventilation, and seasonal operating variations, a 30% safety margin was introduced.

The resulting daily electricity demand for the bus fleet is therefore calculated as:

$$Daily\ electricity\ demand = Safety \cdot Daily\ travel\ distance \cdot Consumption$$

$$Daily\ electricity\ demand = 1.3 \cdot 219\ \frac{km}{day} \cdot 2\ \frac{kWh}{km} = \mathbf{570}\ \frac{\boldsymbol{kWh}}{\boldsymbol{day}}$$

Assuming year-round operation of the buses, including additional summer transport services, the annual electricity demand becomes:

$$Yearly\ electricity\ demand = 570\ \frac{kWh}{day} \cdot 365\ days = 208050\ \frac{kWh}{year} \approx \mathbf{0.208}\ \frac{\boldsymbol{GWh}}{\boldsymbol{year}}$$

The calculated annual electricity demand profile was subsequently implemented in the EnergyPLAN model for simulation and optimization purposes.

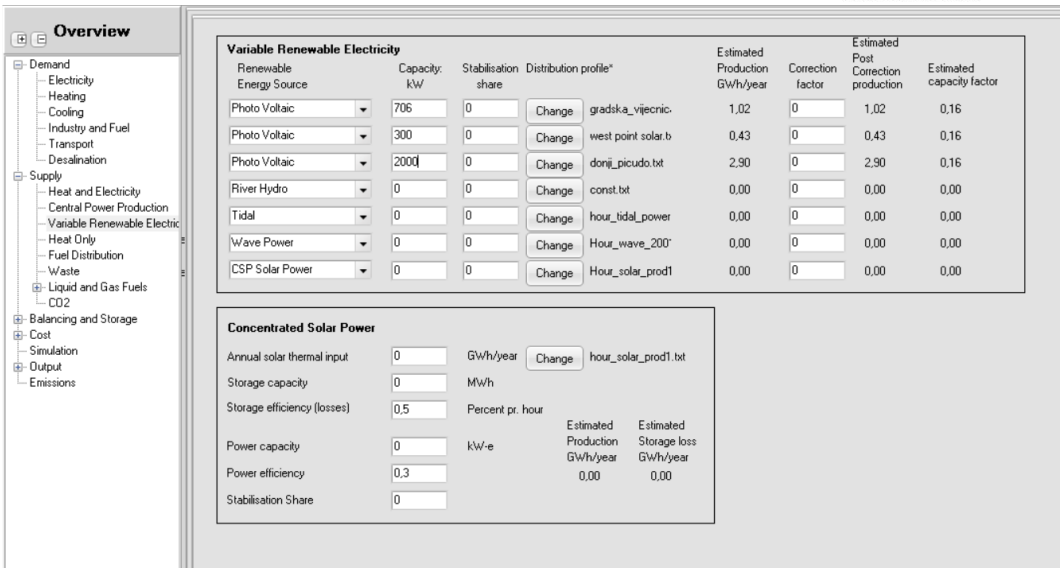


Figure 4 Adding installed PV capacity and hourly profiles of production into EnergyPLAN

For the PV system, a representative yield of 1200 kWh/kWp/year is assumed for the Istria region, together with a performance ratio of approximately 0.8.

6.2.1. Charging strategy and load curve development

Analysis of the operational timetable supplied by the City of Umag showed that buses stop at intermediate stations for less than one minute. Consequently, opportunity charging using PV-integrated bus stop canopies was determined to be technically and economically unjustified.

Table 2 Bus Line 4 Schedule Provided by the City of Umag

Bus line no.4 - MATERADA							
LINE "4. A"				**LINE "4. B"**			
Bus stop	**Arrival**	**Departure**	**[km]**	**Bus stop**	**Arrival**	**Departure**	**[km]**
Umag		6:55	0	Umag		14:10	2
Materada		7:10	8	Finida	14:13	14:13	2
Juricani	7:12	7:12	1	Petrovija	14:16	14:16	3
Picudo	7:13	7:13	1	Picudo	14:19	14:19	3
Petrovija	7:16	7:16	3	Juricani	14:21	14:21	1
Finida	7:19	7:19	2	Materada	14:23		1
Seget	7:22	7:22	3	Umag	14:38		8
Rožac	7:24	7:24	1				
Umag	7:30		3				
In total km:			22	In total km km:			20

Since all routes operate in a circular configuration with the same departure and arrival location, centralized charging infrastructure was proposed at the main depot/terminal area. Charging is assumed to occur during school operating hours, specifically between 07:30 and 14:10, when the buses remain parked between route operations. An hourly charging profile for the entire year was therefore developed and implemented in the model and an hourly solar irradiation profile for different locations in Umag was obtained using the Renewables.ninja platform, enabling realistic hourly PV generation modelling.

