INTERNATIONAL DOCTORAL
SCHOOL OF THE USC

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PhD Thesis

Demand side management in the smart grid technology for a sustainable energy transition: investigations, strategies, and approaches

Santiago de Compostela, 2024

Doctoral Programme in Renewable Energy and Energy Sustainability

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

ESCOLA DE DOUTORAMENTO INTERNACIONAL DA USC

DOCTORAL THESIS

DEMAND SIDE MANAGEMENT IN THE SMART GRID TECHNOLOGY FOR A SUSTAINABLE ENERGY TRANSITION: INVESTIGATIONS, STRATEGIES, AND APPROACHES

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PHD PROGRAMME IN RENEWABLE ENERGY AND ENERGY SUSTAINABILITY

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INDEX OF ACRONYMS

ACO	Ant Colony Optimization
ADAMS	Automatic Dynamic Analysis of Mechanical Systems
AGFI	Adjusted Goodness of-Fit-Index
AGWO	Augmented Grey Wolf Optimization Algorithm
AMOS	Analysis of Moment Structures Software
ATT	Attitude Towards
B2EV	Battery to EV
B2G	Battery to grid
B2H	Battery to home
BESSs	Battery Energy Storage Systems
C.R.	Critical Ratio
CAES	Compressed Air Energy Storage
CEM	Clean Energy Ministerial
CFA	Confirmatory Factor Analysis
CFI	Comparative Fit Index
CO_2	Carbon Dioxide
CPP	Critical Peak Pricing
CR	Composite Reliability
CSA	Crow Search Algorithm
CSOA	Cuckoo Search Optimization Algorithm
DF	Degrees of Freedom
DG	Diesel Generator
DOD	Depth of Discharge
DOE	Department of Energy
DR	Demand Response
EAP	The 8th Environment Action Programme
EEA	European Environment Agency
EFMS	Energy Flow Management System
EFMSA	Energy Flow Management System Algorithm
EIB	European Investment Bank

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ELO	Expected Learning Outcomes
ESSs	Energy Storage Systems
ET	Ending Time
EV2B	EV to battery
EV2G	EV to grid
EV2H	EV to home
EVA	Embodied Voice Assistant
EVs	Electric Vehicles
EU	European Union
FEB	Family's Economic Benefits
G2B	Grid to battery
G2H	Grid to home
G2EV	Grid to EV
GA	Genetic Algorithm
GDP	Gross Domestic Product
GFI	Goodness of-Fit-Index
GHG	Greenhouse Gas Emissions
GSEF	Global Smart Energy Federation
GWDO	Genetic Wind-Driven Optimization algorithm
GWO	Grey Wolf Optimizer
HECs	Household Energy Consumers
HEMSs	Home Energy Management Systems
IBR	Inclined Block Rate scheme
ICTs	Information and Communication Technologies
IEA	International Energy Agency
IEDA	Institute for Energy Diversification and Savings
IFI	Incremental Fit Index
INT	Intention to Use
IRENA	The International Renewable Energy Agency
ISGAN	International Smart Grid Action Network
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MPC	Model Predictive Controller
NFI	Normed Fit Index

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NZE Scenario	Net Zero Emissions by 2050 Scenario
O&M	Operation and Maintenance
P-value	Probability value
PAR	Peak-to-Average Ratio
PE	Ease of Use
PEFMA	Proposed Energy Flow Management Algorithm
PEFMS	Proposed Energy Flow Management Strategy
PFO	Pyrolysis Fuel Oil
PID	Proportional-Integral-Derivative
PSO	Particle Swarm Optimization Algorithm
PSOA	Pattern Search Optimization Solver Algorithm
PV	Photovoltaic
PV2B	PV to battery
PV2EV	PV to EV
PV2G	PV to grid
PV2H	PV to home
PVPC	Voluntary Price for the Small Consumer
PU	Perceived Usefulness
PW	Perceived Awareness
RESs	Renewable Energy Systems
RMSEA	Root Mean Square Error of Approximation
RTE	Electricity Transmission Network
RTP	Real-time Pricing
SE	Standard Error
SEM	Structural Equation Modeling
SG	Smart Grid
SGI	Smart Grid Industry 4.0
SGTF	Smart Grids Task Force
SOC	State of Charge
SPSS	Statistical Package for the Social Sciences Software
ST	Starting Time
TAM	The Technology Acceptance Model
TEN-E	Trans-European Networks for Energy
TOU	Time-of-Use
X^2	Chi-square

