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Article

Prototype of an energy management system for a two-seater urban solar transport vehicle

Prototipo de gestión energética para auto solar biplaza de transporte urbano

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Abstract

This project begins with the design of an algorithm tailored to the functional needs of an intelligent energy management system for a two-seater solar vehicle. The algorithm is implemented in Python to simulate various operating scenarios and define the system's control logic. Based on the results, suitable hardware components—such as Raspberry Pi, Arduino, sensors, and actuators—are selected to meet system requirements. A device interconnection diagram is then created to represent the flow of energy and data, along with each component's role. The system aims to improve efficiency, ensure traceability, and promote sustainable electric mobility in Mexico, with potential for scalability and commercial application in urban and suburban contexts.commercial

Objective	Methodology	Contribution
Develop an intelligent energy management system for a solar two-seater vehicle, optimizing autonomy, traceability, and sustainability.	Development of the intelligent energy management system proposal through: Data acquisition, logical modeling, modular integration with HMI, and energy validation in controlled scenarios	Development of the foundational framework to establish a functional prototype of the energy management system in the solar two-seater vehicle

Sustainable Electric Mobility

Area: Dissemination and universal access to science

Resumen

Este proyecto inicia con el diseño de un algoritmo que responde a las necesidades funcionales del sistema inteligente de gestión energética para un vehículo solar biplaza. Posteriormente, se implementa en Python para simular distintos escenarios operativos y establecer la base del programa principal. A partir de los resultados obtenidos, se seleccionan teóricamente los componentes de hardware —como Raspberry Pi, Arduino, sensores y actuadores— que cumplen con los requerimientos del sistema. Finalmente, se elabora un diagrama de interconexión que representa el flujo de energía y datos, así como la función de cada dispositivo. El sistema busca mejorar la eficiencia, garantizar trazabilidad y fomentar la movilidad eléctrica sustentable en México, con potencial de escalabilidad y aplicación comercial.

Objetivo	Metodología	Contribución
Desarrollar un sistema inteligente de gestión energética para auto solar biplaza, optimizando autonomía, trazabilidad y sostenibilidad	Desarrollo de propuesta del sistema inteligente de gestión energética través de Adquisición de datos, modelado lógico, Integración modular con HMI, validación energética en escenarios simulados controlados	Desarrollo de las bases para establecer el desarrollo de un prototipo funcional del sistema de gestión energética en el vehículo solar biplaza

Movilidad Eléctrica Sustentable

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Introduction

This paper presents the development of a smart solar system for a two-seater vehicle, based on the design previously published in Journal Innovative Design [ISSN: 2523-6830].

The project aims to study materials and components that offer the right characteristics for prototype design and research development focused on energy efficiency and technological advancement.

The proposal will be applied to a two-seater solar car, intended for urban and suburban transport, as a sustainable and modern solution.

To implement the energy management system, capable of automatically optimising the use of solar energy and electrical storage, an algorithm will be analysed that covers both the behaviour of the system and the interconnection of the components responsible for executing the corresponding tasks.

Based on the information collected, a proposal for a functional and sustainable prototype will be developed, tailored to the needs of the two-seater solar vehicle for urban transport.

1. Background

In previous stages, the project began in August 2016 with the development of a single-seater solar car prototype for urban-suburban transport, designed to compete in the ‘Chihuahua Solar Challenge, 2016 edition’ [ISSN online: 2414-4827, ECORFAN]. Subsequently, in July 2017, a solar car competition was held at the Technological University of Northern Aguascalientes.

These activities led to peer-reviewed publications, and the project is currently being revived with the design of a final prototype of a two-seater solar car, based on a study conducted in 2024 which, using statistics and data from the solar car market, demonstrated public acceptance of the project [ISSN: 2523-6830, magazine published by ECORFAN-Mexico].

In this new stage, the aim is to analyse and develop an energy management system capable of automatically optimising the use of solar energy and the electrical storage system.

Justification

Given the growing momentum towards sustainable mobility and energy transition in the transport sector, the development of technological solutions applied to solar vehicles represents a priority line of action for institutions committed to innovation and sustainability, such as SECIHTI. In this context, the design of an electronic module for the energy management of a two-seater solar car not only responds to the technical challenges associated with the efficient use of solar energy, but also promotes capacity building in applied engineering, automation and electrical systems analysis.

