

Research Article

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Design of a Modular Multipoint Electric Vehicle Charging Station Powered by Wind Energy

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Abstract

The present work focuses on the design of a modular electric vehicle charging station powered by renewable energy, specifically wind energy, for installation on interurban roads. The main objective is to create a sustainable and efficient solution for charging electric vehicles, leveraging natural resources, and reducing dependence on non-renewable energy sources.

We develop a comprehensive analysis of the EV market and their energy demand to design a wind farm for powering the electric vehicle charging station. To achieve this goal, we consider critical factors such as wind speed and other environmental characteristics that influence the efficiency of wind energy generation. We evaluate the design through a study of monthly and hourly coverage, developing an algorithm to simulate the operation of this charging station under current demand conditions.

The modular design of the charging station allows for flexible scalability, adapting to different capacity needs and future expansion. The study concludes that the new design is beneficial not only for the economy but for the environment. We propose a system optimization, considering future technological advancements and possible improvements in integration with the electrical grid and other renewable energy systems.

Keywords: Electric Vehicle, Charging Station, Technology, Modular Design, Wind Farm, Simulation, Sizing

1. Introduction

The electric vehicle implementation in the private and public transportation sectors represents a challenge for our society [1-5]. National and supranational authorities, pushed by the scientific and technical reports warning on the continuous growth of vehicle greenhouse gasses emissions, which contribute to climate warming, are dictating rules addressed to replacing internal combustion engines (ICE) with electric motors [6-9]. In the past year of 2023, a prestigious newspaper, The Economist, published an article saying that electric vehicles could be crucial for the European Union to meet its climate goals, but only if the charging infrastructure is ramped up much faster [10].

Electric vehicle charging stations are a question of economy, technology, and design [11-16]. Car manufacturers develop a specific charging socket to avoid using universal chargers with their brand's vehicles [17-19]. The multiple charging socket type

forces the charging station manufacturers to design a complex configuration to give service to the many charger configurations [20-23]. This situation results in higher investment and maintenance costs and the need for larger areas and more complicated designs.

On the other hand, the variable electric vehicle operating voltage, with values between 360 V and 480 V, further complicates, if possible, the charging station design and the energy supply [26- 29]. The recent trend of manufacturing electric motors at 800 V operating voltage adds complexity to the already tangled design. A full service to all types of electric vehicles should include different socket types and electric vehicle-matching operating voltage supply. The large combination number of charging configurations reduces the economic viability of a charging station with all options.

Economic profitability is a crucial factor in charging station \mathcal{L} or $\$ installation, a factor that makes the owners rarely decide to offer all $\zeta_{bat} = C_{bat} V_{bat}$ $\zeta_{bat} = C_{bat}V_{bat}$ (1)
chances of voltage supply and socket type [30-33]. Since stopping for battery recharge is mandatory when traveling long distances Battery capacity deriver because of the reduced electric vehicle driving range compared to discusse of the reduced credite ventile diffulng range compared to dispenses on enarge or discharge rate conventional cars, the uncertainty of finding a suitable charging [60]. point at any charging station provokes rejection in many drivers when buying an electric vehicle [34-36].

An additional problem derives from the availability of charging points if many vehicles stop at the charging station to refill the rate, and f_c is the batter battery. Today, time is precious, and drivers search for the by $[60]$. minimum delay in charging batteries, especially if they come from the conventional vehicle market powered by internal combustion *C* engines, where refilling a gas tank takes a short time [37-41].

The political measurements to reduce greenhouse gasses (GEI) $\frac{b}{2}$ is the battery charge or discharge current. $\frac{1}{2}$ is the battery charge or discharge current. The power I_{bat} is the battery charge or discharge current. generation; in this latter case, power plants progressively abandon
focal finals in fouon of renounchlo energies [42,441, Wind energy. The summat bettery sensaity at any state of fossil fuels in favor of renewable energies [42-44]. Wind energy The current battery capac has become the main contributor to the renewable energy mix due $\frac{1}{2}$ to the on-shore and off-shore installations [45-48]. $\sqrt{SOC} = C SOC$ $\frac{1}{2}$ mix due

Connecting wind farms to electric vehicle charging stations reduces grid dependence and contributes to preserving the environment [49-53]. Besides, wind farms operate as distributed environment $[49-33]$. Besides, which has operate as distributed the relation. power supply system for specific applications like electric vehicle charging stations [54,55].

The interconnection between wind farms and electric vehicle charging stations reduces energy losses if located nearby, limits the power load in the electric transportation lines, and lowers reactive power in the network, which requires lower power generation at the power plant [56.57] the power plant [56,57]. *Phattery voltage with super-index super-index state state*

discharge state as:
Therefore, we should develop a strategy to adapt the charging station to variable operating conditions with minimum changes $(C^{\circ})^{1.0148}$ V^2 in the charging point configuration. This paper focuses on this strategy, adopting a modular design for a multipoint charging pole. The design facilitates the charging station enlargement.

2. Fundamentals

This project intends to design a hybrid modular electric vehicle
observing station novemed by wind approximated by batteries. The charging station powered by wind energy assisted by batteries. The ϵ and C^{o} $\int^{1.0148} V^2$ project goal is to take advantage of both growing markets, wind $t_c = \frac{\xi_{bat}}{\xi_{bat}} = \frac{0.9541}{\xi_{bat}}$ energy, and electric vehicles, and contribute to a more sustainable future development, promoting clean mobility and reducing fossil fuel dependence.