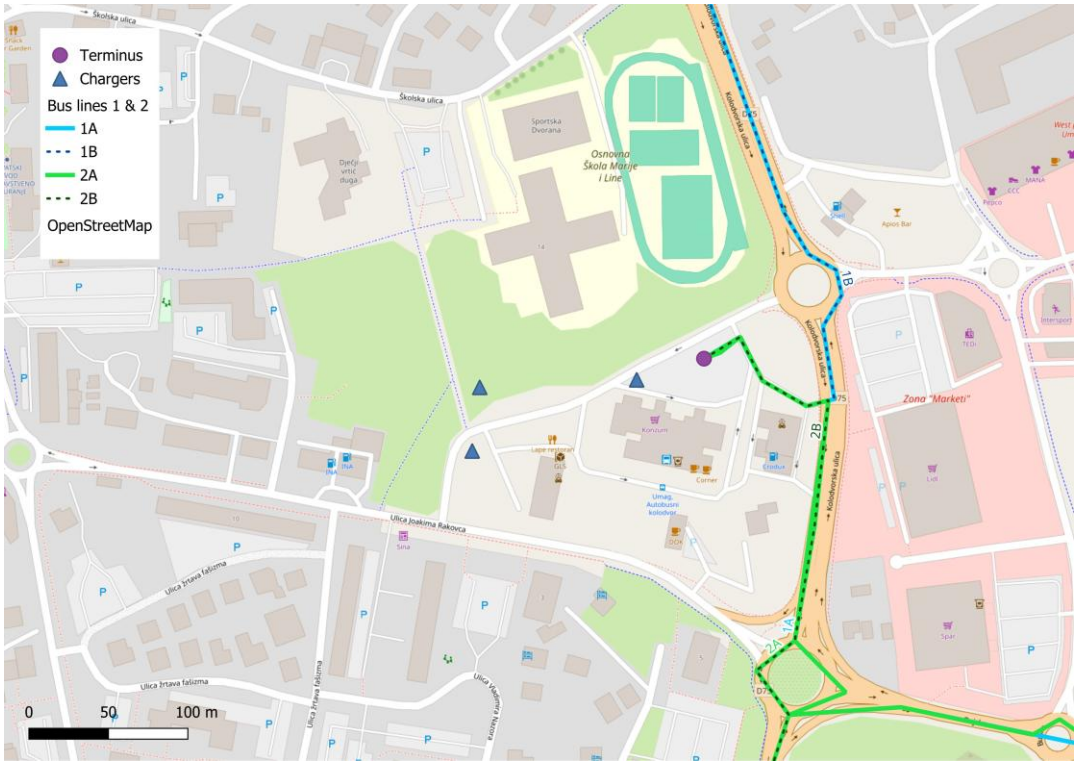


Figure 5 Main terminal and potential charging stations

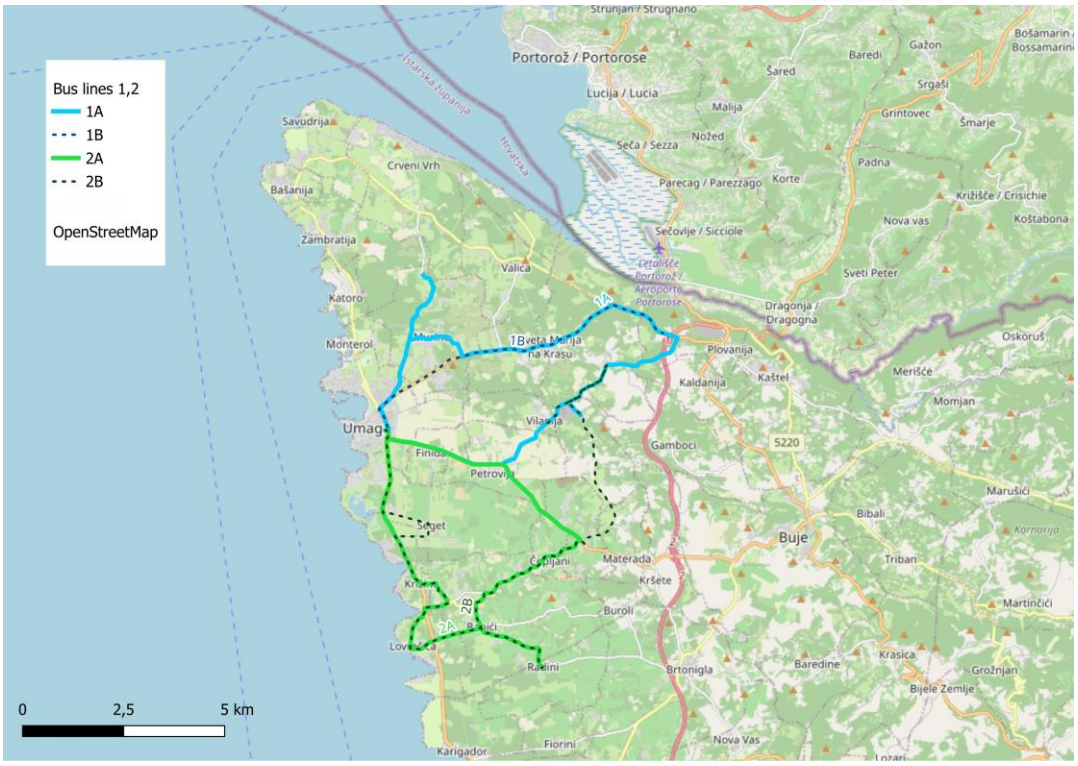


Figure 6 Bus lines 1 & 2

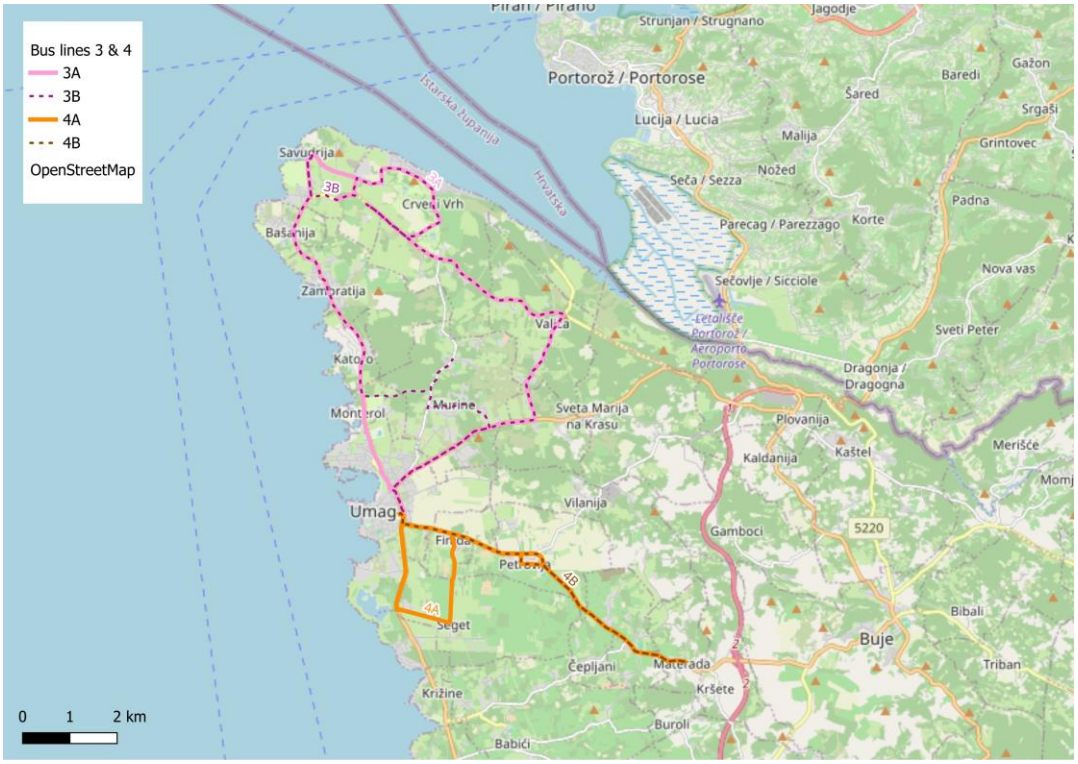


Figure 7 Bus lines 3 & 4

6.2.2. Potential rooftop PV locations

The first phase of the analysis considered rooftop PV systems installed on public buildings, including schools, kindergartens, municipal buildings, and healthcare facilities. Installed capacities were estimated using an online PV installation simulator, based on available roof area, typical system design assumptions, and local solar irradiation conditions.

Table 3 Potential locations with approximated installed capacities for rooftop PV installations

Location	Installed capacity [kWp]	Lokacija	Installed capacity [kWp]
PŠ Bašanija	41	Dječji vrtić Murine	15
PŠ Murine	10	Dječji vrtić Bambi	55
PŠ Marija na Krasu	15	Dječji vrtić Duga	15
PŠ Petrovija	10	Dječji vrtić Radost	10
PŠ Juricani	10	Dječji vrtić Vjeverice	30
PŠ Babići	10	Dječji vrtić Pčelice	35
OŠ Marije i Line	315	Dječji vrtić Doremi	15
Highschool	120		
Total capacity			**706 kWp**

The combined annual electricity demand of all considered public buildings was estimated at approximately 1.7 GWh/year. This estimate was derived using the total conditioned floor area of the analysed buildings and representative energy consumption benchmarks for Croatian educational facilities. According to the *Programme for Energy Renovation of Public Sector Buildings (2016–2020)* published by the Government of the Republic of Croatia, educational buildings have an average annual delivered energy consumption of approximately **147 kWh/m²/year**. Assuming a total conditioned floor area of approximately **11,600 m²** for the portfolio of primary schools, kindergartens and other public buildings included in the project, the expected annual electricity demand is approximately 1.7 GWh/year**.**

An important modelling assumption is that the buildings themselves **prioritize self-consumption** of locally generated electricity. Electric buses utilize only the **surplus** PV generation, remaining after local building demand has been satisfied. Hourly demand curves for the educational and public buildings were developed and incorporated into the simulation framework.

These assumptions provide a consistent and realistic basis for comparing different scenarios.

6.3. Scenario definitions

Four core scenarios were defined to represent different levels of PV integration and system complexity.

6.3.1. Scenario 1 - Low PV integration

The first scenario is based solely on distributed rooftop PV systems installed on public buildings within the City of Umag and surrounding settlements.

The installed PV capacity in this scenario amounts to 706 kWp, distributed across educational institutions (primary and secondary schools), kindergartens and municipal buildings. These installations are primarily designed to offset internal electricity consumption, estimated at approximately 1.7 GWh/year for the aggregated public building stock.

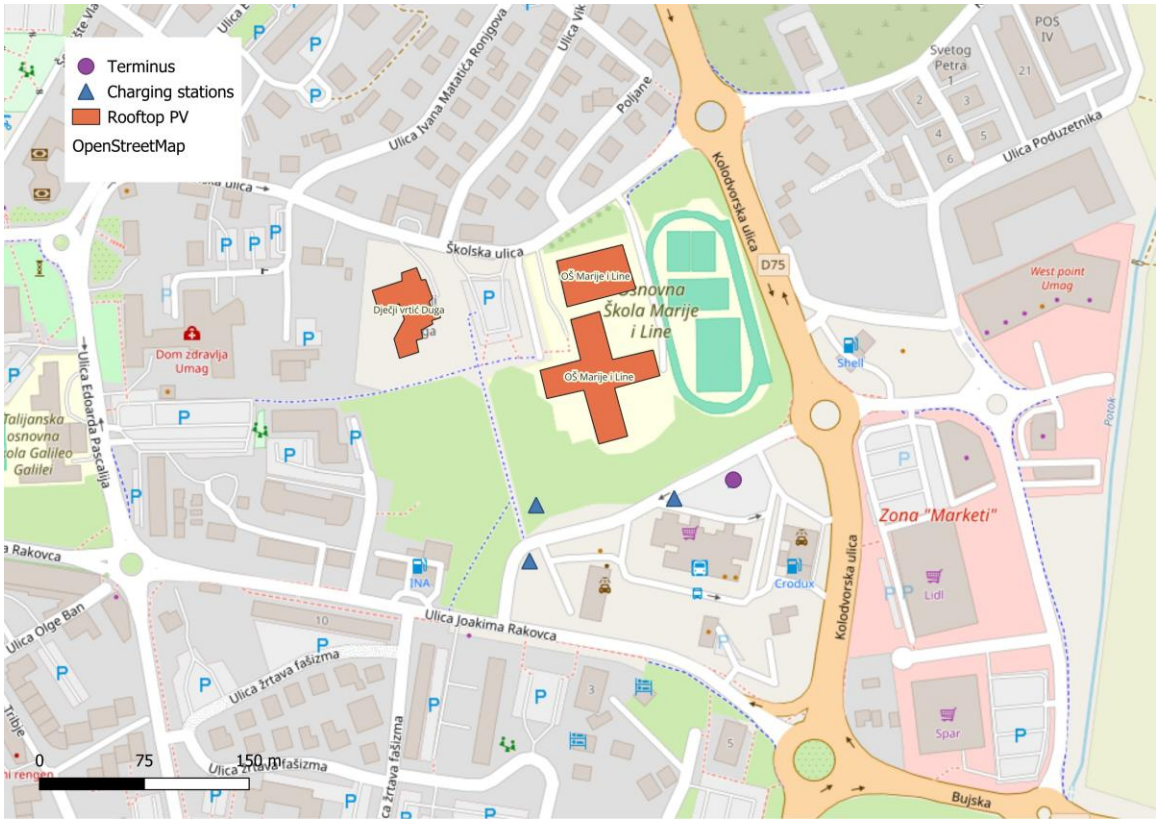


Figure 8 Potential locations for rooftop PV installations in the city centre of Umag

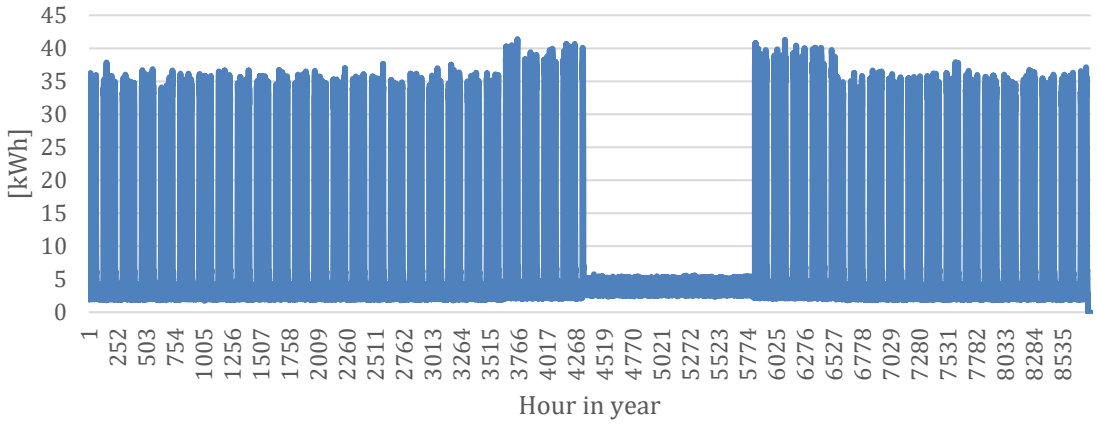


Figure 9 Electricity demand profile for Scenario 1

In this configuration, the electric bus fleet is indirectly supplied through PV surplus generation. Since building demand is prioritised, only excess PV electricity—after covering local consumption—is allocated to bus charging. This creates a realistic constraint that reflects actual energy management practices in public-sector energy systems.

Scenario 1 therefore evaluates the minimum viable PV penetration level required to meaningfully contribute to transport electrification under constrained distributed generation conditions.