The proposal is based on the need to integrate interdisciplinary knowledge—from the identification of functional requirements to the simulation and selection of components—that allows for the construction of viable and scalable solutions for urban and suburban environments. Likewise, the methodological approach guarantees the optimisation of the system's energy performance, contributing to the development of clean technologies and the strengthening of institutional strategies aimed at smart mobility.

This project is aligned with the research and technological development axes promoted by SECIHTI, as it encourages the practical application of scientific knowledge in real contexts, promotes innovation in the design of electro-electronic systems, and generates transferable knowledge for future initiatives in the field of self-sustainable mobility.

Considering the sustained growth in demand for environmentally responsible mobility solutions, the development of a two-seater solar vehicle prototype is proposed as a feasible and strategic alternative to the challenges presented by transport in urban and suburban areas of the country.

At the same time, the study explores the potential of incorporating photovoltaic technologies into the charging infrastructure for electric vehicles, highlighting both the technological advances and the operational limitations that must be addressed for their effective implementation.

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Problem Statement

How can a self-sustaining solar vehicle prototype be developed that guarantees mobility, efficiency and safety, responding to the global challenge of reducing emissions without relying on external energy infrastructure? Currently, there is a significant gap between the conceptual design of solar vehicles and the implementation of energy management modules that integrate photovoltaic technologies, power electronics and adaptive control algorithms.

This gap limits the autonomy, operational efficiency, and scalability of prototypes, hindering their practical application in real-world contexts. In this regard, the development of an energy management system that integrates with the solar car is required so that it is not only technically viable but also responds to the specific conditions of the Mexican environment, considering factors such as urban infrastructure, usage patterns, and the availability of solar resources.

The lack of integrated and validated solutions represents an obstacle to the advancement of solar mobility projects and raises the need to design, simulate and build an electronic module capable of optimising energy flow, ensuring compatibility between components and improving the overall performance of the vehicle

Research Hypothesis

Hypothesis 1

If an electronic energy management module is designed considering criteria of efficiency, compatibility and adaptability to the urban environment, then the use of solar energy in the two-seater vehicle will be optimised, improving its range and operational performance.

Hypothesis 2

If theoretical simulations and functional analyses are incorporated into the energy system component selection process, then it will be possible to develop a technically viable solution tailored to the specific conditions of the two-seater solar car.

Methodology

Step 1. The first step is to develop the algorithm that covers the needs and functionalities of the two-seater solar car's energy management system.

Step 2. To complement the algorithm, programming is carried out in Python programming software to simulate the possible behaviour of the system and establish the basis for the main programme of the energy management system.

Step 3. Once the results of the energy management system's behaviour are available, the necessary hardware elements that theoretically meet the system's requirements are analysed to complement the system and integrate a prototype proposal that would meet the requirements and needs of the energy management system.

Step 4. A device interconnection diagram is developed to interpret the order and function of each device considered in step 3.

4. Results

After conducting this research, the following results were obtained:

Step 1. As a first step, the algorithm covering the functional needs of the energy management system for the two-seater solar vehicle was developed. This algorithm includes the following stages:

1. Load data from the database.
2. Process variables such as average current, motor effort, and energy combination.
3. Encoding categorical variables.
4. Training a classification model based on decision trees.
5. Making predictions and updating the Excel file.
6. Implementing STRIPS-type symbolic logic.
7. Simulating 12 dynamic scenarios.
8. Displaying results in an interactive table.
9. Visualising predictions using interactive graphs.

The corresponding pseudocode is established as follows:

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1. Read Excel file with solar and battery voltage readings.
2. Calculate average current per block of 10 readings.
3. Evaluate motor effort [up, down, normal].
4. Determine initial combination [solar or battery].
5. Encode effort and combination.
6. Train decision tree model with processed data.
7. Predict optimal combination for each record.
8. Save updated Excel file with predictions.
9. For each of the 12 simulated scenarios:

a) Generate random values for solar voltage, battery voltage, and current.
b) Evaluate effort.
c) Code effort.
d) Predict optimal combination with the model.
e) Apply STRIPS logic to decide the energy source.
f) Save result.

10. Display table with the 12 simulated scenarios.
11. Generate scatter plots to visualise the predictions.
12. End.

Step 2. Programming was carried out in the Python environment to simulate the behaviour of the system and establish the basis of the main programme that will manage the energy in the two-seater solar vehicle.

