

# FUNCTIONAL DESIGN OF AN ECO-EFFICIENT PARKING LOT FOR ELECTRIC VEHICLES WITH PHOTOVOLTAIC PANEL INTEGRATION AND CHARGING STATIONS

Ivelina Takeva-Beberova<sup>1</sup> [0009-0003-4765-5020], Sylvester Bozherikov<sup>2</sup> [0009-0003-0004-9912], Georgi Draganov<sup>3</sup>

<sup>1</sup>Technical University of Sofia, Faculty of Engineering and Pedagogy Sliven, Department of Electronics, Automation and Information Technologies, Sliven, Bulgaria

<sup>2</sup>Technical University of Sofia, Faculty of Engineering and Pedagogy Sliven, Department of Mechanics, Mechanical Engineering and Thermal Engineering, Sliven, Bulgaria

<sup>3</sup>Technical University of Sofia, Faculty of Engineering and Pedagogy Sliven, Department of Mechanics, Mechanical Engineering and Thermal Engineering, Sliven, Bulgaria, STUDENT (M.Eng.)

E-mail(s): [s.bozherikov@tu-sofia.bg](mailto:s.bozherikov@tu-sofia.bg) <sup>(✉)</sup>, [beberova.ivelina@tu-sofia.bg](mailto:beberova.ivelina@tu-sofia.bg), [georgidraganov83@abv.bg](mailto:georgidraganov83@abv.bg)

**Abstract** - In the present work a functional design of an eco-efficient parking lot is proposed, with multiple parking spaces for charging electric vehicles. Part of the electricity for the charging is coming from photovoltaic panels mounted on the roof and covering all the parking spaces. The position, design and parking configuration are according to the previously attached project plan for the location. The parking lot should have easy access and enough space for charging all the cars at once. The main point is the design of the whole metal construction covering the parking space and the installing position of the panels.

**Keywords:** Functional design, Eco-efficient, Electric vehicles, Parking lot, Charging stations, Photovoltaic panel.

## 1. Introduction

The modern infrastructure must evolve beyond its current technological level to respond to the pressing global challenges of climate change, urban pollution, and the increasing demand for clean energy. There are many promising technologies and ideas for developing renewable energy integration for transportation, urban planning, and reform. Such a promising new idea is the integration of solar-powered systems within parking facilities, specifically designed for electric vehicles (EVs). This concept merges future technology and planning with environmentally conscious engineering to meet and expand the needs of green mobility and energy efficiency [1, 2].

The reduced environmental impact and zero emissions of the electric vehicles cleared the path to transition to a more sustainable transportation ecosystem. The wide implementation of such technology depends heavily on the accessible, reliable, and renewable energy-based charging infrastructure to support it. With integrating photovoltaic (PV) panels into roof-mounted, solar

parking lot-based systems, there is a possibility to harness clean solar energy and use it. This can supply electricity for EV charging and also reduce the reliance of the system on conventional grid electricity [3, 4, 5].

Several studies have examined photovoltaic carports and solar parking systems as distributed energy solutions in urban territories. Existing research primarily focuses on estimating annual photovoltaic energy yield, environmental benefits, and architectural integration aspects in mainly urban areas. Parallel investigations into EV charging infrastructure have addressed charging demand modeling, grid impact assessment, and smart load management strategies. Furthermore, techno-economic analyses of PV-powered charging stations have demonstrated potential economic feasibility under favorable regulatory and climatic conditions. However, these studies typically address energy performance, charging management, or economic evaluation separately, without integrating them into a unified structural and functional design framework. [6, 7]

The mechanical design of such a parking system must address multiple important factors, including functionality, structural integrity, optimal panel orientation and position, energy output efficiency, safety, and organization. This system design can provide additional benefits by offering shaded parking spots, reducing urban heat, and potentially supplying the excess energy back to the local power grid. This implementation and structure of the system further enhance the usability and ecological footprint of the facility.

A systematic review of the available literature reveals several research gaps. First, there is a lack of integrated methodologies that simultaneously consider structural load verification (including wind and snow loads), photovoltaic tilt-angle optimization, shading constraints between panel rows, and detailed system energy balance analysis. Second, many proposed photovoltaic parking concepts remain at the conceptual level, without quantitative validation through structural calculations or energy simulations. Third, limited attention has been given to linking technical design parameters with comprehensive economic performance indicators such as payback period, net present value, and life-cycle cost. [8, 9, 10]

Therefore, the research problem addressed in this study can be defined as the absence of a comprehensive engineering framework for the functional design and quantitative evaluation of eco-efficient photovoltaic parking lots equipped with EV charging stations.

This study develops the construction elements involved in the design of an eco-efficient parking system supporting electric vehicle charging stations supplied by photovoltaic panel integration. It aims to highlight the critical elements in the design, expectations, performance, and benefits of such a system, offering a layout and a blueprint for future ideas, designs, and development in the urban infrastructure [11].

In this study, the term eco-efficient is defined as the capacity of the proposed parking system to reduce or remove the reliance on grid-supplied electricity through on-site photovoltaic generation, thereby improving the overall energy balance and operational sustainability of the facility. Eco-efficiency is evaluated using measurable indicators, including annual PV energy yield, percentage coverage of EV charging demand, reduction of grid electricity consumption, and the associated potential decrease in CO<sub>2</sub> emissions based on national emission factors. This definition ensures that the concept is treated as a quantifiable engineering performance metric rather than a general environmental descriptor.

The scientific objective of this study is to develop and evaluate an integrated functional design methodology for a photovoltaic parking facility that

incorporates: (i) optimization of panel orientation and spatial configuration, (ii) structural verification under applicable load conditions, (iii) energy yield estimation and system energy balance assessment, and (iv) techno-economic feasibility analysis.

The following research hypotheses are formulated:

H1: Optimization of photovoltaic tilt angle significantly affects annual energy yield; however, tilts lower than the theoretical optimum can maintain more than 90% of maximum energy production under certain conditions.

H2: A properly dimensioned structural system designed according to relevant load standards ensures mechanical safety without disproportionate increases in investment cost.

H3: Integration of on-site photovoltaic generation with EV charging infrastructure reduces long-term operational costs compared to grid-dependent charging systems.