Pure electric vehicles require a power supply to charge batteries, which depends on the model and driving range [58,59]. The most characteristic parameter regarding the EV power requirement is the battery energy capacity, which defines how much energy a battery contains at full state-of-charge (SOC). This value depends on the battery capacity and operational voltage, as in Equation 1. *C C C C bat bat*

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inty of finding a suitable charging. [60] [60]. *^o C fC bat C bat* (2) depends on charge or discharge rate according to the expression $[60].$

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C_{bat} = f_C C_{bat}^o \tag{2}
$$

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f_C = 0.9541 \left(\frac{C_{bat}^o}{I_{bat}} \right)^{0.0148}
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\n $f_C = 0.9541 \left(\frac{C_{bat}^o}{I_{bat}} \right)^{0.0148}$

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SOC = \frac{V_{bat}}{V_{bat}^o}
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 (5)

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\xi_{bat} = 0.9541 \frac{\left(C_{bat}^o\right)^{1.0148}}{I_{bat}^{0.0148}} \frac{V_{bat}^2}{V_{bat}^o}
$$
 (6)

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The charging time depends on the current rate and battery voltage depends on the current rate and battery voltage on the current rate and battery voltage *b* on the current rate and battery voltage

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\n\n (7)\n

 I_c and V_c are the charging current and voltage. The product I_cV_c represents the required power for battery charging.

batteries I_c and V_c are the charging current and volt
represents the required power for battery ch *C* $\frac{1}{2}$ *C* $\frac{1}{2}$ presents the required power for battery charging. I_c and V_c are the charging current I_c and V_c are the charging current and voltage. The product *Charging current and voltage. The product <i>i* the charging current and voltage. The product I_cV_c
required power for battery charging. red power for battery charging. power for battery charging. 0.0148 *IV IV CALLETY CHAIGHIS.*

3. Electric Vehicle Characteristics

The operational battery voltage has two options: matching the electric motor voltage or using a booster. The first option avoids energy losses in voltage conversion but increases battery stack complexity, cost, and required space for battery placement. The

second option involves power losses in voltage conversion at the booster but reduces the space for the battery and the number of battery cells; thus, the investment and replacement cost [61-64].

charging pole, carrying electric current at the selected voltage and power. Unfortunately, the connecting socket is not normalized; therefore, we can find various types corresponding to different World regions and electric vehicle manufacturers. Four models of connecting sockets are used today in the electric vehicle industry (Figure 1).

The interconnection between the electric vehicle and the charging station runs on a specific socket, communicating the car and the

regions and electric vehicle manufacturers. Four models of connecting sockets are used

Figure 1: Models of Electric Vehicle Sockets [65].

Figure 1 Models of electric vehicle sockets [65] E current (AC) for variable input voltage, current, and \sim 2 show the world region and electric characteris power. Depending on the charging speed, we classify the socket to every socket model. Electric vehicle sockets may operate at continuous (DC) or alternate current (AC) for variable input voltage, current, and

types into two categories: slow and fast charge mode. Tables 1 and 2 show the World region and electric characteristics corresponding to every socket model.

Socket type	J1772		Mennekes	GB/T	Supercharger	
World region	Japan	USA	Europe	China	All markets	
Maximum power (kW)	1.9	19.2	$4 - 2.2$	$7 - 27.7$	$7.7 - 11.5$	
Input voltage (V)	120	240	250-480	250-400	$120/240 - 208/250$	
Maximum current (A)	16	80	$16 - 32$	$16 - 32$	$16/32 - 48$	

Table 1: World Region and Characteristics of Electric Vehicle Sockets (Slow Charging Mode) [66].

Table 2: World Region and Characteristics of Electric Vehicle Sockets (Fast Charging Mode) [66].

A second relevant parameter for the electric vehicle characterization is the driving range. Since operating voltage, battery energy capacity, and driving range for electric vehicles depend on the car model, we analyze a group of 363 light-duty and 31 heavy vehicles.

The first part of the study is classifying the vehicle according to the energy capacity; the classification for light-duty and heavy cars corresponds to separate groups as shown in Table 3.

Type of vehicle	Energy capacity (kWh)	\vert Group	$\frac{0}{0}$
Light-duty	$<$ 30	A	3.0
	$30 - 50$		15.0
	50-70		28.0
	>70		54.0
Heavy duty	$<$ 200	E	23.4
	>200		76.6

Table 3: Electric Vehicle Classification as for the Energy Capacity

The second part of the study corresponds to the operating voltage. According to the literature, the electric vehicle operating voltage distribution is (Table 4) $[67]$.

Type of vehicle	Operating voltage (V)	\vert Group	$\mid \frac{9}{6} \rangle$
Light-duty	360	\mathbf{L}	3.0
	400	В	64.6
	480	◡	27.5
	800	D	4.9
Heavy duty	400	<u>تا</u>	69.4
	480		30.6

Table 4: Electric Vehicle Operating Voltage Distribution adie 4: Electric venicle Operating v \overline{C} There is the most point that the most popular There is encourage that the most popular voltages are 400 V and 480 V.

Using data from Table 4, we notice that the most popular voltages $\frac{1}{1}$ are 400 V and 480 V. Nevertheless, if we try to serve all kinds of P_{out} EVs, we should design a charging station, including all required voltages, no matter the voltage distribution.