6.3.2. Scenario 2 - Partial PV integration

The second scenario builds upon Scenario 1 by introducing an additional 300 kWp PV system installed in the Umag Sport zone, increasing the total installed PV capacity to 1006 kWp. The PV system planned for the Umag sports centre can be implemented as a parking lot canopy, as a rooftop PV system on buildings within the sports centre, or as a ground-mounted PV system, as there is available space within the cadastral parcels which are owned by the City of Umag.



Figure 10 Umag sports centre cadastral parcel and potential rooftop & canopy locations [30]

In addition to the expanded generation capacity, this scenario introduces a new electricity consumer: the sports centre itself, with an estimated annual electricity demand of 0.5 GWh/year. Its inclusion increases system complexity by adding a significant commercial load with a daily profile that partially overlaps with public building consumption patterns.

By aggregating the demand profiles of public buildings and the sports centre, Scenario 2 provides a more realistic representation of urban energy systems, where multiple sectors compete for locally generated renewable electricity.

6.3.3. Scenario 3 - High PV generation

The third scenario represents a high-penetration renewable energy pathway, combining all rooftop PV systems from Scenario 2 with a large-scale ground-mounted photovoltaic plant located at the former landfill site in Donji Picudo.



Figure 11 Donji Picudo location & cadastral units, potential location for PV powerplant [30]

The utility-scale installation is assumed to have a capacity of approximately 2 MWp, significantly increasing the total PV generation potential of the system. This introduces a structural shift from a predominantly distributed generation model to a hybrid system combining distributed rooftop PV with centralized renewable generation.

Unlike rooftop installations, the utility-scale PV plant is not constrained by local self-consumption requirements and therefore injects a large share of electricity directly into the system, substantially increasing overall renewable availability during daylight hours.

6.3.4. Scenario 4 - PV and BESS integration

Scenario 4 extends the high-renewable Scenario 3 by introducing a Battery Energy Storage System (BESS) at the Donji Picudo site, co-located with the utility-scale photovoltaic plant. The installed battery system is assumed to have a power rating of 1 MW and an energy capacity of 2 MWh, corresponding to a two-hour storage duration. This configuration is selected as a technically realistic solution for smoothing intra-day PV fluctuations and enabling effective shifting of solar energy from midday production peaks to morning and late-afternoon demand periods.

The primary objective of this scenario is to increase the temporal flexibility of the energy system and improve the match between PV generation and electricity demand from both the electric bus fleet and the local building sector. While Scenario 3 already demonstrates high renewable penetration through large-scale PV integration, it remains constrained by the inherent variability of solar generation and the limited simultaneity between production and consumption.

A key methodological change in Scenario 4 concerns the development of a revised charging demand profile for the electric bus fleet. Unlike previous scenarios, where charging was strictly constrained to daytime hours (07:30–14:10) in direct alignment with PV generation availability, the introduction of the 1 MW / 2 MWh battery system fundamentally relaxes this constraint by decoupling energy availability from instantaneous solar production.

In this configuration, the battery system enables the utilization of stored photovoltaic electricity during evening and nighttime periods. As a result, the bus charging strategy is no longer limited to operational downtime within school hours, but is extended to include night-time charging windows, particularly after the completion of daily bus operations. This reflects a more flexible depot-based charging strategy, where vehicles can be charged whenever stored renewable energy is available, rather than being strictly synchronized with PV generation peaks.

To represent this operational shift in the model, a new hourly charging load curve is developed. The total daily energy demand of the bus fleet remains unchanged; however, the temporal distribution of this demand is redistributed across a longer time horizon.

6.3.5. Scenario comparison

A qualitative comparison of scenarios is presented below.

Table 4 Scenario comparison

Indicator	Scenario 1	Scenario 2	Scenario 3	Scenario 4
PV Capacity	Low	Medium	High	Very high
Bus RES Share	67%	67%	95%	97%
Grid Dependency	High	High	Medium	Low
Investment Cost	Low	Medium	High	High
System Complexity	Low	Low	High	High
Fleet CO_2 Reduction	83%	85%	97%	**≈98%**

7. Results

7.1. Scenario 1 results

In Scenario 1, the energy system is based exclusively on distributed rooftop PV installations on public buildings, with a total installed capacity of 706 kWp. Under the assumed regional solar yield of 1200 kWh/kWp/year and a performance ratio of 0.8, the system generates approximately 1.02 GWh of electricity annually. This level of generation represents the baseline renewable contribution available for both local building consumption and electric bus charging within a constrained, self-consumption-oriented configuration.

The system energy balance shows that a portion of the generated electricity is not directly consumed on-site and is therefore exported to the grid, amounting to 0.24 GWh per year. At the same time, due to the limited simultaneity between PV production and demand profiles, the system still requires a significant level of grid support, with electricity imports reaching 1.12 GWh per year. This indicates that, despite the presence of distributed PV generation, the system remains partially dependent on external electricity supply.

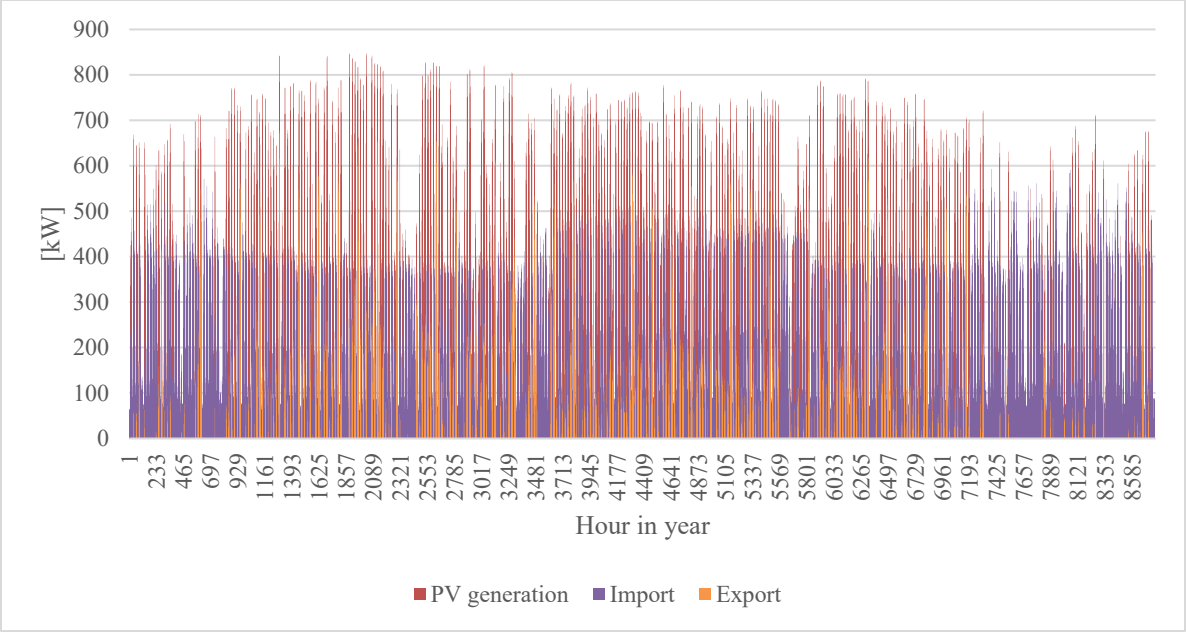


Figure 12 Hourly electricity Import, Export, and PV Generation in Scenario 1

Focusing specifically on the electrified bus fleet, the results show that 0.14 GWh per year of electricity is supplied directly from PV surplus, while an additional 0.068 GWh per year is drawn from the grid. In relative terms, this corresponds to approximately 67% coverage of the annual bus electricity demand by locally generated renewable energy. The remaining demand is still dependent on conventional electricity supply, primarily due to temporal mismatches between PV generation peaks and charging requirements.

At the level of public buildings, the rooftop PV systems enable a self-consumption of approximately 0.65 GWh per year, which corresponds to around 38% of their total annual electricity demand. This demonstrates that even without dedicated storage or advanced load management, rooftop PV can significantly reduce grid dependency in municipal infrastructure.

7.2. Scenario 2 results

Scenario 2 expands the system boundary by including an additional PV installation in Umag's sports centre, increasing the total installed PV capacity to 1.006 MWp. This expansion leads to a higher annual electricity generation of approximately 1.45 GWh, reflecting the increased generation potential of the combined public and commercial rooftop PV portfolio.

Despite the increased generation, the system continues to exhibit a significant interaction with the electricity grid. Total electricity export rises slightly to 0.30 GWh per year, indicating periods of PV surplus that cannot be locally absorbed. At the same time, electricity imports remain relatively high at 1.25 GWh per year, driven by the combined demand of public buildings and the newly introduced commercial load.

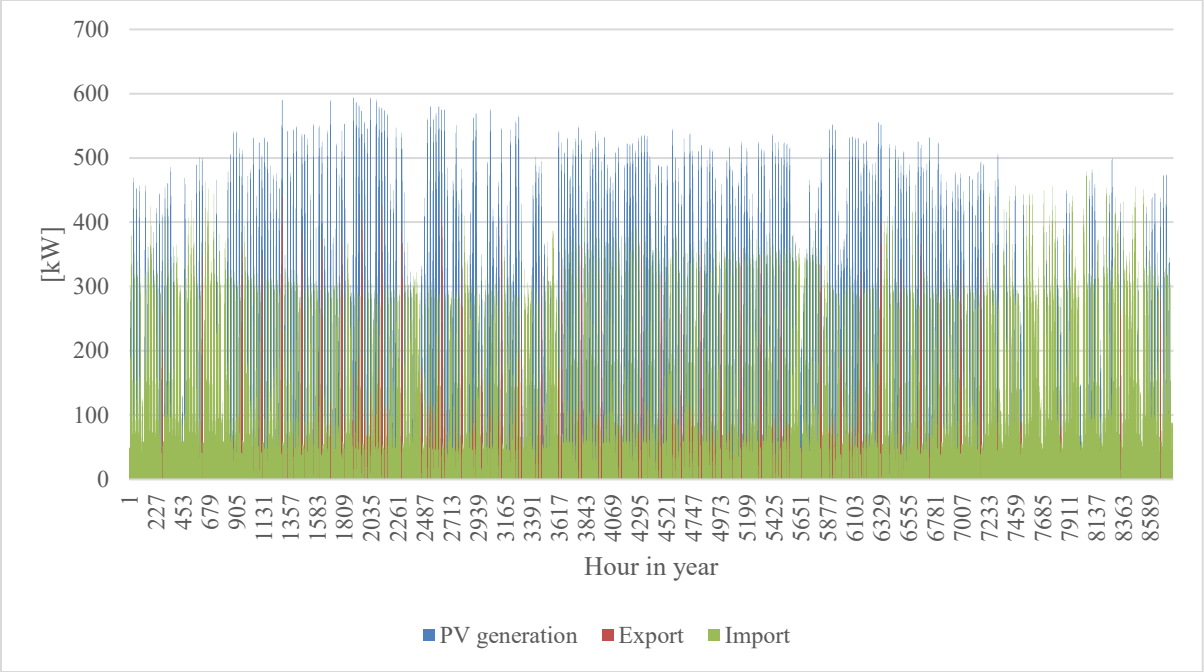


Figure 13 Hourly electricity Import, Export, and PV Generation in Scenario 2

In terms of electric bus operation, the buses are supplied with 0.12 GWh per year of PV-derived electricity, while 0.06 GWh per year is still sourced from the grid. Interestingly, despite the increased installed PV capacity, the renewable coverage of bus demand remains approximately at the same level as in Scenario 1, around 67%. The coverage remains at the same level due to the simultaneous increase in total electricity demand and increase of electricity generation due to additional installed capacity compared to Scenario 1.