The main objective of the study is to create a design and plan to meet the growing needs for EV infrastructure and also the integration of photovoltaic panels. The key aspects of the design include optimal orientation and spatial arrangement of the parking system and each parking space [12]. The metal structure design [13] and the panels themselves are a major part of the project, taking into account the given initial sketch/layout. A very important detail is the selection and sizing of the panels and the integration of the EV charging station to correspond with the energy storage and management systems [14]. An important feature is the accessibility, safety, and ease of operation of the facility [15, 16, 17].

The novelty of the presented work lies in the holistic integration of structural engineering analysis, photovoltaic performance optimization, and economic assessment within a single functional design model for sustainable EV parking infrastructure. [18, 19]

Research is conducted to analyze the benefits of such a system in the urban areas, taking into account both environmental and economic factors. By addressing and managing these critical design elements of the system, the work provides a fundamental approach for engineers to develop scalable and green infrastructure solutions [20, 21, 22].

## **2. Input Data and Preliminary Plan**

### **2.1 Starting Points**

Initially, a plan of the free space where the facility should be located was presented with the main dimensions, without specifying the exact location and the position orientation of the parking spaces. (Figure 1)

The main sketches and designs were developed in AutoCAD in order to create an initial idea for the location of each element of the parking system. All elements were taken into account in the available space and the requirements for distance and safety.

The metal structure and all its elements were designed in a 3D CAD environment, using the SolidWorks software product. All other elements of the parking system were also added to the 3D model, each of them being located in consideration of the initial design.

## 2.2 Main Elements

The main parameters of the parking system are:

- 12 parking spaces – this requirement is not subject to change. It is important that each of the designated spaces has a size and parameters specified by the requirement.
- Free entrance and separate exit – this will allow free passage of the incoming and outgoing vehicles;
- EV charging stations – each of the parking spaces must have its own charging station;
- Modular metal structure – stable enough to support the photovoltaic panels and serve as a canopy for all cars. Stable enough to withstand the climate changes in the area – high wind velocity, snow weight, etc.
- Green areas and recreational areas – as a requirement for the construction of green infrastructure, the site must have a certain percentage of green space and a place for rest and recreation.

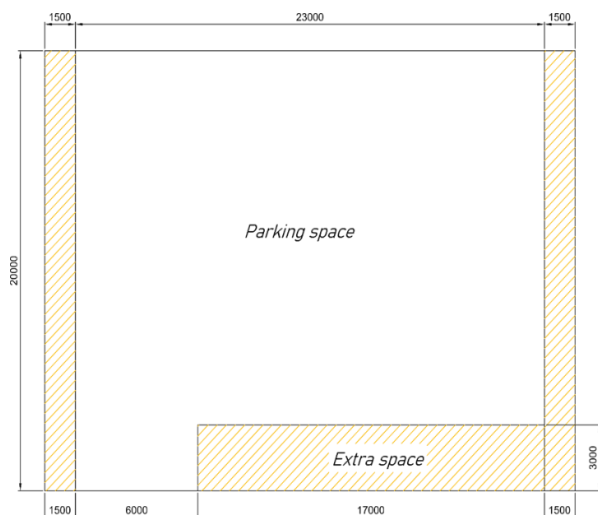


Figure 1: Preliminary sketch of the parking space

### Basics:

According to the plan shown in Figure 2, the parking lot has all the elements specified at the beginning:

- 12 parking spaces, the dimensions of which will be indicated and explained in the next pages. Each of

the spaces has free access and the possibility of easy parking and departure;

- Separate entrance and exit, which facilitates the flow of traffic;

- Each parking space has an EV charging station. The spaces have easy access to the station;

- Columns to support the entire structure and a roof with solar panels. Each row of columns has its own designation due to the different height – C1 (Row 1), C2 (Row 2), C3 (Row 3), C4 (Row 4). There are 5 columns in each row, making their total number 20. The distance between them provides sufficient space for parking in the designated spaces.

- Benches with the possibility of rest and relaxation;

- Lighting around the recreation areas;

- Green areas to ensure a pleasant stay;

- The external outlines provide additional shelter on all sides and additional space for the panels.

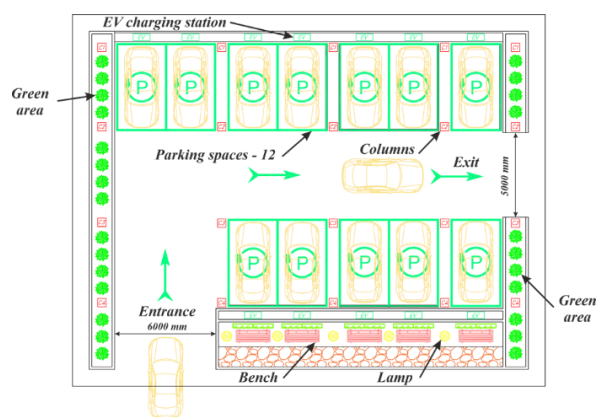


Figure 2: Full plan according to the preliminary sketch

## 2.3 Roof Tilt Angle

The tilt is the angle between the surface of the panel and the horizontal surface. It has a significant impact on the energy output and the stored energy. This value varies depending on the location. The value of the tilt angle also depends on the season, which affects the efficiency of the whole system.

The orientation in the northern hemisphere is south, while in the southern hemisphere it is north. The observation tilts from about 40 degrees, and depending on the location and season, it can vary to 10, 15, 20, or 30 degrees.

The photovoltaic canopy is designed with a fixed tilt angle of 10°, selected through an integrated structural–energy assessment. Although the optimal tilt angle for maximum annual energy production in Sofia (latitude  $\approx 42.7^\circ$  N) is approximately 30°, simulations indicate that reducing the tilt to 10° results in a small annual energy yield reduction (Section 3.3). However, increasing the tilt angle significantly affects the structural configuration of the multi-row cantilever canopy system.

For higher tilt angles (e.g., 25–30°), the progressive elevation of successive rows would increase the rear column heights beyond 15 m, substantially amplifying bending moments at the column bases and increasing slenderness ratios. This would require larger steel cross-sections, heavier foundations, and significantly greater material consumption and from there - cost.

In contrast, a 10° tilt limits column heights to approximately 4,8–7,8 m, reducing wind-induced bending moments, improving global stability, and maintaining structural efficiency while preserving approximately close to the maximum achievable annual energy production.

Therefore, the selected 10° tilt represents a rational engineering compromise between energy optimization and structural feasibility, ensuring both eco-efficiency and constructability of the proposed parking canopy system – Figure 3.