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INDEX OF NOMENCLATURES

Δt	The simulation time (Hour)
η	The converter efficiency (%)
μ_{conv}	The efficiency of the (DC/AC) inverter
$\mu_{driving}$	The vehicle efficiency (kWh/km)
γ	The efficiency of the PV system (%)
γ_T	The temperature coefficient
A	The area of the solar panel (m^2)
a, b	The simulated parameters for lithium-ion lifecycle calculation
$B_{capital}$	The capital cost of the battery system (EUR)
$B_{con.}$	The total daily contribution of the battery (EUR)
$B_{con.}^{lifecycle}$	The total contribution of the battery (EUR)
B_{cost}	The electricity cost without using the PV battery system (EUR)
$B_{daycycles}$	The number of charging/discharging cycles throughout the day
$B_E^{lifespan}$	The expected amount of charged/discharged energy to/from the battery (kWh)
$B_{LC}(t)$	The battery energy losses cost at each time slot *t* (EUR)
B_{LCOS}	The cost of using the battery throughout its lifespan (kWh)
B_{life}	The expected lifespan of the battery (Year)
$B_{losses}(t)$	The battery energy losses at each time slot *t* (kWh)
$B_{price}(t)$	The price of the battery energy usage in the time slot *t* (EUR /kWh)
$B_{price}^{ch.}(t)$	The price of the total purchased energy from the PV, grid, and EV and stored in the battery (EUR/kWh)

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$B_{price}^{overall}(t)$	The battery energy usage price (kWh)
C_B	The battery capital cost (EUR)
$C_{batt}(t)$	The cost of battery energy usage in the home at each time slot t (EUR)
C_{BOP}	The infrastructure cost of the battery system (EUR/kWh)
$C_{btev}(t)$	The cost of purchased energy from the battery and stored in the EV's battery (EUR)
$C_C(t)$	The energy consumption cost (EUR)
$C_{ch}(t)$	The price of total charged energy (EUR/kWh)
$C_{EV}(t)$	The cost of EV's battery energy usage in the home at each time slot *t* (EUR)
$C_{evtb}(t)$	The cost of purchased energy from the EV and stored in the battery at each time slot *t* (EUR)
$C_{Grid}(t)$	The cost of power imported from the grid to home at each time slot *t* (EUR)
$C_{gtb}(t)$	The cost of purchased energy from the grid and stored in the battery at each time slot *t* (EUR)
$C_{gtev}(t)$	The cost of purchased energy from the grid and stored in the EV's battery (EUR)
C_{PCS}	The power conversion system cost (EUR/kW)
$C_{PV}(t)$	The cost of PV energy consumed in the home (EUR)
$C_{pvtb}(t)$	The cost of purchased energy from the PV and stored in the battery at each time slot *t* (EUR)
$C_{pvtev}(t)$	The cost of purchased energy from the PV and stored in the EV's battery (EUR)
$C_{Trip}(t)$	The cost of EV energy usage cost for the vehicle trip at each time slot *t* (EUR)
C_{Unit}	The cost of the battery per unit (EUR/kWh)
Ch_B^{max}	The maximum charge rate of the battery during the time slot *t* (kWh)
Ch_{EV}^{max}	The maximum charge rate of the EV's battery during the time slot *t* (kWh)
$ch_{losses}(t)$	The battery charging losses at each time slot *t* (kW)

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$Ch_{price}(t)$	The total price of purchased and stored energy in the battery at each time slot *t* (EUR/kWh)
CH_{rate}	The maximum charge rate of the battery at each time slot *t* (kWh)
CO_2	The amount of CO_2 emissions ($kgCO_2$)
D	The vehicle travel distance (km)
d_{saving}	The daily saved cost (EUR)
d_y	The total days within a year
Dis_B^{max}	The maximum discharge rate of the battery (kWh) during the time slot *t* (kWh)
Dis_{EV}^{max}	The maximum discharge rate of the EV's battery during the time slot *t* (kWh)
$dis_{losses}(t)$	The battery discharging losses at each time slot *t* (kW)
Dis_{rate}	The maximum discharge rate of the battery at each time slot *t* (kWh)
DOD_{ev}	The depth of discharge of EV's battery (%)
$E_B(t)$	The amount of current energy in the battery at each time slot *t* (kWh)
$E_B(t+1)$	The amount of energy in the battery in the next time slot *t*+1 (kWh)
E_{batt}	The nominal energy of the battery system (kWh)
$E_{controllable}(t)$	The total energy consumption of the controllable appliances at each time slot *t* (kWh)
$E_{EV}(t)$	The energy stored in the EV's battery at each time slot *t* (kWh)
$E_{EV}(t+1)$	The energy stored in the EV's battery at the time slot *t*+1 (kWh)
$E_{fixed}(t)$	The total energy consumption of the fixed appliances at each time slot *t* (kWh)
$E_{home}^{hourly}(t)$	The total energy demand of fixed and controllable appliances at each time slot *t* (kWh)