The combined building and commercial sector consume approximately 0.33 GWh per year of PV electricity through self-consumption, which corresponds to only about 15% of the aggregated annual demand of these sectors. This relatively low share indicates that the additional PV capacity is increasingly constrained by temporal mismatch and internal competition between loads.

Overall, Scenario 2 highlights an important systemic effect: increasing installed PV capacity alone does not necessarily improve renewable utilization efficiency when demand growth and temporal misalignment are not addressed. Without complementary flexibility measures such as storage systems or demand-shifting strategies, a significant portion of renewable potential remains either exported or underutilized.

7.3. Scenario 3 results

Scenario 3 introduces a major structural change to the energy system through the addition of a utility-scale PV plant located in Donji Picudo. This significantly increases the total installed generation capacity and transforms the system from a predominantly distributed rooftop-based configuration into a hybrid system combining distributed and centralized renewable generation.

As a result, total annual PV electricity production rises substantially to approximately 4.35 GWh per year. This represents a step-change in renewable energy availability compared to the previous scenarios and fundamentally alters the energy balance of the system.

Within this high-generation context, electric bus charging becomes almost fully decarbonized. The buses consume 0.19 GWh per year of PV-generated electricity, while only 0.01 GWh per year is supplied from the grid. This corresponds to approximately 95% coverage of the bus fleet's annual electricity demand by renewable energy. The remaining grid dependence is marginal and primarily associated with periods of low solar availability or temporary mismatches between generation and charging demand.

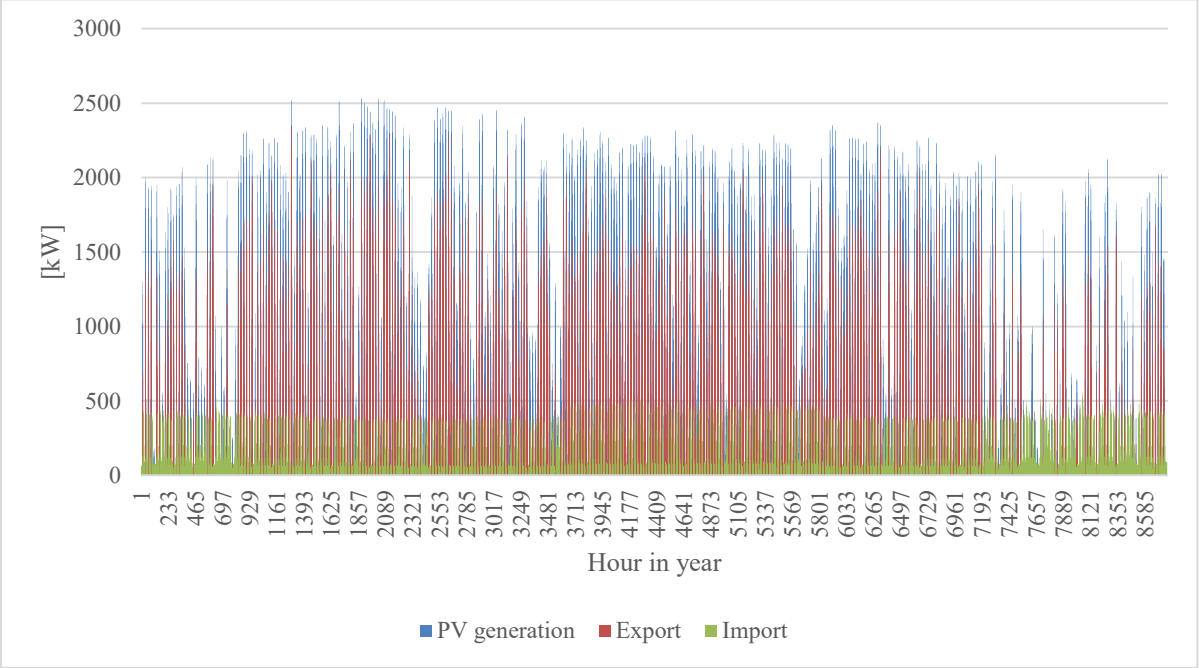


Figure 14 Hourly electricity Import, Export, and PV Generation in Scenario 3

At the level of buildings and the sports centre, the system achieves a significantly higher degree of renewable integration. Together, these consumers self-consume approximately 1.28 GWh per year of PV electricity, which corresponds to about 58% of their total aggregated electricity demand. This represents a substantial improvement compared to both previous scenarios and demonstrates the impact of large-scale renewable generation on local energy autonomy.

7.4. Scenario 4 results

Scenario 4 builds upon the previous scenario 3 by introducing a battery energy storage system with a power capacity of 1 MW and an energy storage capacity of 2 MWh. While the installed PV generation capacity remains unchanged, the addition of storage improves the temporal balancing between local electricity production and consumption. This results in approximately 97% coverage of the bus fleet's annual electricity demand by renewable energy.

Total annual electricity demand in the system remains at 2.2 GWh, while annual PV electricity production stays at 4.35 GWh, identical to Scenario 3. However, the battery enables a larger share of locally generated renewable electricity to be consumed within the system instead of being exported to the grid during periods of excess generation.

Before the battery was introduced, in Scenario 3, the system imported approximately 0.94 GWh of electricity annually and exported around 2.88 GWh. After integrating the battery storage system, annual electricity imports decrease to 0.88 GWh, while exports are reduced to 2.80 GWh. This indicates that the battery increases local utilization of PV electricity by approximately 0.14 GWh per year.

The operation of the battery is strongly seasonal. The majority of electricity storage occurs during the summer months, when PV production is highest and substantial surplus electricity is available during daytime hours. In contrast, during the winter period only very small amounts of electricity are stored in the battery due to significantly lower solar generation and a closer match between production and demand. As a result, the battery is utilized far more intensively during periods of high solar availability.

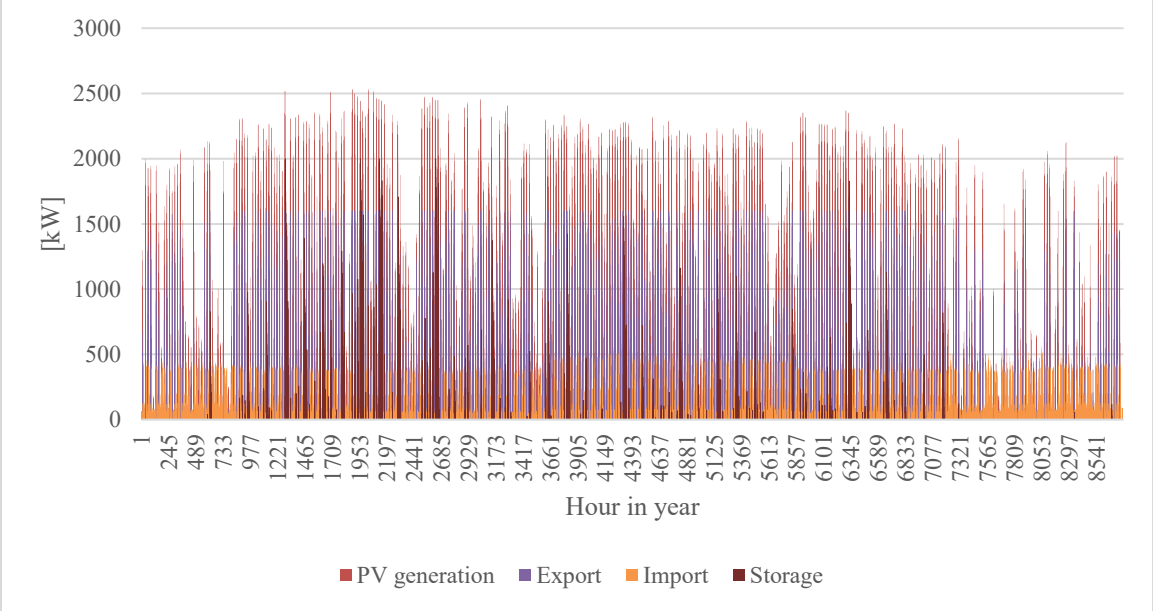


Figure 15 Hourly electricity Import, Export, battery storage and PV Generation in Scenario 4

Although the reduction in imports and exports is moderate relative to total PV generation, the results demonstrate the role of battery storage in improving self-consumption and reducing dependence on external electricity supply. The battery shifts excess solar generation from periods of high production toward periods of higher demand, thereby enhancing local energy flexibility and increasing overall renewable energy utilization within the system.

The results also indicate that even a relatively small storage system can contribute to better integration of renewable electricity in systems with high PV penetration. However, due to the

significant mismatch between annual PV generation and electricity demand, substantial electricity exports still remain unavoidable during periods of high solar production.