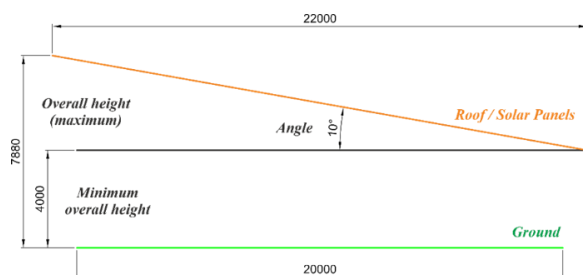


Figure 3: Roof / Panels tilt angle

### 3. System Elements

#### 3.1 Parking Space

Parking spaces are designated areas intended for the temporary stationary storage of vehicles, usually cars, but sometimes motorcycles, bicycles, and electric vehicles (EVs). They are a key component of transportation infrastructure in both public and private facilities. The dimensions of parking spaces vary depending on the type of car. Different standards and requirements exist depending on the country and the norms and regulations adopted there. (Table 1).

Table 1. Parking space sizes according different types of vehicles

Type	Width [m]	Length [m]
Standard car	2.4 – 2.7	4.8 – 6.0
Compact car	2.2 – 2.4	4.2 – 4.8
Parallel space	2.2 – 2.5	6.0 – 6.5
Accessible space	3.6	5.5 – 6
EV	2.5 – 3	5 – 6

In Figure 4 are shown the dimensions of the marked parking area of each parking spot. In Figure 5 is the sample of the EV, used as reference – Tesla Model Y.

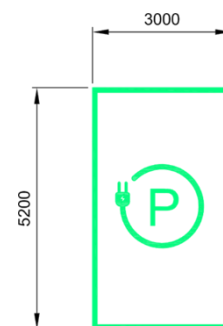


Figure 4: Parking space dimensions

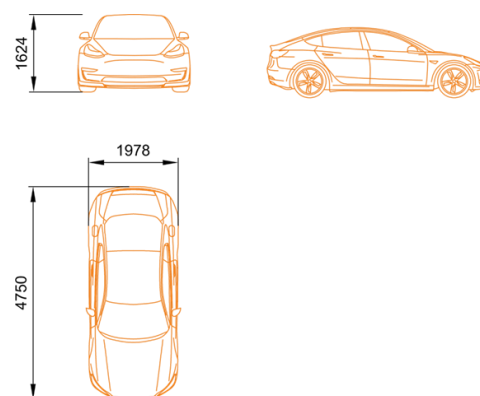


Figure 5: Tesla Model Y dimensions

#### 3.2 Solar Panels

Figure 6 presents a model of a selected solar panel, which in turn can provide up to 768 W of power (Himalaya G12-132). By carefully allocating the roof space and available dimensions, using solar panels of this type, it is calculated that a total of 198 panels could be placed (including the additional space on all sides).

A global performance ratio (1) is introduced to account for system losses, including temperature effects, inverter efficiency, cable losses, mismatch, and soiling.

$$P = P_t \cdot \eta \quad (1)$$

where:

- P – real power generated by a single panel – 768 W;
- P<sub>t</sub> – theoretical power by a single panel;
- η – efficiency (calculating temperature losses, inverter losses, Cable losses, mismatch and soiling).

$$P = 768 \cdot 0,91 \approx 700 \text{ W}$$

The chosen efficiency value is described in Table 2.

Table 2. Loss Breakdown Table

Loss Type	Range (%)	Value (%)
Temperature	2 - 3	3
Inverter	2 - 3	2
DC/AC cables	1 - 3	3
Mismatch & soiling	1 - 2	1
<b>Total losses</b>	<b>6 - 11</b>	<b>9</b>

This gives us a value of  $\approx 700$  W for the future calculations and nominal value.

Then:

$$P_0 = S \cdot P \quad (2)$$

where:

-  $P_0$  – total power generated by the system;

-  $P$  – power generated by one panel;

-  $S$  – number of panels.

In this case, a power value of 700 W is used.

$$P_0 = 198 \cdot 700 = 138\,600 \text{ W} = 138,6 \text{ kW}$$

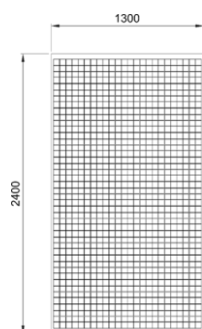


Figure 6: Solar panel Himalaya G12-132 dimensions

This is the total power that solar panels can generate in one hour of operation in sunny weather. When the parking lot is completely filled, part of the energy must be provided by the network. This value is constantly changing according to atmospheric conditions and other factors that affect solar panels and their operation [23,24].

This can best be checked in operating conditions at different times of the day. Then the information would be more accurate and reliable and will certainly vary in lower ratios than the one presented above.

### 3.3 Roof Tilt Angle Validation and Calculation

As mentioned above, a tilt angle of approximately  $30^\circ$  is the optimal tilt angle for maximum annual energy production in Sofia, Bulgaria. From a structural point of view, this will significantly increase the structural height and wind-induced bending moments.

Although a  $10^\circ$  inclination results in approximately 7% lower annual energy production compared to the near-optimal  $30^\circ$  configuration, the reduced structural height and wind-induced loading justify its selection in parking canopy applications where structural economy is prioritized. Lower tilt angle reduces: wind uplift forces, overturning moment, column height, visual impact, and construction cost. (Table 3 and Table 4). Most PV carports in Europe use a 5–15% tilt, because the

structural savings often outweigh the small energy loss. [9]

Higher tilt angle will significantly increase the rear column height from 7,8 m to 15.5 m in order to keep the same plan of the project (front column height must be kept above 4.5 for easy access and design requirements). The minimal accessible height is 4 m on the front end.

Changing the design with each panel's row having a tilt of  $30^\circ$ , while keeping the overall roof incline at  $10^\circ$ , can be achieved, but this will result in overshadowing of the panels and losing more energy - Figure 7.