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$E_{home}^{min}(t)$	The total energy demand at each time slot *t* (kWh)
E_{home}^{total}	The total daily energy demand (kWh)
$EB_{ch}(t)$	The total charged energy (kWh)
$ESS_{daycycles}$	The number of charging/discharging cycles throughout the day of ESS, whether for battery or EV
$ESS_{LC}(t)$	The cost of energy losses associated with the ESSs charging and discharging process at each time slot *t* (EUR)
ESS_{life}	The expected ESS lifetime (year)
$EV_{capital}$	The replacement cost of the EV's battery (EUR)
$EV_{con.}$	The total daily contribution of the EV (EUR)
$EV_{con.}^{lifecycle}$	The total contribution of the EV (EUR)
EV_{LCOS}	The cost of using the EV's battery throughout its lifespan (EUR/kWh)
EV_{life}	The estimated battery and EV lifetime (year)
$EV_{price}^{ch.}(t)$	The price of the total purchased energy from the PV, grid, and battery, which is stored in the EV's battery at each time slot *t* (EUR/kWh)
$EV_{price}^{overall}(t)$	The EV's battery energy usage price at each time slot *t* (EUR/kWh)
EV_{trip}	The required energy for the EV trip (kWh)
$Grid_{price}^{buy}(t)$	The grid price at each time slot *t* (EUR/kWh)
$Grid_{sell}$	The energy selling price to the grid at each time slot *t* (EUR /kWh)
I_{CO_2}	The carbon emission intensity of electricity generation ($kgCO_2/kWh$)
Inv_{sys}	The investment cost of the installed PV-battery system (EUR)
$Ir(t)$	The solar irradiance (W/m^2)
I_r, STC	The solar irradiance at STC (kW/ m^2)
$LCOE_{pv}$	The PV energy usage price (EUR/kWh)
N_{cycle}	The number of battery cycles

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$N_{cycle,ESS}$	The ESS lifecycle
n_{ev}	The number of charging/discharging cycles of the EV's battery
NE_{ev}	The nominal energy of the EV's battery (kWh)
$OP(a_P(t))$	A variable that indicates whether the home appliances are operating or not at each time slot *t* (0, 1)
$OP(b_X(t))$	A variable that indicates whether the fixed appliances are operating or not at each time slot *t* (0, 1)
$OP\left(C_y(t)\right)$	A variable that indicates whether the controllable appliances are operating or not at each time slot *t* (0, 1)
$P_b(t)$	The battery net power at the time slot *t* (kW)
$P_B^{ch}(t)$	The total stored power in the battery at each time slot *t* (kW)
$P_B^{dis}(t)$	The total supplied power from the battery at each time slot *t* (kW)
$P_{btev}(t)$	The amount of power sent from the battery to the EV at each time slot *t* (kW)
$P_{btg}(t)$	The amount of power sent from the battery to the grid at each time slot *t* (kW)
$P_{bth}(t)$	The amount of power sent from the battery to the home at each time slot *t* (kW)
$P_{ESS}^{ch}(t)$	The charged power to the ESS at each time slot *t* (kWh)
$P_{ESS}^{dis}(t)$	The discharged power from the ESS at each time slot *t* (kWh)
$P_{EV}^{ch}(t)$	The charging power to the EV battery at each time slot *t* (kW)
$P_{EV}^{dis}(t)$	The discharging power from the EV battery at each time slot *t* (kW)
$P_{evtb}(t)$	The amount of power sent from the EV to the battery at each time slot *t* (kW)
$P_{evg}(t)$	The power exported from the EV battery to the grid at each time slot *t* (kW)