4. Wind Farm Power Source
The generated power by a wind turbine derives from the wind turbine derive

The generated power by a wind turbine derives from the wind speed and wind turbine area according to:

$$
P_w = \frac{1}{2} C_p \rho_{air} A u^3 \tag{8}
$$

 C_p is the power coefficient, which defines the wind turbine efficiency, ρ_{air} is the air density, A is the surface covered by the In the case of Figure 2, this range wind turbine rotor blade, and u is the wind speed. $point$, the wind energy is negligity

> Considering the mechanic transmission and electricity generation, the wind turbine output power is:

$$
P_{out} = \frac{1}{2} C_p \rho_{air} A u^3 \eta_v \eta_{gen}
$$
 (9)

η is the efficiency with sub-indexes *tr* and *gen* for mechanical transmission and electric generator.

Since the wind resource is variable, we must select an appropriate to:
location where wind energy is high enough to cover the charging
the same dense of the substitute of the wind form leading station's power demand. The selection of the wind farm location (8) depends on the wind resource, which derives from the Weibull $\frac{1}{2}$ distribution (Figure 2). The Weibull distribution shows the defines the wind turbine probability of occurrence on a wind speed within a specific range. the surface covered by the In the case of Figure 2, this range extends to 30 m/s; beyond this ind speed. point, the wind energy is negligible.

The Y-axis in Figure 2 indicates the relative frequency of any wind and electricity generation, The Y-axis in Figure 2 marcates the relative requency of any wind
speed (X-axis). According to data in Figure 2, the most probable $\frac{1}{2}$ and the value of power is.
wind speed (x axis). According to data in 1 igure 2, the most product Considering the mechanic transmission and electricity generation, the wind turbine

Figure 2: Weibull Distribution Figure 2. Weidun Distribution

efficiency of 91% for an output power range between 15 70] \mathcal{L} and \mathcal{L} and 25 kW (Figure 3) \mathcal{L} Once the wind resource is known, we size the wind turbine and 25 kW (Figure 3), a transmission efficienc once the which resource is known, we size the which thome and 25 kw (Figure 3), a transmission efficiency of 40% and μ to supply the required power. Considering an average electric wind turbine efficiency of 40%, the s generator efficiency of 91% for an output power range between 15 70].

resource is known, we size the wind turbine and 25 kW (right 3), a damsifiesion efficiency of 34.1% , and a equired power. Considering an average electric wind turbine efficiency of 40% , the surface power density and 25 kW (Figure 3), a transmission efficiency of 94.1%, and a 70].

$$
\frac{P_{out}}{D^2} = (\pi/4)(0.5)(0.4)(1.225)(12^3)(0.941)(0.91) = 284.7 W/m^2
$$
 (10)
d turbine diameter.

ameter. *D* is the wind turbine diameter.

Figure 3: Electric Generator Efficiency

Applying the power density from Equation 10 to a wind turbine diameter between 20 and 40 m, we obtain the following output power (Figure 4):

Figure 4: Wind Turbine Output Power vs Rotor Blade Diameter

We observe that, for a 40 m diameter, the wind turbine produces an engineering design consists of a output power of 455 kW. The number of wind turbines depends on the charging station's energy requirements.

4.1 Engineering Design

4.1 Engineering Design
The engineering design of the electric vehicle charging station resources, easy access, available space, and connectivity to the density and on secondary roads with reduced vehicle circulation, for this configuration is 211 m2. The space dedication the proposed system has a modular design easily adapted to the vehicle parking during the charging process is 5 m should focus on specific requirements like enough wind energy grid. Since we try to provide battery charging service for electric vehicles both on interurban roads or highways with high traffic needs of the users as well as growing proportionally to the increase in traffic in the location of the charging station.

Based on a modular structure for the charging station, the $\frac{1}{2}$

station's energy requirements. 800 V. The number of charging poles is variable depending on the charging station configuration and the traffic density of the road. engineering design consists of a multipoint charging pole, which supplies energy at the selected voltages: 360 V, 400 V, 480 V, and We place the charging poles in parallel, as in Figure 5.

h on interurban roads or highways with high traffic car's front fin, the electric vehicle position reverses. The total area which is enough for a conventional right-duty vehicle. We
he location of the charging station. reserve a 1 m wide aisle for the charging poles and another aisle of secondary roads with reduced vehicle circulation, the proposed system in the proposed system of the parking space. The position of the electric vehicle corresponds to the case where the charging connection is at the rear of the vehicle or in the car's rear fin; if the charging connection is located at the front or in the for this configuration is 211 m2. The space dedicated for electric vehicle parking during the charging process is 5 m long and 2.3 m wide, which is enough for a conventional light-duty vehicle. We

Figure 5: Layout of the Charging Station

The charging station layout includes three charging places for every built-in socket type depends on the World zone pole, allowing three electric vehicles to charge simultaneously; manufacture the charging station; the engineerin therefore, the charging pole configuration should have three sockets with the same or different supplying voltage.
sockets with the same or different supplying voltage.

4.2 Charging Pole Configuration

Every charging pole includes three voltage sockets, vertically distributed and with easy access for drivers. The charging pole

mg three electric vehicles to charge simultaneously; manufacture the charging station; the engineering design only electric vehicles to configuration should have three includes fast charging sockets: Combo Type 1 for USA and built-in socket type depends on the World zone to which we its influencing geographic area, Combo Type 2 for European countries, CHAdeMO for the Japanese market, and GB/T for China and neighboring area. Charging stations specifically built for Tesla models equip charging poles with supercharger sockets. Figure 6 shows the schematic view of a charging pole.