Table 3. Angle - Yield

Tilt Angle	Yield (kWh/kWp)	Relative Yield Factor
$10^\circ$	1,321	0.93
$20^\circ$	1,392	0.98
$30^\circ$	1,420	1
$40^\circ$	1,406	0.99

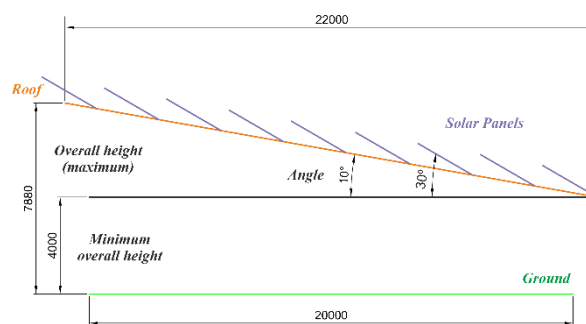


Figure 7: Adding extra tilt angle of the panels

Table 4 shows the calculated loss according to the use of a not optimal tilt angle. The calculation is based on the total power generated by the system – 138,6 kW.

Table 4. Annual Energy production and Loss

Tilt Angle	Relative Yield Factor	Annual Energy (kWh)
$10^\circ$	183 090	-6.9%
$20^\circ$	192 931	-1.9%
$30^\circ$	196 812	0%
$40^\circ$	194 872	-1.0%

The angle of inclination of the roof with the panels of  $10^\circ$  and the arrangement of the panels on its structure exclude the possibility of mutual shading of the panels between the individual rows. In addition, the selected panels have shading-resistant modules, integrated with bypass diodes. In fact, if the panels were installed on a horizontal surface, and the inclination was determined by the inclination of the panels, then to avoid shading between the individual rows of panels, the distance

between them should be in the ratio 1:2 (panel height to distance).

### 3.4 Full Design of the Parking Space

In Figure 8 is shown the full 3D design of the parking lot space and all its elements.

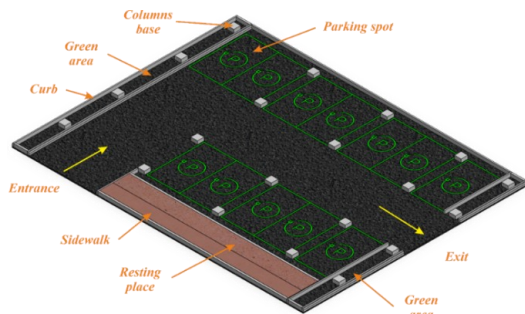


Figure 8: 3D Design of the parking space

### 4. Choice of Inverters

Panel model HS-210-B132-DS700 Given panel electrical data (STC) in Table 5:

Table 5. Panel electrical data

Data	Value
Voc	50.13 V
Vmp	42.10 V
Imp	16.63 A
Isc	17.43 A
Power	700 W

Total system: 138 kW DC  $\approx$  198 panels Orientation: South, 10° tilt

Maximum string length (cold condition check)

In Bulgaria, winter design temperature is typically -15°C. Voltage increases  $\approx$  +0.3% / °C Temperature delta: 25-(-15)=40°

Voltage increase:

$$V_{inc} = 50,13 \cdot (1 + 0,0034) \approx 56 V \quad (3)$$

Typical inverter max DC voltage: 1100 V

$$1100 \div 56,1 \approx 19,6 \quad (4)$$

Maximum safe string = 19 panels.

Operating voltage check (MPPT range).

For 19 panels per string:

$$19 \cdot 42,1 = 800 V \quad (5)$$

Perfectly inside typical MPPT range (550-850 V)

Current check (very important with 700 W panels)

String current = Imp = 16.63 A Isc = 17.43 A

Most modern 60-110 kW inverters:

Max input current per MPPT: 26-30 A

Max per string input: 20 A

ONLY 1 string per MPPT input Do NOT parallel 2 strings on one MPPT, this is critical with high-current 700 W modules.

Number of strings Using 19 panels/string:

$$198 \div 19 = 10,4 \quad (6)$$

Design: 11 strings  $\times$  18 panels = 198 panels (138.6 kW).

Check voltage:

$$V_{mp} = 18 \cdot 42,1 = 758 V \quad (7)$$

$$ColdVoc = 18 \cdot 56,1 = 1010 V \quad (8)$$

Very safe Excellent MPPT operation

Inverter sizing (AC)DC = 138 kW Target DC/AC ratio

$\approx$  1,15-1,25;  $138 \div 1,2 = 115$  kW AC

INVERTER CONFIGURATION (RECOMMENDED)

2 $\times$ 60 kW STRING INVERTERS.

Each inverter: Handles 5-6 strings Each string on its own MPPT input No paralleling  $\rightarrow$  safe with high current panels. Table 6 shows example split.

Table 6. Example split

Inverter	Strings	DC Power
Inverter 1	6 strings $\times$ 18 panels	75,6 kW
Inverter 2	5 strings $\times$ 18 panels	63,0 kW



Figure 9: Inverter Huawei SUN2000-60K-M

Total DC = 138,6 total AC = 120 kW DC/AC = 1.155 ratio.

Compatible inverter models (HIGH INPUT CURRENT) Huawei SUN2000-60K-M (Figure 9).

Inverter selection condition:

$$V_{Opv} < MaxInputVoltage_{inv}$$

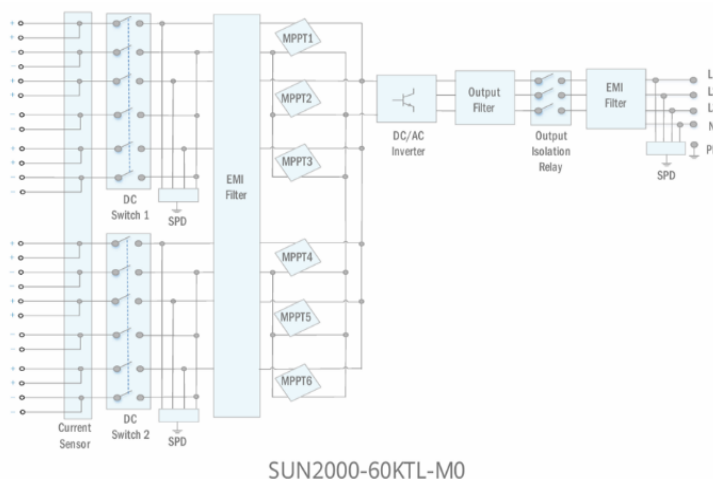
$$MPPT_{min_{inv}} \leq V_{Opv} \leq MPPT_{max_{inv}} \quad (9)$$

$$I_{mpp_{pv}} \leq I_{MPPT_{inv}}$$

Determining the inverter input voltage (for one string):

$$18 \cdot 50,13 V = 902,34 V_{dc} \quad (10)$$

Max Input Voltage 1100V and MPPT Operating Voltage Range 200 - 1000 V - Chosen inverter. (Figure 10).