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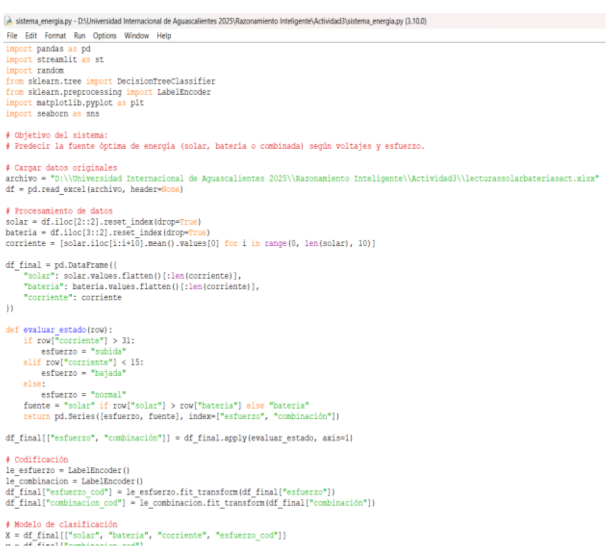
Box 1


sistema_energia.py - D:\Universidad Internacional de Aguascalientes 2025\Razonamiento Inteligente\Actividad3\sistema_energia.py (3.10.0)

File Edit Format Run Options Window Help

```python
import pandas as pd
import streamlit as st
import random
from sklearn.tree import DecisionTreeClassifier
from sklearn.preprocessing import LabelEncoder
import matplotlib.pyplot as plt
import seaborn as sns

# Objetivo del sistema:
# Predecir la fuente óptima de energía (solar, batería o combinada) según voltajes y esfuerzo.

# Cargar datos originales
archivo = "D:\\Universidad Internacional de Aguascalientes 2025\\Razonamiento Inteligente\\Actividad3\\lecturassolarbateriasact.xlsx"
df = pd.read_excel(archivo, header=None)

# Procesamiento de datos
solar = df.iloc[2::2].reset_index(drop=True)
bateria = df.iloc[3::2].reset_index(drop=True)
corriente = [solar.iloc[i:i+10].mean().values[0] for i in range(0, len(solar), 10)]

df_final = pd.DataFrame({
    "solar": solar.values.flatten()[:len(corriente)],
    "bateria": bateria.values.flatten()[:len(corriente)],
    "corriente": corriente
})

def evaluar_estado(row):
    if row["corriente"] > 31:
        esfuerzo = "subida"
    elif row["corriente"] < 15:
        esfuerzo = "bajada"
    else:
        esfuerzo = "normal"
    fuente = "solar" if row["solar"] > row["bateria"] else "bateria"
    return pd.Series([esfuerzo, fuente], index=["esfuerzo", "combinación"])

df_final[["esfuerzo", "combinación"]] = df_final.apply(evaluar_estado, axis=1)

# Codificación
le_esfuerzo = LabelEncoder()
le_combinacion = LabelEncoder()
df_final["esfuerzo_cod"] = le_esfuerzo.fit_transform(df_final["esfuerzo"])
df_final["combinacion_cod"] = le_combinacion.fit_transform(df_final["combinación"])

# Modelo de clasificación
X = df_final[["solar", "bateria", "corriente", "esfuerzo_cod"]]
y = df_final["combinacion_cod"]
```

Figure 1

Python Program for Algorithm Simulation

Once the programming of the algorithm in Python has been completed, the program is run to observe the results obtained. The data generated by the simulations are then presented, including the predictions of the classification model, the application of the STRIPS symbolic logic and the interactive visualisation of the dynamic scenarios.

These results make it possible to validate the behaviour of the energy management system and to evaluate its capacity to optimise the use of solar energy in the two-seater vehicle:

Box 2


Sistema Inteligente de Energía Vehicular

Este sistema predice la fuente óptima de energía según voltajes y esfuerzo.