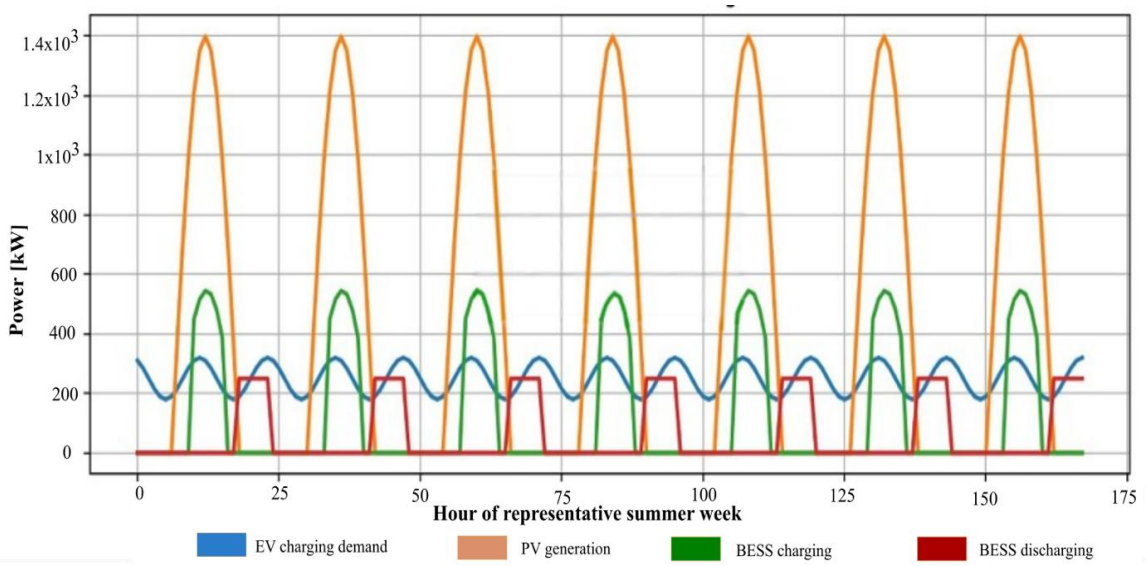


Figure 16 Hourly interaction between PV generation, storage and bus electricity demand in Scenario 4

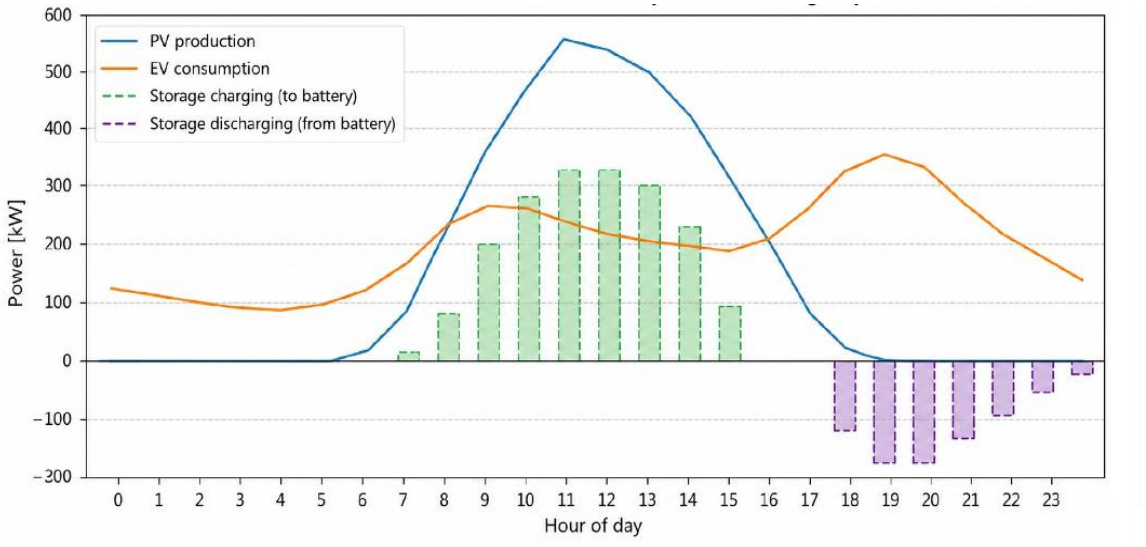


Figure 17 Storage charging and discharging distribution in Scenario 4

7.5. GHG emissions results

Replacing the diesel school bus fleet with an electric bus fleet reduces CO_2 emissions by almost half, even when they are charged only from the grid, specifically from 64.3tCO_2/year to 34.1 tCO_2/year. Local PV production raises savings to 83-98%, depending on the scenario, as shown in table below.

Table 5 Annual CO2 emissions and savings by scenario

Scenario	Bus CO_2 emissions [t/year]	Emission by kilometre [$kgCO_2/km$]	Transport savings vs diesel [%]	Grid credit: PV export + building self use [tCO_2/year]
Diesel baseline	64.3	0.80	-	-
Grid only bus charging	34.1	0.43	47%	-
Scenario 1	11.2	0.14	83%	146.0
Scenario 2	9.8	0.12	85%	103.3
Scenario 3	1.6	0.02	97%	682.2
Scenario 4	≈1.0	≈0.01	≈98%	≈680

The Croatian grid is relatively clean, considering the most recent grid emission factor, therefore electrification itself delivers most of the benefit. The switch from diesel to an electrical fleet saves around 30 tCO_2 per year, and covering the buses with PV add a further 23-33 tCO_2 yearly. Scenario 1 already cuts bus emissions by 83%, while the Donji Picudo plant in Scenario 3 adds only about 10 tCO_2 per year of transport savings. However, the energy exported from the PV powerplant to the grid avoids 472 tCO_2 yearly. The diesel consumption is an assumption and therefore should be confirmed from the contractor's fuel records.

8. Economic and financial feasibility analysis

8.1. Baseline assumptions

The economic and financial feasibility analysis of integrating photovoltaic (PV) systems into the newly electrified public transport fleet of the City of Umag is conducted over a comprehensive 25-year operational lifetime. To accurately quantify the viability of the project, all future cost and savings flows are discounted back to their present value, using the current transport system as the baseline status quo.

The existing baseline public transport system creates a persistent annual recurring expenditure of €242 500 which includes €184 000 for elementary school transport and €58 500 for high school student transport. Over the full 25-year analysis horizon, this represents an undiscounted €6,062,500 in avoided cost that the project can draw on as its principal revenue line, once the diesel-based service is fully replaced by the electric bus fleet.

The financial model assumes that the entire project is funded via a 10-year loan with a fixed annual interest rate of 4%. This rate is also used as the discount rate to calculate the Net Present Value (NPV).

8.2. Grid connection costs

To connect the high-power fast chargers to the local electricity grid, a mandatory grid connection fee must be paid. According to the official HERA decision, the standard rate for the low-voltage network is €193/kWp of connected capacity. Since there are 4 busses, there are also 4 charging station at the central bus terminal, each rated at 50kW, resulting in a total capacity of 200kWp. Applying the HERA unit rate, the net grid connection charge is calculated as:

$$Net\ charger\ connection\ cost = Connected\ capacity \cdot HERA\ rate\ low\ voltage$$

$$Net\ charger\ connected\ cost = 200\ kWp\ \cdot 193\ \frac{€}{kWp} = 38\,600\ €$$

After accounting for the standard Croatian VAT rate of 25%, the gross grid connection fee capitalised within the project's upfront costs totals €48,250. This mandatory grid connection expenditure is fully integrated into the CAPEX of all four proposed development scenarios.

Scenarios S3 and S4 additionally include the Donji Picudo solar power plant, with 2 MWp of solar capacity connected to the medium-voltage network, for which HERA applies a standard rate of €106/kWp:

$$Net\ PV\ connection\ cost = Connected\ capacity * HERA\ rate\ medium\ voltage$$

$$Net\ PV\ connection\ cost = 2000\ kWp \cdot 106\ \frac{€}{kWp} = 212\,000\ €$$

Grossed up by the 25% VAT rate, the net price of €212,000 becomes a gross connection charge of €265,000, which — together with the €48,250 low-voltage charger connection fee — brings the combined grid connection cost in S3 and S4 to €260,250 once VAT and rounding within the model's connection-cost roll-up are applied (see Table 4).

Table 6 CAPEX structure by scenario

Component	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Grid connections	48.250	48.250	260.250	260.250
Electric buses (4×)	1.400.000	1.400.000	1.400.000	1.400.000
Chargers (4x)	40.000	40.000	40.000	40.000
PV – municipal buildings (706 kWp)	564.800	564.800	564.800	564.800
PV – sports centre (300 kWp)	—	240.000	240.000	240.000
PV power plant Donji Picudo (2 MWp)	—	—	1.400.000	1.400.000

BESS (2 MWh)	—	—	—	1.100.000
TOTALCAPEX (€)	**2.053.050**	**2.293.050**	**3.905.050**	**5.005.050**

Total investment ranges from €2,053,050 in the base electrification scenario (S1) up to €5,005,050 in the fully-integrated PV-plus-storage scenario (S4) — a roughly 2.4-fold increase in CAPEX driven almost entirely by the Donji Picudo plant (€1,400,000) and the battery storage system (€1,100,000).

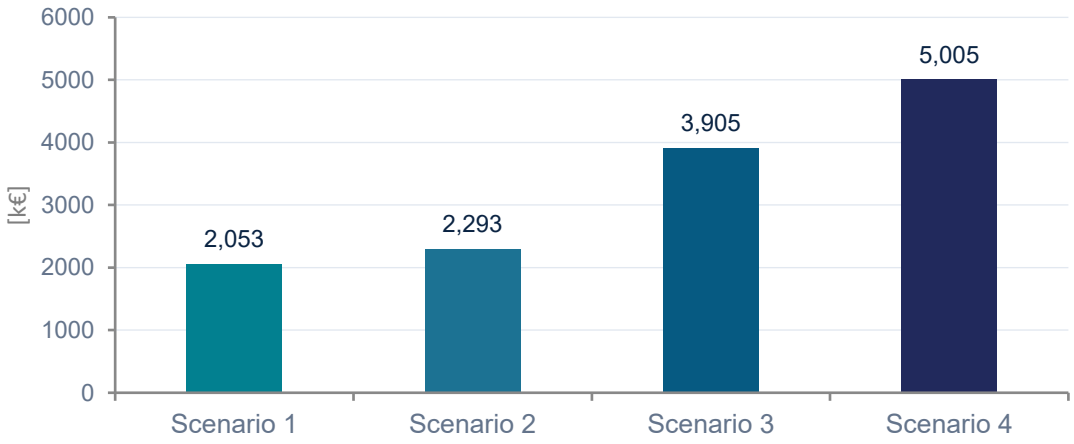


Figure 18 Total CAPEX by scenario

8.3. Financing & Debt service

Under the assumption of 100% debt financing at a fixed 4% annual rate over a 10-year term, the annual loan payment (principal plus interest) is calculated using standard mortgage-style amortisation. Table 5 illustrates the amortisation profile for Scenario S1, whose €2,053,050 loan principal generates a level annual payment of €253,122 for 10 years; interest declines from €82,122 in Year 1 to under €9,735 by Year 10, as the outstanding balance is paid down.