SUN2000-60KTL-M0  
Figure 10: Inverter Circuit Diagram

## 5. Charging Stations

Panel model HS-210-B132-DS700 Given panel electrical data (STC) in Table 5:

Based on our needs 12 parking places per 11kW=132kW.

The product parameters of the 11 kw EV charger are shown (Table 7) as follows:

Table 7. Product parameters

Parameters	Requirements
<b>General Requirements</b>	
EV Charger Type	AC
Charger Capacity	11KW
Equipment size	L359*140*H510(mm)
Product Model NO.	ENC-ACB/L011A
Mounting	Wall-Mounted/Column Type
<b>Input Requirements</b>	
AC Supply System	Single-Phase, 3 Wire AC system (ANSI)
	Three-Phase, 5 Wire AC system (ENC)
Nominal Input Voltage	AC380V±15%(ENC) / AC240V±15%(ANSI)
Input Frequency	50±3Hz
<b>Environmental Requirements</b>	
Ambient Temperature Range	-25 to 55°C
Ambient Humidity	5 to 95%
Storage Temperature	-40 to 70°C
<b>Mechanical Requirements</b>	
IP Ratings	IP 55
Cooling	Natural Cooling
<b>Output Requirements</b>	
Number of Outputs	1

Type of Each Output	AC380V±15%(ENC) / AC240V±15%(ANSI)
Single Output Max.Current	16 Amp/50 Amp
<b>User Interface &amp; Display Requirements</b>	
Display & Touch-Screen Size	4.3 Inches Screen
User Authentication	QR Code/RFID Card /Password Login
Metering Information	Consumption Units
<b>Communication Requirements</b>	
Communication between EVSE and Central server	Protocol (Optional)
Interface between Charger and CMS	Ethernet/3G/4G/WIFI (Optional)
<b>Protection &amp; Safety Requirements</b>	
Executive Standard	IEC 62196 2017, IEC 61851 2017, SAE J1772, etc.
Safety Parameters	Over Current, Over Voltage, Under Voltage, Residual Current, Surge Protection, Leakage Protection, Short Circuit, Over Temperature, etc.

## 6. Typical Solar Resource in Sofia

### Annual Average Solar Irradiance:

Global Horizontal Irradiation (GHI) — on a horizontal surface (no tilt):

Approximately ~1 450 – 1 500 kWh/m<sup>2</sup> per year in the Sofia region.

This is the total global (direct + diffuse) solar energy falling on a flat surface over a year.

### South-Facing Surface (Tilted/Vertical):

For a south-facing surface like a parking canopy or solar array tilted toward the equator:

A south-oriented plane will receive more irradiance than a horizontal one, especially if tilted optimally (close to latitude, ~42–43°).

Typical PV system models for Sofia show annual plane-of-array (POA) irradiation of roughly 1 600 – 1 800 kWh/m<sup>2</sup> or more on a well-tilted south-facing surface (estimates from solar modeling tools such as PVGIS / Global Solar Atlas).

### Daily Equivalent:

If you convert annual figures to a daily basis for a south-tilted surface: ~4.4 – 5.0 kWh/m<sup>2</sup>/day average over the year is a reasonable approximation, with much higher values in summer months and lower in winter.

### Seasonal & Orientation Notes:

*Summer:* Peak irradiance and long daylight; south orientation sees the highest daily collection.

*Winter:* Much lower total irradiance due to low solar elevation; still proportionally higher on south orientations than east/west or north.

*Direct vs Diffuse:* South orientation captures more direct irradiance (important for PV) in clear skies.

### Design Implications for a Parking Lot (South Position):

If you're assessing a south-facing parking structure (e.g., for canopy PV or shading):

Estimate solar resource:

Annual irradiation on horizontal: ~1 450–1 500 kWh/m<sup>2</sup>/yr.

Annual irradiation on optimally tilted south plane: ~1 600–1 800 kWh/m<sup>2</sup>/yr (typical PV case).

Useful rules of thumb:

Multiply the annual figure by system efficiency to estimate energy output if you mount photovoltaics.

For electrical output, typical PV panels in Sofia yield ~4–5 kWh/m<sup>2</sup>/day average.

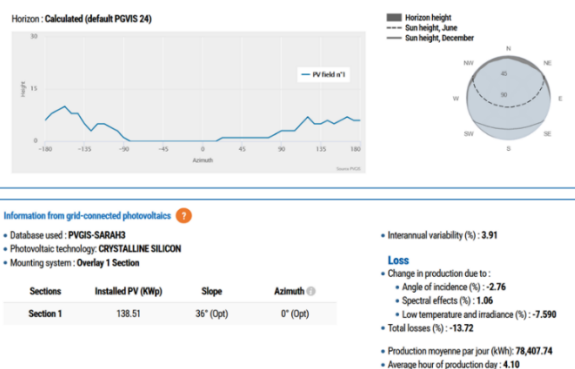


Figure 11: Grid – connected PV

Figure 11 shows the information from the grid – connected PV.

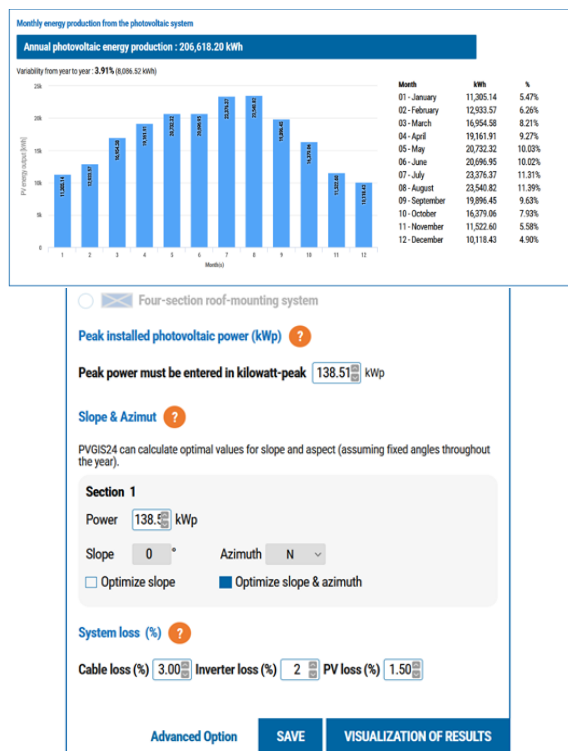


Figure 12: Monthly energy production from the PV system

Figure 12 shows the monthly energy production of the system, calculated with the losses between 3 – 4 %. The results correlate with the previous calculation in Section 3.3, with a difference in the range of 5-10 %.