Datos procesados

	solar	bateria	corriente	esfuerzo	combinación	esfuerzo_cod	combinacion_cod	prediccion_cod	prediccion
0	43	17	22.9	normal	solar	0	1	1	solar
1	21	40	31.6667	subida	bateria	1	0	0	bateria

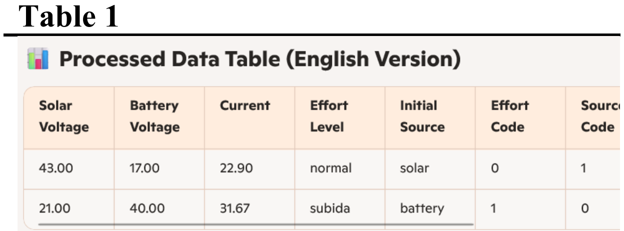
Figure 2

Sample of the result on screen

La tabla de datos procesados que se muestra en la Figura 2 representa el resultado del análisis preliminar del sistema inteligente de gestión energética, evidenciando las variables clave utilizadas en la simulación y entrenamiento del modelo de clasificación.

Box 3

Table 1


Processed Data Table (English Version)

Solar Voltage	Battery Voltage	Current	Effort Level	Initial Source	Effort Code	Source Code
43.00	17.00	22.90	normal	solar	0	1
21.00	40.00	31.67	subida	battery	1	0

Figure 3

Energy System – Processed Data Table

Description of columns in the processed data table

- Solar Voltage: Voltage measured directly from the solar panel system.
- Battery Voltage: Voltage measured from the vehicle's battery system.
- Current: Average current calculated from solar readings in defined blocks.

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- Effort Level: Symbolic classification of engine effort, coded as uphill, downhill, or normal.
- Initial Source: Initially selected energy source, determined by direct comparison of voltages.
- Effort Code: Coded numerical value representing the level of engine effort.
- Source Code: Coded numerical value representing the initial energy source.
- Prediction Code: Numerical output generated by the classification model [decision tree].
- Predicted Source: Final energy source recommended by the intelligent system, based on the model's prediction and symbolic logic.

The simulation section illustrates the response of the intelligent energy management system to 12 dynamic scenarios, generated using random values for solar voltage, battery voltage and current. In each scenario, the vehicle's effort level is evaluated — symbolically classified as downhill, uphill or normal — and an action based on STRIPS logic is applied, determined by comparing the available voltages. Subsequently, the trained classification model [decision tree] generates a prediction about the optimal energy source to use.

These results validate the system's ability to make autonomous and adaptive decisions under variable conditions, optimising energy flow and improving the operational performance of the two-seater solar vehicle.

Key observations:

Consistency between STRIPS and the classification model: In several simulated scenarios, the action determined by STRIPS symbolic logic coincides with the prediction generated by the classification model, demonstrating a functional alignment between the two approaches. For example, in scenario 0, both STRIPS and the model recommend using the battery as the energy source.

Informative divergences: In certain cases, such as scenario 1, STRIPS suggests the use of solar energy due to a higher recorded voltage, while the model predicts battery use. This discrepancy can be explained by the model's learning, which associates normal stress conditions and similar voltages with greater energy stability provided by the battery.

Predominance of the battery in predictions: In the 10 scenarios analysed, the model shows a tendency to favour the use of the battery, suggesting that it has identified patterns where this source is more reliable in the event of high stress or insufficient solar voltage.

Validation of the hybrid system: The coincidence between STRIPS and the model in multiple scenarios reinforces the validity of the energy management system. The divergences, on the other hand, open up opportunities to adjust the symbolic rules or enrich the model's training set, thus improving the system's adaptive capacity.

Box 4

Simulation of Scenarios – English Version

Solar Voltage	Battery Voltage	Current	Effort Level	STRIPS Action	System Prediction	Final State
10.23	12.76	12.42	downhill	use_battery	battery	battery
13.73	10.42	29.19	normal	use_solar	battery	solar
12.32	11.81	33.38	uphill	use_solar	battery	solar
13.57	11.23	31.74	uphill	use_solar	battery	solar
10.64	11.83	30.48	normal	use_battery	battery	battery
11.18	13.83	34.91	uphill	use_battery	battery	battery
12.47	11.75	32.66	uphill	use_solar	battery	solar

Figure 4
Results of Simulation of Scenarios.

Column Descriptions

Solar Voltage: Voltage measured from the solar panel system, representing the available solar energy.

Battery Voltage: Voltage measured from the battery system, indicating the stored energy capacity.

Current: Average current used to estimate motor load and energy demand.