Figure 6: Charging Pole Prototype. Left: Model 1; Center: Model 2; Right: Model 3

Lanes 1, 2, and 3 in Figure 7 equip the charging poles of model 1, while lane 4 equips model 2. This distribution corresponds to the demand voltage by electric vehicle users, with 400 V and 480 V as the most popular and 800 V as the lowest demanded voltage.

Applying the charging pole distribution to the charging station layout, we develop the following engineering design (Figure 7).

Figure 7 Charging station layout **Figure 7:** Charging station layout

region where the charging station is (USA, Europe, Japan, or double-side charging pole with different socket ty China); however, to service imported vehicles with different (Figure 8). The socket type on the charging pole corresponds to the World

socket types, we have modified the engineering design, building a double-side charging pole with different socket type on each side (Figure 8).

Figure 8: View of the Charging Pole Prototype (Model 5)

4.3 Charging Mode

The charging station provides a configurable charging mode fast, and ultrafast speed, corresponding for the users; therefore, the driver can select the charging mode 50 , 100, and 150 kW. Lov depending on the available time or charge needed. Charging speed depends on battery energy capacity and power supply; nowadays, a compromise solution between battery energy capacity and power supply; nowadays, a compromise solution between battery the power supply ranges from 3.7 kW for domestic uses to 250 kW reduced charging time, and it is prob for public charging stations, which may charge an electric vehicle Fast and ultrafast charging speed and preserve integrations, which may charge an electric vehicle Fast and ultrafast charging speed and battery in less than 15 minutes. stations, which hay charge an electric venicle Γ ast and unitariast charging speed and reduced Γ

e and a reduced the speed on this project, we propose four charging speeds: low, medium, fast, and ultrafast speed, corresponding to a supplying power of 25, 50, 100, and 150 kW. Low charging speed preserves battery health due to the low intake current. Medium charging speed represents a compromise solution between battery health preservation and reduced charging time, and it is probably the most suitable option. Fast and ultrafast charging speed applies to people in a hurry, 15 minutes. Searching for a minimum delay in a battery charging stop. The ultrafast speed is associated with the highest operating voltage, 800 V. 800 V.

Figure 9 Charging protocol flowchart **Figure 9:** Charging Protocol Flowchart

The charging mode selection by the user is associated with a protocol ruled by an algorithm developed for this project. This protocol pursues to provide the user easy access to practical charging pole configure 5 and the charging station layout shown in Figure 5 and the charging pole configure 5 and the charging pole configure 5 and the charging information and selectable charging options. The developed distributed in the following way: protocol follows the flowchart shown in Figure 9. The developed V , 4 for 480 V, and one for 800 for 360 V, five for 400 V, and 360 V, five for 400 V, and 360 V. The power associated with t mormation and selectable enarging options. The developed distributed in the following wave the flowchart chown in Figure 9. The developed $\Delta V = 4$ for 480 V and c

state of charge

Mode 1. The user selects the charging time and speed; the charging battery capacity. Since people arrivers pole provides information about the battery state of charge and the interurban road or a highway look electric vehicle driving range at the end of the process the minimum charging time for a function

· Mode 2. The user selects the supplied charge percentage and the energy capacity and socket power charging speed; the charging pole provides information about the vehicle operating voltage relates to
charging time and final bettery state of charge charging time and final battery state of charge our case, the relation is 48 kWh for the charge

• *Mode 3*. The user selects the driving range after the charging kWh for 480 v, and 200 V, and 200 V, and 200 V. process; the charging pole provides information about the charging time and the final battery state of charge T_{max} and T_{max} for T_{max} function T_{max} T_{max} for T_{max} for T_{max} $\frac{1}{2}$ charging time and man battery state or enarge *C C*

4.4 Power Demand

Applying the charging station layout shown in Figure 5 and the charging pole configuration from Figure 6, we have 12 sockets distributed in the following way: two for 360 V, five for 400 V, 4 for 480 V, and one for 800 V. The power associated with every socket derives from the charging time and electric vehicle battery capacity. Since people arriving at a charging station on an interurban road or a highway look for a fast charge, we estimate the minimum charging time for a full charge depending on battery energy capacity and socket power supply (Table 5). The electric vehicle operating voltage relates to the battery energy capacity; for our case, the relation is 48 kWh for 360 V, 64 kWh for 400 V, 92 arging kWh for 480 V, and 120 kWh for 800 V.
arging *I A A A <i>A I A <i>A A <i>A <i>A <i>A <i>A <i>A <i>A <i>A <i>A <i>A* FIGHT TOO $\frac{1}{20}$ and $\frac{1}{20}$ and $\frac{1}{20}$ and $\frac{1}{20}$ over $\frac{1}{20}$. *I A I A* k and k of k and k and k and k of k and k of k and k and

	Battery energy capacity (kWh)		
$\frac{1}{8}$	64	92	120
58	77	110	144
44	59	85	111
32	40	61	80
24	32	46	60
	Socket power supply (kW)		

Table 5: Estimated Time (Min) for Battery Fully Charge [71]. \Box Table 3: ESU We determine the battery capacity using the relationship of the relationship of the relationship of the relations of the

We determine the battery capacity using the relation:

$$
C_{bat} = \frac{\xi_{bat}}{V_{op}}\tag{11}
$$

 ζ_{bat} is the battery energy capacity, and V_{op} is the operating voltage.