## 7. Battery Storage

Design assumptions our system Grid-tied BESS, 120 kW AC inverters (2x60) LFP (LiFePO<sub>4</sub>) type of battery, continuous operation allowed, typical commercial duty (peak shaving, PV firming, arbitrage), Inverter efficiency: **97%**; Battery usable DoD (LFP): **80–90%**; Round-trip efficiency: **92–95%**; target continuous c-rate: ≤0.5C (for long cycle life); Design margin: **20%**.

### Required battery power (DC)

$$PDC = 120 / 0.97 \approx 124 \text{ kW}$$

Add margin:  $124 \times 1.2 \approx 150 \text{ kW}$  DC Battery system power rating: **150 kW**.

### Battery energy sizing (4-hour discharge) Energy calculation

Assumptions:

LFP usable DoD = **85%**; System efficiency = **95%**

$$E = \frac{120 \cdot 4}{0.85 \cdot 0.95} = 594 \text{ kWh} \quad (11)$$

Rounded, bankable size:600kWh LFP

$$C - rate = \frac{150}{600} = 0,25 C \quad (12)$$

Excellent for LFP, Low heat, long cycle life (>6000 cycles), Suitable for daily cycling.

**Typical LFP rack layout (example)**

Using 100 kWh LFP racks (very common) – Table 8:

Table 8. Panel electrical data

Item	Quantity
LFP battery racks	6 × 100 kWh
Total energy	600 kWh
Parallel strings	3–6 (depends on DC voltage)
Nominal DC voltage	700–900 V

Match this exactly to Huawei LUNA2000 (Figure 13).



Figure 13: Battery system

**8. Design of the Metal Structure for the Parking System**

The main elements used in the construction of such a structure are

- columns – the main elements of the parking structure. They must be firmly anchored in the ground, in previously prepared places. Made of steel, and in this case, 4 different types of columns are present, and an extra piece for the angle correction;
- beams – the main element connecting the individual columns. There are different types of execution here, according to the design solutions;
- additional beams (in length) – connect the columns and elements in the horizontal direction;
- base plates – serve to connect the columns to the ground and anchor them;
- ribs – to strengthen the structure;
- brackets – for additional stability and connection of the panels;
- mounting rails – for solar panels.

**8.1 Columns**

The structure has four main types of columns of different lengths. The height is consistent with the end element, which is used to maintain the slope of the entire roof. Here, the options are to use columns of the same type and have different end elements or to change the length of the columns according to the increase in the slope and use the same element as the end element.

As already mentioned, each row of columns has its own designation due to the different height – C1 (Row 1), C2 (Row 2), C3 (Row 3), C4 (Row 4). Each of the four types of columns consists of the same type of elements, the only difference is in the length of the HEB 300 and in the number of internal ribs, which correspond to a certain step of 500 mm. (Figure 14 and Table 9)

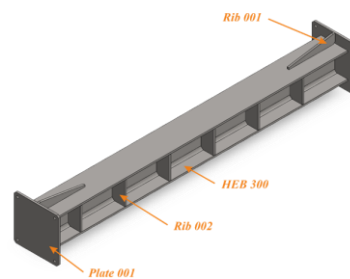


Figure 14: Base column design C1-C2-C3-C4

Table 9. C1-C2-C3-C4 components

Component	Qty.	Length / Drawing
HEB 300	5	3338 mm
HEB 300	5	4176 mm
HEB 300	5	5172 mm
HEB 300	5	6000 mm
RIB 001	80	Drawing R001
RIB 002	340	Drawing R002
Plate 001	40	Drawing P001

In Figure 15 are indicated the additional elements that give the roof slope and are connected to the crossbeams. They are denoted conditionally as C5, following the sequence of elements. For each column, its dimensions remain the same. Their description and their total number are calculated according to all columns, and it is shown on Table 10.

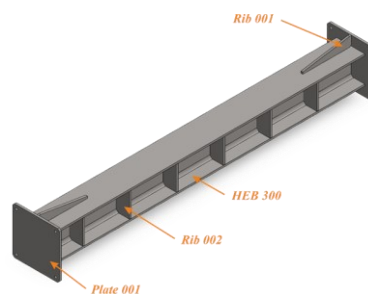


Figure 15: C5 column design

## 8.2 Beams

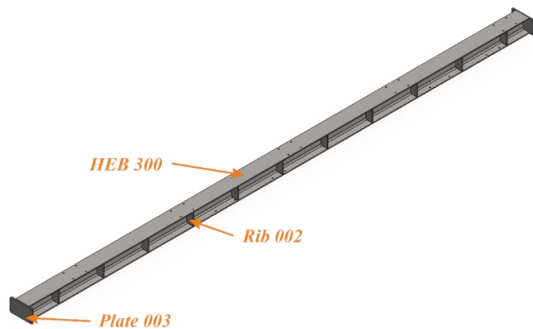


Figure 16: B1 / B2 frame design

Table 11. B1/B2 components

Component	Qty.	Length / Drawing
HEB 300	10	11 170 mm
RIB 002	220	Drawing R002
Plate 003	20	Drawing P003

The structure has two types of crossbeams of different lengths. The length is tailored to the possibility of their placement transversely to all four types of columns, following the slope of the roof – B1 and B2.

Figure 16 shows the construction of beam B1. B2 has the same type of construction. Their element description is calculated and shown on Table 11.

## 8.3 Frames

The structure also has three types of longitudinal frames of different lengths. The length is tailored to the possibility of placing them longitudinally along the entire length of a row of columns, following the length of the roof – F1, F2 and F3. Figure 17 shows the construction of frame F1. F2 and F3 have the same construction but different dimensions and different weight.

The design principle is the same. The frames are constructed to easy connect to the columns below and to have a strong and secure connection.