Table 7 Illustrative loan amortisation schedule, Scenario 1 for selected years

Year	Beg. balance (€)	Payment (€)	Interest (€)	Principal (€)	End balance (€)
1	2.053.050	253.122	82.122	171.000	1.882.050
5	1.326.903	253.122	53.076	200.046	1.126.856
10	243.387	253.122	9.735	243.387	0

The annual loan payment scales with the size of the investment: it rises to €282,712 for scenario 2, €481,457 for scenario 3, and €617,077 for scenario 4. In every scenario, Year-1 net cash flow (avoided baseline transport cost plus PV/PPA revenue, net of O&M) exceeds the annual loan obligation, giving a Year-1 debt-service coverage ratio (DSCR) above 1.0 throughout — from a

comfortable 1.40 in scenario 3 down to a tighter 1.11 in scenario 4, reflecting the larger debt burden taken on to finance the battery storage system (BESS).

8.4. Financial performance & performance indicators

Discounting each scenario's 25-year stream of net cash flows (avoided baseline transport costs plus PV self-consumption and export revenue, net of O&M and BESS augmentation costs) at the 4% loan/discount rate yields the following performance indicators.

Table 8 Key performance indicators by scenario

Indicator	Scenario 1	Scenario 2	Scenario 3	Scenario 4
NPV @ 4%, 25 yrs (€)	2.812.577	3.491.038	6.307.458	5.057.742
IRR, 25 yrs (%)	14,8%	15,9%	16,6%	12,4%
BCR	1,87	1,99	2,36	1,81
Simple payback period (yrs)	6,5	6,1	5,8	7,4
Discounted payback period (yrs)	7,7	7,1	6,8	9,0
Year-1 net cash flow (€)	318.818	380.738	675.938	684.638
Annual loan payment, yrs 1–10 (€)	253.122	282.712	481.457	617.077
Year-1 DSCR	1,26	1,35	1,40	1,11

All four scenarios are NPV-positive and self-financing under the stated loan terms. Scenario 3, which includes rooftop PV and Donji Picudo powerplant, delivers the strongest risk-adjusted return: the highest NPV (**€6,307,458**), the highest IRR (**16,6%**), the strongest Benefit–Cost Ratio (BCR) (**2,36**), and the shortest payback, at 5,8 years simple / 6,8 years discounted. Scenario 4, which adds the 2 MWh BESS on top of Scenario 3, produces the second-highest absolute NPV (€5,057,742) but the weakest IRR (12,4%) and longest payback (7,4 / 9,0 years) of all four options: the additional €1.1 million CAPEX dilute returns even though the BESS improves self-consumption of the Donji Picudo output.

Scenarios 1 and 2, which rely on rooftop PV only, are the most conservative options: lower absolute CAPEX (**€2,053,050** and **€2,293,050** respectively) and lower absolute NPV (€2,812,577 and €3,491,038), but still attractive IRRs of 14,8% and 15,9% and the fastest paybacks after Scenario 3 in nominal terms. Because the bus fleet in Scenario 1 and 2 still draws paid grid electricity for charging, these scenarios carry a bus grid-charging cost line absent from Scenario 3 and 4, where the Donji Picudo plant's output first covers the fleet's ~208,000 kWh/yr charging demand before any surplus is exported.

In conclusion, across all four scenarios the analysis confirms that shifting the City of Umag's school transport service from the current diesel-based baseline (€242,500/yr) to an electric bus fleet supported by municipal, and where applicable utility-scale, photovoltaic generation is financially viable at a 4% cost of debt: every scenario clears a Benefit–Cost Ratio above 1,8 and an IRR above 12%, comfortably exceeding the financing rate. On a purely financial basis, **Scenario 3** offers the best combination of NPV, IRR, and payback period. Scenario 4's battery storage adds resilience and higher-value self-consumption of solar output, but at the analysed cost of capital, the extra investment is not yet recovered by additional financial return within the 25-year horizon; its case

would strengthen under higher wholesale-export/self-consumption price spreads, a lower BESS capital cost, or non-financial objectives such as grid-independence and export-price risk mitigation that fall outside this discounted cash-flow analysis.

8.5. Available subsidy and grant instruments

The baseline financial model in Sections 6.1–6.6 assumes 100% debt financing of CAPEX. In practice, the City of Umag has access to several national and EU-backed grant instruments that could substantially reduce the financed portion of CAPEX and improve every performance indicator in Table 6. The main instruments relevant to this project are summarized below.

Environmental Protection and Energy Efficiency Fund (**FZOEU**) runs recurring national calls for co-financing of grid-connected PV plants and BESS for public-sector applicants, financed via the EU Modernization Fund. Beyond the vehicle-purchase calls it finances through FZOEU, the Modernization Fund also directly finances “zero-emission road transport investment”, and periodically opens calls for charging infrastructure.

National Recovery and Resilience Plan (**NPOO**) has been the single largest funding source for Croatian municipal e-bus fleets to date. Under the NPOO measure "Nabava vozila na alternativni pogon za javni gradski i prigradski linijski promet," 17 Croatian towns and municipalities received contracts for 206 e-buses worth over €53.2 million, with roughly 80% of that value covered by NPOO grants — in several cases (e.g., Zadar's 13-bus, €7.6 million contract) the co-financing reached 100%, leaving no burden on the local budget. Umag, as a municipality operating school/public transport buses, would be a natural candidate for a similar or successor call once NPOO measures are renewed or replaced by follow-on EU financial-perspective programs.

For any residual CAPEX not covered by grants, the Croatian Bank for Reconstruction and Development (HBOR) offers financial instruments for zero-emission vehicles, indicatively €45 million earmarked nationally for 2026, which offer favorable loan terms that could substitute for or blend with the commercial 4% financing assumed in this analysis, potentially lowering the effective cost of debt below the model's baseline rate.

If Umag secured, indicatively, an 80% grant rate on the electric buses and chargers, which is consistent with recent NPOO precedent, and a 50% grant rate on the PV and BESS components, which is consistent with FZOEU public sector calls, the financed share of CAPEX, and therefore the annual loan payment and DSCR, would sharply decline in value, relative to the 100%- debt baseline.

9. Discussion and interpretation of results

The scenario analysis carried out for the City of Umag demonstrates that the integration of PV systems into the electric public transport system is both technically feasible and capable of significantly reducing dependence on grid electricity and conventional energy sources. However, the results also highlight important differences between scenarios in terms of renewable energy utilization, infrastructure requirements, system complexity, and overall economic feasibility.

The comparison of the four analysed scenarios reveals a gradual transition from a relatively simple distributed renewable energy system toward a highly integrated and flexible urban energy-transport system. Each scenario introduces additional renewable generation capacity and higher levels of system sophistication, resulting in improved renewable energy coverage but also increased investment requirements and operational complexity.

Scenario 1, based exclusively on distributed rooftop PV systems installed on public buildings, represents the minimum viable renewable integration pathway. Although the total installed PV capacity of 706 kWp enables meaningful renewable contribution to electric bus charging, the system remains strongly constrained by the limited availability of surplus electricity after local building demand has been satisfied. Nevertheless, the results show that approximately 67% of the annual electricity demand of the electric bus fleet can already be covered through locally generated PV electricity. This demonstrates the substantial value of utilizing existing public infrastructure for distributed renewable energy generation.

From an operational perspective, Scenario 1 represents a relatively simple and low-risk implementation pathway. Since rooftop PV installations are directly connected to existing public facilities, the system requires limited additional infrastructure and only moderate changes to existing grid operation. However, the scenario also illustrates the limitations of purely distributed self-consumption-oriented systems. Temporal mismatch between PV production and charging demand leads to significant electricity imports from the grid, while a portion of renewable generation is exported due to insufficient simultaneity between production and consumption.

Scenario 2 expands the distributed PV concept by integrating an additional rooftop PV installation on the Umag's sports centre, thereby increasing the total installed PV capacity to just over 1 MWp. Although this leads to higher annual renewable electricity generation, the overall improvement in renewable coverage for electric buses remains limited. This result is particularly important from a systemic perspective, as it demonstrates that increasing installed PV capacity alone does not automatically improve system efficiency or renewable utilization.

The addition of a large consumer significantly increases total electricity demand within the system boundary, resulting in increased competition for locally generated renewable electricity. Consequently, the share of PV electricity available for bus charging remains relatively similar to Scenario 1. This highlights a key challenge in integrated urban energy systems: renewable generation must be analysed together with demand structure and temporal consumption patterns rather than through installed capacity alone.

Despite these limitations, Scenario 2 remains highly relevant from a practical and economic standpoint. The additional PV installation can likely be implemented with relatively low complexity and without major grid reinforcement requirements. The scenario therefore represents an achievable medium-term development pathway that can increase renewable electricity production while maintaining manageable investment levels.

Scenario 3 introduces a fundamentally different system architecture through the addition of a utility-scale PV power plant located in Donji Picudo. This transition from predominantly

distributed generation toward a hybrid distributed-centralized renewable system significantly changes the energy balance of the analysed system.

The introduction of approximately 2 MWp of centralized PV generation enables near-complete decarbonisation of electric bus charging, with renewable energy covering approximately 95% of the fleet's annual electricity demand. At the same time, self-consumption within the building and commercial sectors increases substantially, reducing dependence on imported grid electricity and improving local energy autonomy.

From both technical and environmental perspectives, Scenario 3 represents a highly effective solution. The utility-scale PV installation provides sufficient renewable generation capacity to overcome many of the limitations observed in the rooftop-only scenarios. In particular, the system is no longer primarily constrained by lack of available renewable electricity, but rather by temporal mismatch between production and demand.