Applying the setup values for the various operating voltages, we historian: obtain: *ξbat* is the battery energy capacity, and *Vop* is the operating voltage. α botain: α btain: α

$$
C_{bat}^{360} = \frac{48000}{360} = 133.3 \ Ah; C_{bat}^{400} = \frac{64000}{400} = 160 \ Ah \qquad \zeta_{ch-s}^{500}
$$

$$
C_{bat}^{480} = \frac{92000}{480} = 191.7 \ Ah; C_{bat}^{800} = \frac{120000}{800} = 150 \ Ah \qquad \text{then} \qquad \text{cons}
$$

Because the charging sockets are all of the fast charging type, the charge current is: **All of the charging sockets are all of the fast charging type, the fast charging type, the fast charging type, the fast charging type, the charging type, the fast charging type, the charging type, the c** $B = \frac{1}{2}$ **WIND FARM** marging type, the \hat{c} ast charging type, the charging station.

$$
I_C^{360} = \frac{133.3}{(58/60)} = 138 A; I_C^{400} = \frac{160}{(77/60)} = 125 A
$$

$$
I_C^{480} = \frac{191.7}{(85/60)} = 135 A; I_C^{800} = \frac{150}{(60/60)} = 150 A
$$
 (13)

Therefore, the socket power is: Therefore, the socket power is: $T_{\rm eff}$ the socket power is $\frac{1}{2}$ T and T is:

$$
P_1^{360} = (138)(360) = 50 \, kW \, ; \, P_2^{400} = (125)(400) = 50 \, kW \quad \text{(14)}
$$

relation: Computing all sockets, the maximum required power if all sockets operate simultaneously is: simultaneously is:

(11)
$$
P_T = (2)(50) + (5)(50) + (4)(65) + (1)(120) = 730 \text{ kW}
$$
 (15)

Energy demand depends on charging station coverage factor and he operating voltage. socket usage time. Assuming a 75% coverage factor during day hours and $25%$ at nighttime, which is a consistent value for a voltages, we highway or interurban charging station, the daily energy demand is: *δ***_{***b***} is the operation of** *V***_p is the operation of** *V* perature voltage. Socket usage time. Assuming a 75% coverage factor during day
hours and 25% at nighttime, which is a consistent volue for a liours and 20% at ingitually, which is a consistent value for a perating voltages, we internet or interurban enarging station, the dairy energy demand

$$
\xi_{ch-st} = (0.75)(12)(730) + (0.25)(12)(730) = 8760 \text{ kWh} \quad (16)
$$

The energy value in Equation 16 corresponds to a monthly energy $= 150$ *Ah* demand of 262.8 MWh, considering 30 days per month and daily 20 days per month and daily constant use of the charging station. $\frac{1}{2}$ The energy value in Equation 16 corresponds to a monthly energy demand of 262.8 μ *ch st* (0.75)(12)(730) (0.25)(12)(730) 8760 *kWh* (16)

4.5 Wind Farm

The wind farm design and sizing depend on the wind resource and The wind resource and power demand from the charging station. We base the calculation $5 \hat{A}$ $\overline{600}$ = 125 A of this latter parameter on a critical power demand for sixteen (13) working hours per day and a coverage factor of 75%. We define the (12) working hours per day and a coverage factor of 75%. We define the
 -150 λ coverage factor as the ratio of charging poles' operational time over $\overline{0}$ = 150 A the global daily time; in our case, the coverage factor corresponds to 12 hours. On the other hand, the average power demand during electric vehicle charging is 150 kW, applying statistical analysis to $(400) = 50 \; kW$ the charging poles; applying these values, we obtain a daily energy $\frac{100}{2000}$ = 120 LW (14) demand of 1800 kWh per charging pole, equivalent to 21696 kWh $f(800) = 120 \text{ kW}$ for the charging station [72]. The wind cause are go and resource and power demand from the wind resource and power demand from the charging station. We hase the calculation

Since the energy demand is moderate, we select intermediate wind $Sine \, \theta$ end $Sine \, \theta$ $Sinee$ the energy demand is moderate, we select intermediate wind where the energy with a 6 m eventure, we select intermediate a final $Sinee$ the energy demand is moderate, we select intermediate wind where the energy withing to inducting, we serve intermediate a fit

turbines in the 500 kW to 1 MW range, with a 660 kW power turbine according to wind resource and wind turbine diameter [73]. The selected model is VESTAS V47 [74]. Table 5 shows the technical characteristics of the wind turbine.

Table 5: Wind Turbine Technical Characteristics Fabie 5. White Turbine Technical Characteristics

Using this wind turbine type, the wind farm consists of 2 turbines Figure 10 shows the power curve correspondin to supply a global power of 1320 kW, representing 1.8 times more turbi power than required at the peak point charging station. The surplus of 80% in power supply is necessary since the wind farm does not supply the maximum power continuously.

Figure 10 shows the power curve corresponding to the wind turbine.

Using data from the New European Wind Atlas, we determine the statistical parameters regarding the wind resource. Figure 11 shows the results of the database statistical treatment for the monthly evolution [75].