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$P_{evth}(t)$	The power discharged from the EV battery to the home at each time slot *t* (kW)
$P_{gtb}(t)$	The amount of grid stored power in the battery at each time slot *t* (kW)
$P_{gth}(t)$	The amount of grid power sent to the home at each time step *t* (kW)
$P_l(t)$	The home load at each time slot *t* (kW)
$P_{PV}(t)$	The PV output power (kW)
$P_{pvtb}(t)$	The amount of PV stored power in the battery at each time slot *t* (kW)
$P_{pvtev}(t)$	The amount of power sent from the PV to the EV battery at each time slot *t* (kW)
P_{pvtg}	The amount of PV power sent to the grid at each time slot *t* (kW)
$P_{Pvth}(t)$	The amount of PV power usage in the home at each time slot *t* (kW)
P_a	The rated power of the home appliances (kW)
P_X	The rated power of the fixed appliances (kW)
P_Y	The rated power of the controllable appliances (kW)
$Pch_{grid}(t)$	The cost of the energy purchased from grid and stored in the battery at each time slot *t* (EUR)
$Pch_{pv}(t)$	The cost of the energy purchased from PV and stored in the battery at each time slot *t* (EUR)
$Profit_{btg}(t)$	The economic benefit of selling energy from battery to the grid at each time slot *t* (EUR)
$Profit_{evtg}(t)$	The economic benefit of selling energy from EVs to the grid at each time slot *t* (EUR)
$Profit_{pvtg}(t)$	The economic benefit of selling energy from PV to the grid at each time slot *t* (EUR)
$Profit_{sell}(t)$	The overall profit of selling energy to the grid at each time slot *t* (EUR)
P_{STC}	The maximum power of the PV module at standard test condition (kW)
$PV_{con.}$	The total daily contribution of the PV (EUR)
$PV_{con.}^{lifecycle}$	The total contribution of the PV (EUR)

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PV_{saving}	The PV daily cost saving after the battery stops working (EUR/day)
PVB_{saving}	The overall saved cost during the battery lifespan integrating with PV (EUR)
Sch_{cost}	The scheduling strategy electricity cost (EUR)
$SOC(t)$	The ratio of the total amount of energy stored in the battery relative to its overall energy capacity at each time slot *t* (%)
$SoC\ (t)_B$	The state of charge of the battery (%)
$SoC\ (t)_{EV}$	The state of charge of the EV's battery (%)
$T_o(t)$	The ambient temperature at each time slot *t* (C^o)
$T_b^{cost}(t)$	The total cost of the purchased energy and stored in the battery at each time slot *t* (EUR)
$T_b^{energy}(t)$	the total purchased energy stored in the battery at each time slot *t* (kWh)
$T_{ev}^{cost}(t)$	The total cost of the purchased energy and stored in the EV's battery at each time slot *t* (EUR)
$T_{ev}^{energy}(t)$	The total purchased energy and stored in the EV's battery at each time slot *t* (kWh)
T_{STC}	The reference temperature at STC (C^o)
Y_{BP}	The expected breakeven point of the PV-battery system (year)

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SUMMARY

Sustainability has become a global theme in recent years mainly due to limited resources and climate change concerns. There is a growing recognition of the need to adopt sustainable practices to ensure the well-being of current and future generations. Promoting sustainability has gained attention across various sectors, such as energy, transportation, industry, and education. Consequently, sustainability has become an integral part of policy frameworks, community responsibility, and educational curricula, reflecting a shared commitment to building a more resilient and equitable future.

Regarding energy sustainability, the European Union makes efforts in energy transition and achieving a global net-zero emission, by outlining policies and providing initiatives for establishing a sustainable future energy system. The "European Green Deal", "Paris Agreement", "Net Zero Emissions by 2050 Scenario" (NZE Scenario), the "8th Environment Action Programme" (EAP), and "REPowerEU plan", synergy together to shape the energy landscape to be aligned with the global effort in terms of developing the renewable energy sector, reducing reliance on fossil fuel, and decarbonisation.

The integration of "Renewable Energy Systems" (RESs) is key to enhancing energy security, reducing emissions, and advancing economic and technological growth. The progress in penetration of high RESs into the main grid has challenges due to variations of energy demand and the fluctuations of RESs generated energy influenced by weather conditions, leading to power balance and grid stability problems. Besides, the continual growth in population and technology has led to a notable increase in energy consumption, underscoring the necessity for a reliable future energy system. Therefore, tackling these challenges is imperative for sustainable advancement. The residential sector accounts for a substantial portion of overall energy consumption, indicating its potential role in adopting efficient energy practices

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aligned with global efforts towards net-zero emission and energy transition.