Effort Level: Symbolic classification of vehicle effort according to terrain conditions [uphill, downhill, normal].

STRIPS Action: Decision on the energy source, derived from symbolic logic rules based on voltages and effort.

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RENIECYT: 1702902

System Prediction: Energy source recommended by the classification model trained through machine learning.

Final State: Energy source resulting from applying STRIPS logic, used to validate or contrast with the system prediction.

Visualisation of forecasts

Graph: Solar vs Battery by Prediction

Box 5

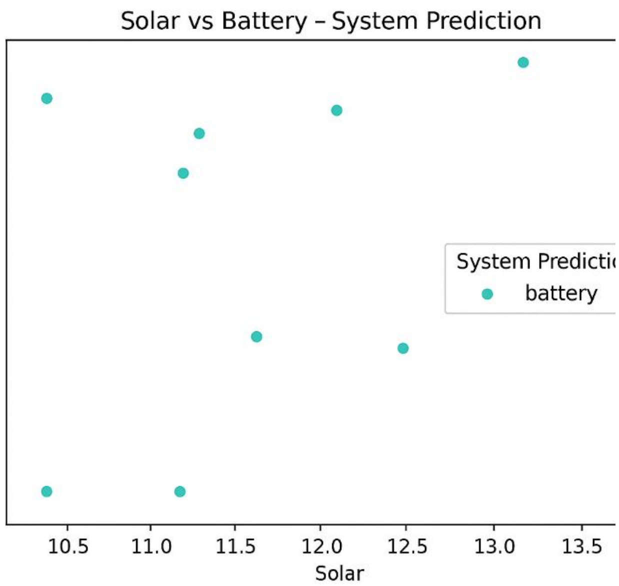

Figure 5
Solar vs Battery – System Prediction

- **Title**: *Solar vs Battery Voltage – System Prediction*
- **X-axis**: *Solar Voltage*
- **Y-axis**: *Battery Voltage*
- **Legend**: *System Prediction – Batter*

Interpretation of the energy decision graph
What does it represent?

The graph shows how the intelligent energy management system makes decisions about the energy source based on solar and battery voltages. Each point represents a simulated scenario, and the colour indicates the classification model's prediction. In this case, all points are labelled "battery".

Technical interpretation

X-axis [Solar]: Voltage available from the solar panel system.
Y-axis [Battery]: Voltage available from the battery system.

Colour: All points are classified as 'battery', indicating that the model considers this source to be more suitable in the scenarios represented.

Observations

Although some points have a higher solar voltage than battery voltage, the system still recommends battery. This suggests that the model has learned that, under certain conditions—such as high effort or similar voltages—the battery offers greater reliability.
• The dispersion of points indicates that the decision does not depend solely on which voltage is higher, but on how it relates to other variables such as average current and vehicle effort level.

Graph: Current vs. Battery according to Prediction: [Figure 6]

Box 6

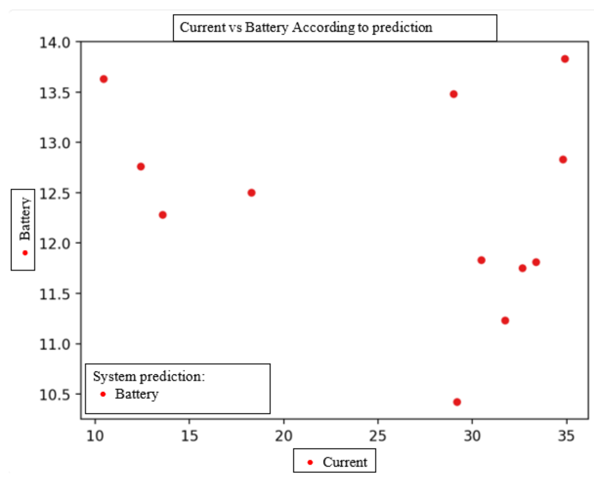

Figure 6
Current vs Battery According to prediction

¿ What does it represent?
Interpretation of the graph: Current vs.

Battery voltage

General description

The graph shows how the intelligent energy management system determines the energy source based on the motor current and battery voltage. Each point represents a simulated scenario, and the colour indicates the model's prediction. In this case, all points are classified as 'battery'.