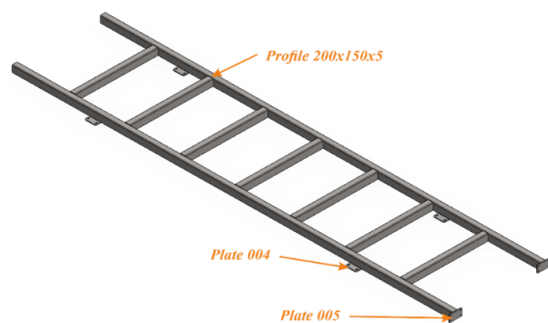


Figure 17: F1 / F2 / F3 frame structure

Table 12. F1 / F2 / F3 / F4 frame components

Component	Qty.	Length / Drawing
Profile 200x15x5	20	12 000 mm
Profile 200x15x5	10	4920 mm
Profile 200x15x5	85	2250 mm
Profile 200x15x5	20	1052 mm
Profile 200x15x5	20	331 mm
Plate 004	90	Drawing P004
Plate 005	40	Drawing P005

Frame F4 supports the structure. It is installed between the columns and crossbeams, providing additional support against slipping and shifting of the entire structure due to its heavy weight. Purely mechanically, the frame does not allow the movement of the remaining beams. Similar frame are installed on all columns. (Figure 18). Table 12 lists all the needed components for the frames.

## 8.4 Total Amount of Material and Final View of the System

In Table 13 is calculated the total amount of material required to build the metal structure of the parking system. All elements of the structure are considered – columns, beams, and frame. With the table information, the material cost and weight of the construction can be approximately calculated. With this information, a future analysis of the structural integrity can be presented with a calculation of the load capacity.

Table 13. Material

Component	Qty.	Length / Drawing
HEB 300	-	234 730 mm
Profile 200x15x5	-	513 330 mm
RIB 001	120	Drawing R001
RIB 002	640	Drawing R002
Plate 001	60	Drawing P001
Plate 002	20	Drawing P002
Plate 003	20	Drawing P003
Plate 004	90	Drawing P004
Plate 005	40	Drawing P005

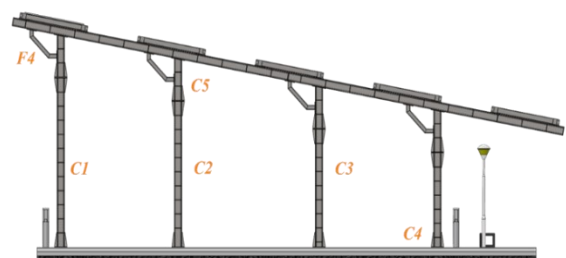


Figure 19: Side view of the structure

Figure 19 shows the side view of the construction with the tilt and the main column position clearly visible.

Here the height difference is clearly visible, confirming the choice of the 10° tilt. In the case of 25 - 30 - 35° the structure will not be structurally optimized.

Figure 20 shows the full metal construction installed, with a detailed description of each main element and the beams and frame positions.

Figure 21 is the same image with full photovoltaic panels mounted on top of the construction.

All elements of the 3D model are described previously in the preliminary plan with each position kept according to the design.

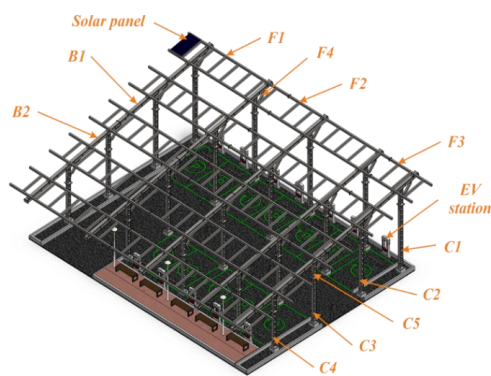


Figure 20: Metal construction of the parking system

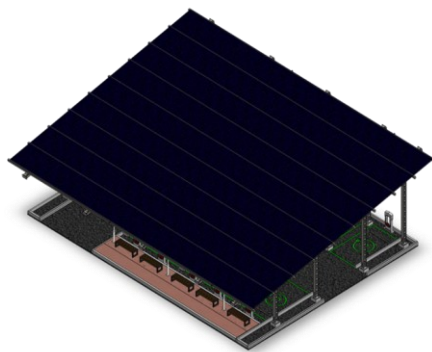


Figure 21: Solar parking system

## 8.5 Structural Calculations

The proposed PV parking structure consists of four inclined cantilever portal frames composed of HEB300 steel columns rigidly connected to roof beams. The canopy supports photovoltaic panels mounted at a fixed tilt angle of 10°. The column heights vary progressively from 4,8 m (front row) to approximately 7,8 m (rear row).

The structural system is designed and verified according to:

- EN 1991-1-3 (Snow loads)
- EN 1991-1-4 (Wind loads)
- EN 1993-1-1 (Steel structures)
- Steel grade: S355.

### 8.5.1 Dead Load

- Heavy frames - (F1, F2) - 10 . 1141 kg = 11410 kg;  
 - Light frames - (F3) - 5 . 500 kg = 2500 kg;  
 - Beams - (B1, B2) - 10 . 1500 kg = 15 000 kg;  
 Total frame mass - 28 910 kg;  
 Total force - 28 910 . 9,81 = 283 607 N = 283,6 kN;  
 Distributed load / column - 283,6 kN / 20 = 14 kN per column;  
 Installed capacity: 138,6 kWp;  
 Assume ~15 kg per m<sup>2</sup> (typical module + mounting);  
 Approximate area: 620 m<sup>2</sup>  
 Panel load: ~0,15 kN per m<sup>2</sup>  
 This gives us" 620 . 0,15 = 93 kN;  
 Per column: 93 kN / 20 columns = 4,65 kN per column;  
**Total Dead Load per Column:**  
**14 + 4,65 = 18,65 kN.**

### 8.5.2 Snow Load

Ground snow load - sk=1.0 kN/m<sup>2</sup>;  
 Shape coefficient - μ=0.8 (slope 10°);  
 Snow load - s = 0.8 kN/m<sup>2</sup>;  
 Total snow force:

**Stotal = 0,8 . 620 = 496 kN;**  
**Scolumn = 496 / 20 = 24,8 kN (per column);**

### 8.5.3 Wind Load

Basic wind velocity for Sofia: Vb≈24 m/s;  
 Velocity pressure: pb = ≈0,6 kN/m<sup>2</sup>;  
 For 10° tilt:  
 Assume net pressure coefficient: Cpe≈0.8;  
 Wind pressure: w=0,6 . 0,8=0.48 kN/m<sup>2</sup>

**Total wind force: Wtot = 0,48 . 620 = 297,6 kN**  
**Wcolumn (W) = 297,6 / 20 = 14,88 kN (per column);**

### 8.5.4 Load Combinations

- Snow + Dead Load:

$$N_s = 1,35 \cdot F + 1,5 \cdot F \quad (13)$$

$$N_s = 1,35 (18,65) + 1,5 (24,8) = 62,4 \text{ kN}$$

This is the design axial compression force with no significant bending from snow (vertical load assumed concentric).