Demand side management is essential in advancing the energy transition and the development of the renewable energy sector. It involves optimizing and monitoring energy consumption and controlling grid operations efficiently, enabling the seamless integration of RESs while maintaining grid stability and reliability. Demand side management strategies can include the implementation of energy-efficient technologies, smart home systems, and behavior change initiatives. In the realm of RESs development, demand side management facilitates the integration of RESs into the main grid, employing techniques such as "Demand Response" (DR) and "Energy Storage Systems" (ESSs) within "Smart Grid technology" (SG), to accommodate the fluctuations inherent in RES such as wind and solar power, ensuring a reliable and stable energy supply. In line with the established policies and regulations towards a sustainable energy system, demand side management enables energy consumers to meet these regulatory requirements by adopting clean energy technologies, reducing carbon footprints, and improving energy efficiency. In summary, demand side management has multi-faced benefits including energy cost reduction, preserving the environment, and ensuring energy security.

Besides, the "smart industrial revolution" emphasizes the need for sustainable practices in energy consumption, efficient production processes, and integration of the principles of sustainability in manufacturing utilizing the "Information and Communication Technologies" (ICTs). The European Commission established the "Sustainable and Efficient Energy Use in Industry" working group in 2016 and revised it in 2021 to be aligned with recent research, innovation, and policies such as the European Green Deal. It aims to help industries become less energy, resources, and emissions intensive and more competitive. In this context, engineers perform many tasks in industry, such as process optimization, energy recovery, solving problems, and data analytics and automation. Consequently, it's important to prepare future engineers with the knowledge and skills required to perform sustainable tasks within the industry sector.

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The main objective of this thesis is to comprehensively investigate the efficacy and potential of demand side management in fostering sustainable energy practices within the residential sector using SG technology. This approach is mainly focused on enhancing energy security, energy transition, and energy efficiency, corresponding closely with the goals set forth in the European Green Deal, Paris Agreement, the NZE Scenario, EAP, and the REPowerEU plan.

Specific objectives are: **investigate** the main drivers for "Home Energy Management Systems" (HEMSs) implementation, including: the evaluation of HEMSs capacity to optimize energy consumption, reduce energy costs, reduce carbon emissions, and enhance energy security; explore innovative **strategies** for promoting demand side management, considering factors such as technological advancements, policy incentives, and energy consumers' behavior (emphasis is placed on achieving environmental, financial, lifecycle consideration, and behavior change objectives); provide **approaches** to raise awareness regarding society's role in establishing a sustainable energy system and equipping future engineers to bridge the gap between theoretical knowledge and real-world applications.

The methodology follows three parts connected to the three specific objectives, each part has different chapters. In general, the research methodology for each chapter involves a comprehensive literature review, data analysis of energy consumers' intention toward efficient energy practice, mathematical model development for demand-side management strategies, and technologies and approaches utilization for raising awareness and skilled education on energy for industry sectors development.

Part 1 includes only a chapter (CHAPTER 4). An extended model of the "Technology Acceptance Model" (TAM) is proposed to **investigate** the factors that might affect the intention to use HEMSs and participate in DR after applying the new electricity tariff in Spain in 2021. Based on the literature review, the "perceived customer's environmental awareness" and "family's economic benefits" are added to the TAM model. The study is done in Galicia, Northwest Spain. After gathering the data, it is analyzed using the data analysis software *Amos 20*. The data analysis results fulfills the research objectives, providing

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valuable insights into the influence of each factor on the "intention to use HEMSs". The study elucidates the impact that various factors exert on shaping the "attitude toward HEMSs" and "intention to use HEMSs". The results show a positive impact of the "consumers' environmental awareness" and "family's economic benefits" on the "attitude toward using HEMSs". In addition, the results show a direct positive effect of "usefulness" and "attitude toward use" on the "intention to use HEMSs". It is worth noting that the higher the economic benefits and environmental awareness, the more attitude to use HEMSs, which in turn leads to formulating positive intention to use HEMSs. The perceived "family's economic benefit" stands out as the most important factor in improving consumer acceptance, which is consistent with the function of HEMSs; saving energy and consuming energy in the low-price periods reduces the bill. Likewise, the influence of "environmental awareness" on the "attitude toward using HEMSs" holds notable significance. In other words, energy consumers are willing to manage their energy consumption to preserve the environment. This willingness is contingent upon them gaining adequate awareness of climate change issues and realizing their essential role in participating in DR aimed at environmental enhancement. Besides, the results reveal that "usefulness" has a positive and direct impact on "intention to use", and the "attitude" does not mediate the relation between "usefulness" and "intention to use". Hence, the higher the usefulness of using HEMSs in enhancing life quality, the more intention to use HEMSs. In contrast, the perceived "ease of use" and "usefulness" have insignificant effects on the "attitude toward use". In light of the findings, policymakers should take measures that accentuate the economic benefits for energy consumers and the positive impact on the environment of adopting HEMSs and draw up policies that support these factors. The researchers can use the above-mentioned findings as a foundation to further develop the proposed model and explore additional factors that could potentially impact consumer acceptance in Spain. By doing so, researchers can offer policymakers a richer understanding of the factors at play, thereby assisting in the formulation of more effective strategies aimed at enhancing consumer acceptance of the new electricity tariff. To gain a