However, these benefits come at the cost of substantially higher investment requirements and increased system complexity. The implementation of a utility-scale PV power plant requires land availability and permitting procedures, grid connection reinforcement, higher upfront capital investment, as well as a more advanced system management and operational coordination

Despite these challenges, Scenario 3 appears to provide the strongest balance between renewable energy performance and practical feasibility at larger system scale.

Scenario 4 extends the high-renewable configuration of Scenario 3 by introducing battery energy storage system (BESS) integration. The addition of storage fundamentally changes the operational logic of the system by enabling temporal decoupling between PV generation and charging demand.

Unlike previous scenarios, where charging activities remained strongly constrained by instantaneous solar availability, the inclusion of BESS enables renewable electricity generated during midday hours to be shifted toward evening and night time charging periods. This creates substantially higher operational flexibility and allows the electric bus fleet to operate with significantly reduced dependence on direct solar generation timing.

From a technical perspective, Scenario 4 represents the most advanced and resilient configuration analysed within the study. The combination of centralized PV generation, distributed rooftop systems, smart charging strategies, and storage integration creates a highly flexible urban energy system capable of maximizing renewable energy utilization.

Nevertheless, the economic implications of this configuration are considerably more complex. Battery storage systems remain associated with high investment costs, which significantly increase overall system CAPEX. While storage improves renewable utilization and reduces grid dependency, the resulting financial benefits may not yet fully justify the additional investment under current market conditions, particularly for relatively small transport systems such as the initial electric bus fleet planned in Umag.

For this reason, Scenario 4 should primarily be interpreted as a long-term development pathway rather than an immediately optimal investment solution.

Overall, the results suggest that Scenario 3 currently represents the most economically and strategically feasible solution for the City of Umag. It achieves very high renewable penetration and near-complete decarbonisation of bus charging while avoiding the substantial additional costs associated with large-scale battery storage integration.

At the same time, Scenario 2 may represent the most realistic short-term implementation pathway due to its lower investment requirements and simpler infrastructure needs. A phased transition from Scenario 2 toward Scenario 3 therefore appears to represent the most balanced and practical development strategy.

The analysis also demonstrates several broader systemic insights. Distributed rooftop PV alone can provide a meaningful renewable energy contribution; however, its impact is constrained by the limited availability of surplus electricity. In contrast, large-scale centralized PV generation significantly improves renewable energy penetration and increases overall energy autonomy. The results further highlight that the temporal mismatch between electricity generation and demand remains one of the key challenges of PV-integrated transport systems. Although smart charging and storage technologies can improve system flexibility, they also introduce additional economic complexity. Together, these findings provide a strong analytical basis for evaluating the environmental, social, and implementation implications discussed in the following chapters.

10. Environmental and social impact

The integration of photovoltaic (PV) systems into the electric public transport system of Umag has the potential to generate substantial environmental and social benefits, extending beyond direct energy and economic impacts. The combined electrification of transport and deployment of renewable energy contributes to broader sustainability objectives related to climate change mitigation, air quality improvement, energy transition, and urban quality of life.

One of the most significant environmental benefits identified in this study is the reduction of greenhouse gas emissions associated with public transport operation. Conventional diesel-powered buses contribute directly to CO_2 emissions as well as other pollutants such as nitrogen oxides (NOx) and particulate matter (PM), which negatively affect both climate and local air quality.

By replacing diesel buses with battery electric buses supplied partially or predominantly by renewable electricity, the transport system can significantly reduce its carbon footprint. The magnitude of these reductions depends on the selected scenario and corresponding renewable energy share.

In Scenario 1 and Scenario 2, where renewable energy covers approximately 67% of electric bus demand, substantial emission reductions are already achieved compared to conventional diesel operation, achieving savings of 83-85%. However, grid electricity imports still contribute indirectly to emissions depending on the Croatian electricity mix.

Scenario 3 enables near-complete decarbonisation of bus operation. The bus emissions are reduced by 97% and 95% of annual electricity demand is covered by PV generation. Transport-related

operational emissions remaining are primarily associated with residual grid imports during periods of low solar availability.

Scenario 4 further improves renewable energy utilization and system flexibility through the integration of battery storage, enabling greater optimization of renewable electricity consumption and a further reduction in grid dependency. It however brings no significant additional transport savings, but increases the local use of PV.

Beyond the reduction of greenhouse gas emissions, the electrification of public transport also contributes significantly to improved local air quality. This is particularly relevant in coastal and tourism-oriented cities such as Umag, where seasonal traffic congestion and high visitor numbers increase local pollutant concentrations during the summer months.

The elimination of tailpipe emissions from electric buses contributes to reduced NOx emissions, lower particulate matter concentrations, and decreased noise pollution in urban areas. These improvements directly affect public health and urban liveability, particularly in densely used tourist and residential zones.

The integration of renewable energy into public transport additionally contributes to greater local energy resilience and energy independence. By generating electricity locally through PV systems, the city reduces its exposure to external energy market fluctuations and long-term electricity price volatility. This aspect has become increasingly important within the European context due to rising energy prices, growing energy security concerns, and the increasing emphasis on decentralized energy systems.

From a social perspective, the project may also generate important demonstration and educational effects. Visible renewable energy infrastructure, such as rooftop PV systems and electric buses, can strengthen public awareness of sustainable technologies and increase public acceptance of climate transition measures. Furthermore, the implementation of such systems may stimulate local green investment, support the development of technical and operational expertise, and create employment opportunities related to renewable energy and sustainable mobility sectors.

At the same time, several potential social and environmental challenges must also be considered. Large-scale PV deployment, particularly in Scenario 3 and Scenario 4, requires careful consideration of land-use impacts, visual integration into the landscape, and the development of supporting grid infrastructure. Although the proposed Donji Picudo location represents a former landfill area with relatively limited competing land-use value, public acceptance and transparent stakeholder communication remain essential elements of successful implementation.

Similarly, the introduction of new charging infrastructure and modifications to urban transport systems may require close coordination with local authorities, distribution system operators, public institutions, and commercial stakeholders.

Overall, the environmental and social assessment demonstrates that the integration of PV systems into electric public transport in Umag can generate substantial long-term benefits across multiple dimensions of sustainability. The project therefore represents not only a transport modernization initiative, but also a broader contribution to the city’s energy transition and climate objectives.

11. Implementation roadmap

The successful implementation of a photovoltaic-integrated electric public transport system in Umag requires a phased and strategically coordinated approach. Due to the technical, financial, and institutional complexity of such systems, gradual implementation represents the most appropriate pathway for reducing risks while enabling progressive system expansion and operational learning. The proposed roadmap is therefore organized through several implementation phases, each corresponding to increasing levels of renewable energy integration and overall system complexity.

11.1. Phase 1 – Initial Electrification and Distributed PV Deployment

The first phase focuses on the introduction of the initial electric bus fleet, the installation of depot-based charging infrastructure, and the deployment of rooftop PV systems on public buildings. This phase corresponds primarily to Scenario 1 and partially to Scenario 2. The main objective is to establish operational experience with electric buses while simultaneously developing the basic charging infrastructure, reducing transport-related emissions, and testing the integration of locally generated renewable electricity. From an implementation perspective, this stage benefits from relatively low investment requirements, limited infrastructure complexity, and faster deployment timelines. Furthermore, the use of existing municipal buildings for rooftop PV installations reduces permitting complexity and facilitates early implementation.

11.2. Phase 2 – Expansion of PV Integration

The second phase involves the expansion of distributed photovoltaic installations, including the integration of PV systems within the commercial sector, alongside the optimization of charging schedules and energy management strategies. This phase aligns with Scenario 2 and represents the transition toward a more integrated urban energy system. At this stage, the focus shifts toward increasing renewable electricity coverage, improving self-consumption rates, and reducing dependence on imported electricity. The implementation of smart charging strategies becomes increasingly important in order to improve the temporal alignment between electricity generation and transport demand.

11.3. Phase 3 – Utility-Scale Renewable Integration

The third phase introduces utility-scale renewable integration through the construction of the Donji Picudo PV power plant and the incorporation of centralized renewable electricity generation into the transport system. Corresponding to Scenario 3, this stage represents the transition toward near-complete decarbonization of electric bus operations. Successful implementation requires detailed technical design, comprehensive grid studies, land-use and permitting procedures, coordination with distribution system operators, and the establishment of long-term financing mechanisms. Although investment requirements become substantially higher during this phase, the resulting renewable energy contribution and emission reduction potential are also significantly greater.

11.4. Phase 4 – Advanced Flexibility and Storage Integration

The final phase reflects Scenario 4 and represents the most advanced level of system integration considered within this study. This stage includes the deployment of battery energy storage systems (BESS), advanced smart charging technologies, and integrated energy management systems aimed at optimizing system flexibility and grid interaction. The primary objective is to increase renewable energy utilization efficiency, reduce the temporal mismatch between PV generation and electricity demand, and minimize dependence on the external grid. However, implementation of this phase should only be considered after sufficient operational experience and system maturity have been achieved through the earlier phases.

11.5. Risk Assessment and Mitigation

Several risks may affect the successful implementation of the proposed system.

Technical risks include potential grid capacity limitations, charging infrastructure reliability issues, and the inherent variability of photovoltaic generation.

Economic risks are primarily associated with high upfront investment costs, uncertainty in electricity prices, and fluctuations in technology costs.

Regulatory risks may arise from permitting delays, grid connection procedures, or future changes in legislation and support schemes.

Operational risks include seasonal variability in transport demand, limited local technical expertise, and the need for coordination among multiple stakeholders.

To mitigate these challenges, several measures are recommended. A phased implementation approach combined with modular and scalable infrastructure design can reduce financial and technical exposure while preserving long-term flexibility. Early engagement with grid operators, public authorities, and other stakeholders is essential for improving coordination and minimizing administrative delays. In addition, the utilization of European Union and national funding opportunities can significantly support investment feasibility, while continuous monitoring and optimization of system operation can improve long-term performance and reliability.

Overall, the proposed roadmap enables gradual transition toward a highly renewable and resilient public transport system while minimizing implementation risk and financial exposure.

12. Conclusions and recommendations

This feasibility study demonstrates that the integration of photovoltaic systems into the electric public transport system of Umag is technically feasible, environmentally beneficial, and economically promising under multiple development pathways.