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Technical interpretation

- X-axis [Current]: Represents the motor effort. High values indicate higher energy demand, typically associated with uphill conditions.
- Y-axis [Battery Voltage]: Voltage available in the battery system.
- Colour: All points are labelled ‘battery,’ indicating that the model considers this source more reliable in the simulated scenarios.

Observations

- As the current increases, the system continues to recommend the battery, even when its voltage is not the highest.
- This suggests that the model has learned that, under high loads, the battery offers greater operational stability than the solar source.
- The dispersion of points shows that the decision does not depend solely on voltage, but on its relationship with variables such as engine load, which reinforces the adaptive nature of the system.

Graph: Current vs Solar Voltage – System Prediction: [Figure 7]

Box 7

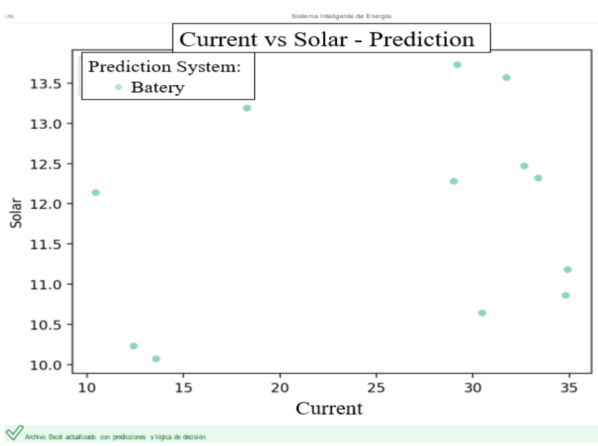

Figure 7

Current vs Solar According to prediction

Title: ***Current vs Solar Voltage – System Prediction***
X-axis: ***Current***
Y-axis: ***Solar Voltage***
Legend: ***System Prediction – Battery***

What does it represent?

This graph shows how the intelligent system decides on the energy source based on the motor current and the available solar voltage. Each point represents a simulated scenario, and the colour indicates the classification model's prediction. In this case, all points are labelled “battery”, indicating that the system considers this source to be more reliable in the scenarios represented.

Technical interpretation

- X-axis [Current]: Represents the motor's effort. Higher currents indicate greater energy demand, such as when climbing a slope.
- Y-axis [Solar Voltage]: Voltage available from the solar system at that moment.
- Colour: All points are classified as ‘battery’, suggesting that the model prioritises this source for its stability.
- **Observations**
- Although some scenarios present relatively high solar voltages, the system continues to recommend battery as the main source.
- This indicates that the model has learned that, in the face of high effort [high currents], solar energy may not be sufficient or stable, so battery use is prioritised.
- The dispersion of points shows that there is no direct linear relationship between current and solar voltage in decision-making, which validates the use of a non-linear classification model such as the decision tree.

Step 3: Modular hardware proposal

Once the results of the energy management system's behaviour were obtained, an analysis was carried out of the hardware components that, in theory, meet the functional requirements of the system. This analysis made it possible to integrate a prototype proposal that meets the operational and technical needs of the intelligent energy management system.

Hardware suggested by function

Energy sensing

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Voltage sensor: INA219 or analogue voltmeters with resistive divider

Current sensor: ACS712 or INA226

Temperature sensor: LM35 or DHT22
Processing and control

Microcontroller: Arduino Mega or ESP32 [with Wi-Fi connectivity]

Embedded computer: Raspberry Pi 4 with Python environment and Streamlit visualisation
Proposed interconnection
Arduino: responsible for sensing and physical control

Raspberry Pi: executes the classification model and STRIPS logic

Communication: UART, I2C or Wi-Fi [if using ESP32]
HMI [Human-Machine Interface]

Touchscreen: Nextion 4.3‘ or 7’ to display voltages, stress and prediction

Alternative: 20x4 LCD with push buttons for basic navigation

Actuators and switching

Power relays: 30A relay module or SSR to switch between solar source and battery

Charge controller: MPPT compatible with feedback to Arduino

Power and protection

Fuses and protections: for system safety

DC-DC converter: to adapt voltages to Arduino and Raspberry Pi

Battery bank: energy storage

Solar panels: primary energy source

System logic integration

1. Arduino measures voltages, current and effort → sends data to Raspberry Pi
2. Raspberry Pi runs the ML classification model → sends decision to Arduino
3. Arduino activates relays according to STRIPS logic
4. HMI displays system status and allows user interaction

Step 4: Interconnection diagram

A device interconnection diagram was developed to interpret the order, function and flow of information between the components considered in step 3. This diagram facilitates the physical implementation of the system and ensures the traceability of each module within the prototype.