Averaging over the whole year, we obtain the following results: $s_{\rm F}$ and whose j can, we concentrate around $\frac{1}{2}$ around $\frac{1}{2}$

Month	Average wind speed (m/s)	\mathbf{v}_{av}	Reference wind speed (m/s)		
Year \rightarrow	11.64	1.9973	19.35	2.1454	13.10

Table 6: Statistical Results of the Monthly Wind Energy Resource radie v. Stauslical results of the monthly wind energy resource

We notice that the yearly average wind speed matches the peak value in Figure 2 by 97%. Besides, the year average standard around the wind speed peak value, the wind speed deviation, σ_{av} is near 2, meaning that the wind speed distribution deviation, G_{av} , is iiear 2, inealing that the wind speed distribution (1.125, which imminizes the concentrates around a center value, which favors a good wind farm accuracy in power determination. design. On the other hand, the average to the reference wind speed is 0.60, which indicates that the performance of the wind resource speed distribution ($1 \le c/u_m < 1.15$). is near ideal $(R=0.593)$.

nat the yearly average wind speed matches the peak speed distribution behaves as a Rayleigh one $(k = 2)$, meaning that around the wind speed peak value, the wind speed distribution is symmetric, which minimizes the calculation and improves accuracy in power determination. The c-coefficient to average wind speed ratio, $c/u_{av} = 1.125$, is in the range for a good wind speed distribution $(1 < c/u_{av} < 1.15)$.

Regarding Weibull coefficients, *k*, and *c*, we realize the wind Repeating the calculation for the hourly distribution, we obtain nts, k , and c , we realize the wind (Figure 12). Averaging over the day, we have the following results:

Table 7: Statistical Results of the Hourly Wind Energy Resource

Figure 12: Wind Resource Daily Evolution for the Selected Location

As in the case of monthly evolution, the average wind speed monthly energy generation over the year by multip Figure 3 and $\frac{1}{2}$ by 96.8%. Likewise, the standard deviation remains low, with a value near 2, proving that power value from the power wind turbine curve. proving the daily wind speed distribution concentrates around a centered generated energy for every speed bin provi matches the peak value in Figure 2 by 96.8%. Likewise, the value.

From the statistical analysis, we calculate the average daily and

monthly energy generation over the year by multiplying the speed bin from the wind speed frequency curve by the corresponding power value from the power wind turbine curve. The sum of the generated energy for every speed bin provides the global energy generation. Figure 13 and Table 7 show the monthly energy generation and coverage factor, while Figure 14 and Table 8 account for the daily case.

Dashed line in Figure 13 represents the average daily energy consumption in the charging station.

Month	January	February	March	April	May	June
CF(%)	107.7	27.5	75.4	52.8	38.3	18.4
Month	July	August	September	October	November	December
CF(%)	22.9	21.5	36.1	81.2	127.6	41.9

Table 8: Wind Energy Monthly Coverage Factor (CF)

Figure 14 Wind farm hourly energy generation **Figure 14:** Wind Farm Hourly Energy Generation

Hour	! 0		∼								10	-11
CF(%)	30.5	28.6	28.6	27.6	26.6	25.6	26.0	125.7	25.1	25.8	29.4	36.3
Hour	12	13	14	15	16	1 ₇	18	19	20	21	າາ 44	\vert 23
CF(%)	45.0	53.4	62.3	67.2	68.7	66.8	63.4	55.1	47.4	39.7	33.3	31.1

Table 9: Wind Energy Daily Coverage Factor (CF) $\mathcal{C} \mathcal{C} \mathcal{$

Computing data from Figure 13 over the entire year, we obtain an $4.58x10^{6}$ average monthly wind energy generation of 18.756 MWh per day, $C_{bat} = \frac{C_{bat}}{400} = 11450 Ah$ which exceeds the charging station demand by a factor of 1.14, 400 enough to cover electric vehicle charging in a year. 5. Electric Engine **ELECTRIC ENGINEERING** as the enarging station demand by a factor of 1.14,
werelectric vehicle charging in a year. The electric Engineering

Nevertheless, in June, July, and August, the wind energy supply operate at intermediate high voltage does not cover the charging station needs, which requires an losses. The first step of the electric engineering designation external power supply from the grid. An alternative to the grid 690 VAC to 24 VAC (Figure 15). connection is storing the excess energy during months when wind energy generation exceeds charging station demand in batteries. Operating at 24 kV in the transm Since the energy surplus is high, this solution is not economically amount of energy, which dep reliable because of the high battery size and the associated cost. $\mathbf x$ in the transmission line saturation line saturation line saturation $\mathbf x$ in the transmission line saturation $\mathbf x$ high voltage, 24kV, to reduce the first step of the first step of the electric step of the first step of the electri ation exceeds charging station demand in batteries. Operating at 24 KV in the transmission line save rgy surprus is mgn, this solution is not economic.