- Wind (Critical for Bending)

$$F_w = 1,5 \cdot W \quad (14)$$

$$F_w = 1,5 \cdot 14,88 = 22,32 \text{ kN};$$

h – maximum height of a column – 7,8 m;

$$M = F_w \cdot h = 22,32 \cdot 7,8 = 174,1 \text{ kN/m}$$

### 8.5.5 Section Resistance of HEB300 (S355)

- Section modulus:  $W = 2.77 \times 10^6 \text{ mm}^3$

$$[M] = \frac{W \cdot \sigma_y}{10^6} \quad (15)$$

$$[M] = 983 \text{ kM.m}$$

$$\eta M = \frac{M}{[M]} \quad (16)$$

$\eta M = 0,19$

This means the structure bending is only 19 % from the maximum allowable bending stress. Safety – 5.

**The axial resistance is around 10 times more.**

$\eta A = 0,02$ .

#### Results:

- Bending from wind governs design.
- Axial load is negligible relative to section capacity.
- Utilization is below 20%.
- The columns are significantly over-safe from pure section strength perspective.

## 9. Economical Analysis

The economical analysis will include several key points:

- Investment cost – IC;
- Operating cost – OC;
- Annual revenue / savings;
- Payback period;
- Comparison with alternative solution (grid-only EV charging).

Table 14 show the main cost for the system:

Table 14. Cost

Component	Type [€]	Total [€]
PV System	1000 / kWh	138 600
Steel / Material	2,5 / kg	100 000
Foundation	500 / column	10 000
Charging station	2000 / station	24 000
Other	-	15 000
TOTAL	-	287 600

PV system – 138, 6 kWh

$$PV \text{ system} = 138,6 \cdot 1200 = 166 \ 320 \text{ €}$$

The HEB profiles are calculated by length/kg and also the Rectangular profiles. With basic price for the

steel + manufacturing and welding of the parts, the basic price is 3 € / kg.

Total calculation – 287 600 €;

Operating cost – 3000 € / year.

This includes – Cleaning, inspection and repairs.

Revenue with 10° tilt – 183 090 kWh;

Price: 0,2 € / kWh

$$183 \ 090 \cdot 0,2 = 36 \ 618 \text{ € / year}$$

$$36 \ 618 - 3000 = 33 \ 618 \text{ € / year}$$

Return period:

$$287 \ 600 / 33 \ 618 \approx 8 \text{ years}$$

Typical Payback Periods

- 3–5 Years: Highly efficient systems with strong incentives, high usage, or high local electricity rates.
- 5–8 Years: The average range for many commercial solar carport installations.
- 8–12 Years: Typical, especially for projects without high incentives or in areas with lower utility rates

**If EV charging is supplied entirely from grid:**

$$183 \ 090 \cdot 0,2 = 36 \ 618 \text{ € / year}$$

Over 25 years: 915 450 €

With PV system: Initial - 287 600 €;

Operating cost = 3000 · 25 = 75 000 €;

**Total: 362 600 €**

$$\text{Savings - 25 years: } 915 \ 450 - 362 \ 600 = \mathbf{552 \ 850 \text{ €}}$$

## 10. Conclusions

This study developed and validated an integrated structural–energy design methodology for an eco-efficient photovoltaic parking lot intended to support electric vehicle charging infrastructure under the climatic conditions of Sofia, Bulgaria. Unlike conventional approaches that optimize photovoltaic systems solely based on energy yield, the present work incorporated structural feasibility, load verification and economic performance into a unified assessment framework.

The energy analysis demonstrated that while the theoretically optimal tilt angle for maximum annual photovoltaic production at the studied latitude is approximately 30–35°, a reduced tilt of 10° maintains approximately 93% of the maximum achievable annual energy yield.

Structural verification of the metal structure and column system under combined dead, snow, and wind loading showed that the selected 10° configuration significantly limits column height (4,8–7,8 m), reduces base bending moments, and ensures

low utilization ratios according to EN 1993-1-1. Increasing the tilt angle to energy-optimal values would substantially increase structural demand, column slenderness, and material consumption, thereby reducing constructability and economic efficiency.

The economic analysis indicates that the proposed PV-integrated parking canopy system has an estimated total investment cost of approximately 287 600 €, with annual operating costs of approximately 3000 €. Based on an annual energy production of 183 MWh and an electricity price of 0.2 €/kWh, the system generates approximately 36,000 € net annual benefit. The simple payback period is approximately 8 years. Compared to grid-only EV charging over a 25-year operational period, the system reduces cumulative electricity expenditure by more than 550,000 €, demonstrating strong economic viability in addition to structural and environmental benefits.

The results validate the central hypothesis that an integrated structural–energy optimization approach leads to a technically feasible, economically viable, and environmentally beneficial solution compared to energy-only design strategies. The selected 10° tilt represents a rational engineering compromise between energy performance, structural stability, and material efficiency.

The main limitation of the study lies in the use of simplified energy modeling and static structural verification without dynamic wind analysis or detailed life-cycle assessment. Future research should therefore focus on:

- (i) Parametric optimization of tilt angle considering structural, economic, and environmental criteria, simultaneously implemented in the 3D model;
- (ii) Life-cycle assessment and embodied carbon analysis of steel-intensive PV canopy systems;
- (iii) Dynamic wind and seismic assessment for different geographic regions;
- (iv) Integration of energy storage systems and smart charging management;
- (v) Long-term performance monitoring of real-scale installations.

The proposed methodology may serve as a framework for the development of scalable, structurally efficient, and economically sustainable photovoltaic parking infrastructures in urban environments.

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