Box 8

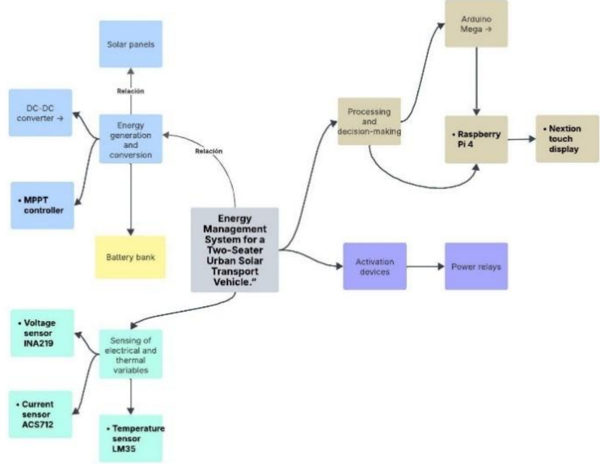

Figure 8
Interconnexions Diagram
Order of interconnection of elements

1. **Energy generation and conversion**

Solar panels → generate electrical energy from solar radiation.

MPPT controller → regulates the charge from the solar panels to the battery bank, maximising energy efficiency.

Battery bank → stores the energy regulated by the MPPT.

DC-DC converter → adapts the output voltage of the battery bank to power the vehicle's electronic systems.

2. **Sensing of electrical and thermal variables**

Voltage sensor INA219 → measures the voltage and current of the solar system or battery.

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Current sensor ACS712 → measures the motor current, useful for estimating the vehicle's effort.

Temperature sensor LM35 → measures the ambient or internal temperature, useful for thermal protection and charging decisions.

All these sensors are connected directly to the **Arduino Mega**, which acts as a data acquisition unit.

3. Processing and decision making

Arduino Mega → receives data from the sensors, processes it and sends it to the **Raspberry Pi 4**.

Raspberry Pi 4 → runs the classification model [machine learning] and determines the optimal energy source [solar or battery].

Nextion touch display → receives the decision from the Raspberry Pi and displays it to the user in real time.

4. Actuation

Power relays → receive control signals from the Arduino or Raspberry Pi to switch between energy sources according to the system's prediction.

5. Summary flow:

Energy: Panels → MPPT → Batteries → DC-DC → System

Sensing: Sensors → Arduino Mega

Processing: Arduino → Raspberry Pi → Display

Actuation: Raspberry/Arduino → Relays → Energy switching

Conclusions:

The intelligent energy management system for a two-seater solar vehicle will be developed by integrating symbolic decision algorithms and classification models based on machine learning, with the aim of efficiently predicting the optimal energy source according to operating conditions.

Simulations in Python and the visualisation of results have made it possible to validate the consistency between the STRIPS logic and the trained model. Subsequently, with the analysis of the hardware components necessary for physical implementation, those that meet the functional requirements of the system have been selected.

The interconnection diagram will establish a clear modular architecture, ensuring traceability between generation, sensing, processing and action, and laying the foundations for a functional prototype aligned with criteria of efficiency, sustainability and intelligent control.

Declarations:

Conflict of interest

The authors declare that they have no conflict of interest. We have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.atito

Contribution of the authors

Arellano-Yáñez, Ricardo, the contribution to this article has been the original idea of the topic, as well as the direction and technical supervision of the research on the topic of this article.

Tomas Moreno Granados, Gerardo Méndez Macías, Carmela Ortiz Negrete, and Oscar Daniel Calvillo Valdez, co-authors of this article, contributed to the technical supervision, investigation of information sources, and writing of this article based on the research carried out.

Availability of data and materials

At this time, only the previous publications that have served to continue this research are available. The final results or those generated during the course of this research will be available in the corresponding publication of this article, as it is currently being developed and is now in the stage of characterising the proposed energy management prototype for a two-seater solar-powered urban transport vehicle.

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Abbreviations

UTNA: Technological University of Northern Aguascalientes References

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