In case the electric vehicle charging station operates disconnected set up at 500 m, and considering from the grid, the battery size should have the following energy diameter for the carrying curre capacity: b_n size showled have the following energy capacity: b_n show the following energy capacity: rging station operates disconnected set up a
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The superscript "+" indicates that we consider only the months wiring resistivity, section and lengt when the charging station energy demand overpasses the wind farm energy supply. I r_{center} $\frac{1}{2}$ $\frac{1}{2}$

Replacing data, we have: Replacing data, we have: Replacing data, we hav

$$
\xi_{bat} = 4.58MWh\tag{18}
$$

Considering the battery operates at 400 V to match the most $\frac{\xi_l^{\alpha}}{\xi_l}$ common operating voltage for electric vehicle charging, the better consequently in \mathbf{r} **is** and \mathbf{r} **x** \mathbf battery capacity is: $\frac{1}{2}$

$$
C_{bat} = \frac{4.58 \times 10^6}{400} = 11450 Ah
$$
 (19)

5. Electric Engineering

ver electric venicle charging in a year.
Since the wind turbines supply alternate current at 690 VAC, we d August, the wind energy supply operate at intermediate high voltage, 24kV, to reduce transmission station needs, which requires an losses. The first step of the electric engineering design is converting id. An alternative to the grid 690 VAC to 24 VAC (Figure 15).

> arging station demand in batteries. Operating at 24 kV in the transmission line saves a significant h, this solution is not economically amount of energy, which depends on the distance between the tery size and the associated cost. wind farm and the charging station. Keeping the minimum distance established by international normative for safety reasons, which is station operates disconnected set up at 500 m, and considering a cooper wiring of appropriate
and here the following angurant discrete for the compion numeral the name here are $[76]$ and the following energy diameter for the carrying current, the power losses are [76]. 2 2 *wr wr* size and the associated cost. Wind farm and the charging station. Reeping the minimum distance
established by international normative for safety reasons, which is *L tr tr* engineering design is converted to 24 VAC to 24 VA
Engineering is not economically amount of energy which depends on the distance between the

$$
\dot{\xi}_{L} = I_{tr}^{2} R = I_{tr}^{2} \frac{\rho_{wr} L_{wr}}{S_{wr}}
$$
\n(20)

 V_{tr} is the transmission line voltage and ρ_{wr} , S_{wr} , and L_{wr} are the wiring resistivity, section and length, respectively. *L tr tr n* and length, respectively.

Retrieving data from technical datasheet [77].

$$
\xi_L^{24kV} = \left(\frac{2x660x10^3}{24x10^3}\right)^2 \frac{(1.68x10^{-8})(500)}{(16x10^{-6})} = 1588 W
$$
\n(18)\n
\nthe battery operates at 400 V to match the most
\nerrating voltage for electric vehicle charging, the
\nity is:\n
$$
\xi_L^{690V} = \left(\frac{2x660x10^3}{690}\right)^2 \frac{(1.68x10^{-8})(500)}{(16x10^{-6})} = 1.92 MW
$$
\n(21)

It is evident that operating at 690 V in the transmission line is energy wasting. It is evident that harging, the
It is evident that operating at 690 V e transmission line is hat operating at 690 V in the transm (1.00) that operating at 690 V in the transmission line It is evident that operating at 690 V in the transmission line is
energy wasting. 2^{3} 3^{3 It is evident that oper 2 **600 10 1.68 10 1.68 10 1.68 10 1.68 10 1.68 10 1.68 10 1.68 10 1.68 10 1.68 10 1.68 10 1.68 10 1.68 10 1.68** It is evident that operating at 690 V in the transmission line ent that operating at 690 V in the tr t operating at 6

voltage converter *Figure 15 Layout of voltage conversion line Figure 15 Layout of voltage conversion line* **Figure 15:** Layout of Voltage Conversion Line

pole or reducing the voltage from 24 kV to a low operative value The second step of the voltage conversion line is adapting the With this architecture, we high surface from the transmission line to the unculing surface of the convention metro The second step of the voltage conversion line is adapting the with this architecture, we guarantee a constant service high voltage from the transmission line to the working voltage at of the conversion systems fails. The the charging station. Two architecture voltage conversions arise: saves money since it reduces the number of voltage lowering the high voltage to every servicing voltage at the charging in the case of individual conversion for every socke and converting this low voltage to every socket voltage.

Analyzing the two architectures, we propose a voltage drop from 24 kV to 400 V since this is the most used working voltage in electric vehicles. The proposed system uses two AC/DC voltage converters to have a redundant power supply in case of failure.

the working voltage at of the conversion systems fails. The proposed architecture also ery servicing voltage at the charging in the case of individual conversion for every socket voltage.
Contains the high voltage from the conversion line is adapting the high voltage from the high voltage from the denting the With this architecture, we guarantee a constant service even if one sions arise: saves money since it reduces the number of voltage converters, as *Figure 15 Layout of voltage conversion line* ge conversions arise. Saves money since it readees the nameer or voltage converters, as
voltage at the charging in the case of individual conversion for every socket voltage. with this architecture, we guarantee a constant service even if one
 f_{eff} is a convenient service of its The groupsed service that

om 24 kV to a low operative value
e to every socket voltage. The voltage conversion system has a principal converter from 24 kV to 400 V and three secondary converters: the first from 400 V *Figure 15 Layout of voltage conversion line* k v to 400 v and three secondary converters: the first from 400 v
propose a voltage drop from to 360 V, the second from 400 V to 480 V, and the third from 400 not used working voltage in V to 800 V. As already mentioned, an auxiliary converter from 24 tem uses two AC/DC voltage kV to 400 V remains in standby mode as a safety power supply in case of failure of the principal converter (Figure 16).