The performed analysis confirms that the combination of transport electrification and renewable energy deployment can substantially contribute to the reduction of greenhouse gas emissions,

improvement of local air quality, increased energy independence, and long-term stabilization of operational energy costs. The study further shows that even relatively moderate levels of distributed rooftop PV integration can provide a meaningful renewable energy contribution to electric bus operation. However, higher levels of renewable penetration require larger-scale generation capacity and increasingly advanced system integration measures.

Among the analysed scenarios, Scenario 3 — combining distributed rooftop PV with a centralized utility-scale PV power plant — appears to provide the most balanced solution in terms of renewable energy coverage, technical feasibility, long-term economic performance, and system scalability. This scenario achieves near-complete renewable coverage of electric bus electricity demand while avoiding the substantial additional investment costs associated with large-scale battery storage integration. Scenario 2, on the other hand, represents a highly realistic and achievable short-term implementation pathway, as its moderate investment requirements and lower infrastructure complexity make it particularly suitable as an initial development phase. Scenario 4 demonstrates the long-term potential of integrating battery energy storage systems into urban transport-energy systems; however, its economic feasibility remains dependent on future reductions in battery costs and further development of flexibility markets and smart energy management systems.

The study also highlights several important systemic insights. Renewable energy integration must be analysed in close relation to demand structure and temporal consumption patterns. Smart charging strategies are essential for improving renewable energy utilization, while distributed and centralized PV systems can effectively complement each other within urban energy systems. In addition, the seasonal alignment between tourism-related transport demand and solar generation creates particularly favourable conditions for PV-based mobility solutions in coastal cities such as Umag.

Based on the obtained results, several recommendations can be made. Implementation should begin with distributed rooftop PV systems and depot-based charging infrastructure, followed by a gradual expansion of renewable generation capacity toward hybrid distributed–centralized systems. Smart charging and advanced energy management systems should be integrated in later phases, while battery storage should only be considered once sufficient system scale and operational maturity are achieved. The use of available EU and national funding mechanisms is strongly recommended to reduce upfront investment barriers, alongside continued development of local institutional and technical capacity for integrated energy and mobility planning.

Overall, the proposed PV-integrated electric transport system represents an important opportunity for the City of Umag to position itself as a regional example of sustainable urban mobility and renewable energy integration within the broader context of the energy transition in the Balkans.

References

[1] A. D. May, “Encouraging good practice in the development of Sustainable Urban Mobility Plans,” Case Studies on Transport Policy, vol. 3, no. 1, pp. 3–11, 2015. https://doi.org/10.1016/j.cstp.2014.09.001

[2] A. May, S. Boehler-Baedeker, L. Delgado, T. Durlin, M. Enache, and J.-W. van der Pas, "Appropriate national policy frameworks for sustainable urban mobility plans," European Transport Research Review, vol. 9, no. 1, p. 7, 2017. https://doi.org/10.1007/s12544-017-0224-1

[3] S. Werland, "Diffusing Sustainable Urban Mobility Planning in the EU," Sustainability, vol. 12, no. 20, p. 8436, 2020. https://doi.org/10.3390/su12208436

[4] D. Sitányiová and S. Masarovičová, "Development status of sustainable urban mobility plans in European Union new member states," International Journal of Transport Development and Integration, vol. 1, no. 1, pp. 16–27, 2017. https://doi.org/10.2495/TDI-V1-N1-16-27

[5] R. Jordová and H. Brůhová-Foltýnová, "Rise of a New Sustainable Urban Mobility Planning Paradigm in Local Governance: Does the SUMP Make a Difference?," Sustainability, vol. 13, no. 11, p. 5950, 2021. https://doi.org/10.3390/su13115950

[6] L. Mladenovič, A. Plevnik, and T. Rye, "Implementing national support programmes for sustainable urban mobility plans in a multilevel governance context," Case Studies on Transport Policy, vol. 10, no. 3, pp. 1686–1694, 2022. https://doi.org/10.1016/j.cstp.2022.06.007

[7] City of Belgrade, Sustainable Urban Mobility Plan Belgrade, Belgrade, Serbia, 2020.

[8] C. Mettke, Sustainable Urban Transport in Tirana: Towards Data-Driven Sustainable Urban Mobility Action in Tirana, Tirana, Albania, 2022.

[9] Regional Development Agency of Ljubljana Urban Region, Sustainable Urban Mobility Plan of the Ljubljana Urban Region, Ljubljana, Slovenia, 2020.

[10] H. Brůhová Foltýnová, E. Vejchodská, K. Rybová, and V. Květoň, "Sustainable urban mobility: One definition, different stakeholders' opinions," Transportation Research Part D: Transport and Environment, vol. 87, p. 102465, 2020. https://doi.org/10.1016/j.trd.2020.102465

[11] M. Lindenau and S. Böhler-Baedeker, "Citizen and Stakeholder Involvement: A Precondition for Sustainable Urban Mobility," Transportation Research Procedia, vol. 4, pp. 347–360, 2014. https://doi.org/10.1016/j.trpro.2014.11.026

[12] G. Michelini, D. Dametto, and A. Michel, "Who is doing what and how? Descriptive analysis of the sustainable mobility planning practice in Germany," Transport Policy, vol. 134, pp. 231–241, 2023. https://doi.org/10.1016/j.tranpol.2023.02.022

[13] H. Brůhová-Foltýnová and R. Jordová, "Innovative Tools of Sustainable Mobility in European Urban Areas: Experience with Evaluation and Role of Political Barriers," Transactions on Transport Sciences, vol. 7, no. 4, pp. 135–142, 2014. https://doi.org/10.2478/trans-2014-0011

[14] K. Anastasiadou, N. Gavanas, C. Pyrgidis, and M. Pitsiava-Latinopoulou, "Identifying and Prioritizing Sustainable Urban Mobility Barriers through a Modified Delphi-AHP Approach," Sustainability, vol. 13, no. 18, p. 10386, 2021. https://doi.org/10.3390/su131810386

[15] E. Arsenio, K. Martens, and F. Di Ciommo, "Sustainable urban mobility plans: Bridging climate change and equity targets?," Research in Transportation Economics, vol. 55, pp. 30–39, 2016. https://doi.org/10.1016/j.retrec.2016.04.008

[16] M. Á. Mozos-Blanco, E. Pozo-Menéndez, R. Arce-Ruiz, and N. Baucells-Aletà, "The way to sustainable mobility. A comparative analysis of sustainable mobility plans in Spain," Transport Policy, vol. 72, pp. 45–54, 2018. https://doi.org/10.1016/j.tranpol.2018.07.001

[17] S. Garcia-Ayllon, E. Hontoria, and N. Munier, "The Contribution of MCDM to SUMP: The Case of Spanish Cities during 2006–2021," International Journal of Environmental Research and Public Health, vol. 19, no. 1, p. 294, 2021. https://doi.org/10.3390/ijerph19010294

[18] R. Okraszewska, A. Romanowska, M. Wołek, J. Oskarbski, K. Birr, and K. Jamroz, "Integration of a Multilevel Transport System Model into Sustainable Urban Mobility Planning," Sustainability, vol. 10, no. 2, p. 479, 2018. https://doi.org/10.3390/su10020479

[19] M. Kiba-Janiak and J. Witkowski, "Sustainable Urban Mobility Plans: How Do They Work?," Sustainability, vol. 11, no. 17, p. 4605, 2019. https://doi.org/10.3390/su11174605

[20] R. Hartl, P. Harms, and M. Egermann, "Towards transformation-oriented planning: what can sustainable urban mobility planning (SUMP) learn from transition management (TM)?," Transport Reviews, vol. 44, no. 1, pp. 167–190, 2024. https://doi.org/10.1080/01441647.2023.2239497

[21] H. Lund, J. Z. Thellufsen, P. A. Østergaard, P. Sorknæs, I. R. Skov, and B. V. Mathiesen, "EnergyPLAN – Advanced analysis of smart energy systems," Smart Energy, vol. 1, p. 100007, 2021. https://doi.org/10.1016/j.segy.2021.100007

[22] H. Lund and W. Kempton, "Integration of renewable energy into the transport and electricity sectors through V2G," Energy Policy, vol. 36, no. 9, pp. 3578–3587, 2008. https://doi.org/10.1016/j.enpol.2008.06.007

[23] M. G. Prina et al., "Multi-objective optimization algorithm coupled to EnergyPLAN software: The EPLANopt model," Energy, vol. 149, pp. 213–221, 2018. https://doi.org/10.1016/j.energy.2018.02.050

[24] X. Liu, P. Payakkamas, M. Dijk, and J. de Kraker, "GIS Models for Sustainable Urban Mobility Planning: Current Use, Future Needs and Potentials," Future Transportation, vol. 3, no. 1, pp. 384–402, 2023. https://doi.org/10.3390/futuretransp3010023

[25] A. Graser, T. Sutton, and M. Bernasocchi, "The QGIS Project: Spatial Without Compromise," Patterns, vol. 6, no. 7, p. 101265, 2025. https://doi.org/10.1016/j.patter.2025.101265

[26] QGIS Development Team. QGIS Geographic Information System. Open Source Geospatial Foundation Project.

[27] EnergyPLAN. Advanced Energy Systems Analysis Computer Model, Documentation, Version 17.0. Aalborg University, 2026.

[28] European Commission. Sustainable and Smart Mobility Strategy - putting European transport on track for the future. COM(2020) 789 final, 2020.

[29] European Commission. The European Green Deal. COM(2019) 640 final, 2019.

[30] State Geodetic Administration of the Republic of Croatia, “OSS Uređena zemlja,” Zagreb, Croatia. [Online]. Available: https://oss.uredjenazemlja.hr/

[31] Ministry of Environmental Protection and Green Transition of the Republic of Croatia (MZOZT), "Vodič za izračun ugljičnog otiska – metodologija" (Guide for carbon footprint calculation), Table 3-17: Emission factors for electricity, Zagreb, Croatia, 2024. [Online]. Available:https://mzozt.gov.hr/UserDocsImages/klimatske_aktivnosti/ugljicni_otisak/vodic_metod_10_24.pdf

[32] Nowtricity, "Croatia – Live CO_2 emissions of electricity consumption." [Online]. Available: https://www.nowtricity.com/country/croatia (accessed Oct. 21, 2026).

[33] HEP Group, "Electricity sources," Hrvatska elektroprivreda, Zagreb, Croatia. [Online]. Available:https://www.hep.hr/opskrba/electricity-market/eletricity-market/electricity-sources/1474 (accessed Oct. 21, 2026).