Figure 16 Electric wiring and voltage conversion **Figure 16:** Electric Wiring and Voltage Conversion

Integrating design of the voltage conversion system also the operational mode of the enarging station is
duplicates the intermediate voltage converters to warranty the algorithms is the applicability of the developed pro $\frac{1}{10}$ constant power source to the charging poles; the only socket with any charging station and working conditions. no redundant voltage converter is the 800 V since the low number The protocol code includes three steps: in the first of electric vehicles equipping this configuration does not justify defines the characteristic parameters of the chargin the voltage converter duplication. The engineering design of the voltage conversion system also

In current conditions, the main voltage converter operates with the nours
the auxiliary one in standby mode; if the main voltage converter • Porct Charge: This is the charge percentage standard modes; if the main voltage converter fails, the main voltage converter fails, the switch closes, and the power is derived to the auxiliary of-charge at the end of the charging process, In current conditions, the main voltage converter operates with one, supplying power to the charging pole and warrantying electric vehicle charge service.

6. Operational Protocol

We have developed a protocol that controls the charging station's operational mode. The protocol simulates the energy demand at the charging station when arriving at electric vehicles; the protocol works with variable battery states of charge, various voltages, and different charging modes to simulate current conditions. The goal of the protocol is to reproduce the living conditions in any electric vehicle charging station around the World with high accuracy.

The protocol parametrizes the operating conditions like electric vehicle voltage, battery energy capacity and state of charge, charging mode, ultrafast, fast, medium or slow, charging time, expected driving range, etc. The advantage of parametrizing the operational mode of the charging station through specific algorithms is the applicability of the developed protocol to almost any charging station and working conditions.

The protocol code includes three steps: in the first one, the system defines the characteristic parameters of the charging station, which are:

- Day hours: Corresponds to the daily working time; in our case 16 hours
- Porct Charge: This is the charge percentage or battery stateof-charge at the end of the charging process, selected by the user. The available range is 20% to 80%, corresponding to the charging mode 2. The user selects a value within the specific range provided by the protocol
- Consumption: Corresponds to the electric vehicle energy consumption rate in Wh/km. The protocol gives three options to the driver: 135 Wh/km, 160 Wh/km, and 210 Wh/km, corresponding to a low rate for light-duty vehicles, a medium rate for SUVs and similar vehicles, and a high rate for heavy vehicles. The driver must select one of the options according to the vehicle type.
- Driving range: Defines the traveling distance the driver wants after charging the battery. The selectable range is 25 km to 250 km in a 25 km step. Corresponds to charging mode 3
- tCharge: It is the available time for charging the electric vehicle. It is configured from 20 minutes to 2.5 hours in 10 minutes step. Corresponds to charging mode 1

• ChargeMode: Vector which defines the charging mode

In the second step, the protocol collects information about the vehicle when connected to the charging pole. The collected information is the battery voltage, state of charge, and energy capacity.

In the third and final step, the protocol calculates the required energy to charge the battery according to the provided information in the previous steps. The protocol code simulates the charging process for the voltage and charge rate defined configuration for the four charging poles. The protocol determines the number of used sockets, checking the charging station coverage factor (CF) database, which provides the CF value as a function of the day hour. The process supplies the operating time (hOper).

The protocol develops the following procedure for every charging pole and socket:

- The program randomly selects an operating voltage (VBati) using the tool "randi"
- Depending on the voltage the program randomly selects a charging rate (ChSpeed). The following restrictions to the charging rate apply: Ultrafast charging is not allowed for low operating voltage (360V), and low charging rate is not allowed for ultrahigh operating voltage (800V) neither
- The program runs a loop"while" until the cumulative socket operating time exceeds the setup value (hOper). The protocol code randomly executes one of the charging modes (Mode1; Mode2; Mode3) within the loop. Every mode returns the operating time and the energy consumption, which are stored as program variable data (Energy, time, Mode) in kWh, hours, and mode type (1,2, or 3)
- At the end of the loop, if time exceeds the hOper value, the protocol code adjusts the energy and time vectors to match the operating time
- The protocol calculates the global required energy by adding the daily energy consumption for every charging pole (TotDem)
- The code determines the monthly and daily wind energy generation, checking the wind turbine power curve and Weibull distribution from the wind energy system database
- The protocol calculates the yearly operating time (HAY) from the Weibull distribution and daily and monthly hours to determine year and monthly wind energy generation
- The program calculates the coverage of energy requirement with wind energy as a percentage by comparing the generation of a typical day for each month of the year and the hourly generation with the total demand and the demand adjusted for the hours of operation, respectively

7. Conclusions

The renewable supply systems implementation in electric stations has numerous benefits, including reducing dependence on fossil fuels and reducing the carbon footprint. Renewable energy sources adoption can also improve energy resilience, offering a more stable and secure supply in the face of fluctuations in fossil fuel prices and supply disruptions.

This work manages to design an electric vehicle charging station powered by renewable energy, specifically wind energy, demonstrating the viability and effectiveness of integrating sustainable energy sources into mobility electrical infrastructures. We develop a modular and scalable design through a detailed analysis of the market context and environmental conditions; the developed system adapts to various capacity needs and future expansion. In addition, we build simulation tools and algorithms that not only validate the system performance under current demand conditions but can also be used to optimize the design of future projects, providing a solid basis for the sustainable energy infrastructures planning and design.

These advances reduce carbon emissions and promote energy independence and efficient use of natural resources, setting a precedent for future innovations in the electric mobility field and renewable energy applications.

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