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more comprehensive understanding of the subject in Spain, it is highly advised to broaden the scope of the research by increasing the sample size and carrying out a larger-scale survey encompassing various cities across the country. Such an approach would yield more comprehensive and robust results, contributing to a more thorough comprehension of consumer behavior and preferences related to the new tariff.

As the first outcome, Part 1 found that “environmental awareness” and “family economic benefits” significantly impact the “intention” toward adopting efficient energy practices using HEMSs after the new electricity tariff in Spain in 2021. In addition, the perceived “usefulness of using HEMSs” directly affects energy consumers' “intention to use HEMSs”. Part 1 revealed the potential of using HEMSs and explored the main key drivers of Spanish energy consumers that affect their energy consumption habits by using HEMSs, resulting in energy costs and carbon emissions reduction.

Part 2 introduces innovative HEMS **strategies** to achieve benefits for energy consumers, the environment, and the overall energy system, in three chapters:

- CHAPTER 5 proposes an energy flow management strategy. An energy usage cost model of “Photovoltaic” (PV) and battery is modeled considering their installation cost. It expresses the cost of storing energy, operation and maintenance costs, and the cost of the purchased energy. The simulation analysis shows the efficient energy distribution, focusing on achieving actual cost reduction and optimal operation of the battery. During periods of PV power shortfall, the proposed strategy strategically conserves battery reserves, prioritizing discharging operations when grid price outweighs battery energy price. Additionally, findings underscore the economic inefficacy of selling surplus energy to the grid, a practice often yielding lower returns than home consumption. The proposed work shows an actual energy cost reduction associated with the PV and battery installation costs, encouraging consumers to install local energy systems and manage their energy consumption. Consequently, these findings underscore the role of decentralized energy solutions in enhancing energy security and sustainability.

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- CHAPTER 6 proposes an efficient optimization method of scheduling appliances in conjunction with an efficient energy flow management system that considers PV and battery life cycles, as well as installation costs. Battery and PV energy usage pricing models are proposed and considered in the optimization strategy and energy flow management system. For optimization, we used the "Augmented Grey Wolf Optimization Algorithm" (AGWO) and "Particle Swarm Optimization Algorithm" (PSO) in MATLAB. Real data was used for a house in Vigo, Spain in order to provide realistic results that encourage Spanish customers to manage their energy consumption after the new electricity tariff in Spain. To show the effectiveness of the proposed system, a comparison is applied with a previous model of pricing energy usage. The proposed system accomplishes a better reduction in cost and energy losses, a longer extension to the lifespan of the battery, and reaches the breakeven point in a short time. In addition, it encourages energy consumers to contribute to grid stability and energy security by highlighting the economic and environmental benefits of scheduling appliances in conjunction with the efficient use of PV and batteries during their lifespan compared to their installation costs. In the future, the authors propose the possibility of studying the energy consumption reduction cost with the integration of electric vehicles. Furthermore, it is recommended to expand the scope of the study by incorporating multiple homes to study the mechanism of energy exchange between them, considering the preferences of each user and integrating thermostatically controlled loads into the energy demand model.
- CHAPTER 7 introduces an effective home energy management system for smart homes that integrates PV, batteries, and electric vehicles. An energy flow management algorithm was developed to control modes between PV, batteries, electric vehicles, and the grid. Additionally, it introduces an optimization strategy using PSO to obtain optimal parameters for the battery (depth of discharge & size) and electric vehicle's battery (depth of discharge) and schedule the household appliances. The PV, battery, and electric vehicle energy usage cost models were formulated and introduced into the optimization process, considering each system's installation costs and lifecycle,

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resulting in an actual cost reduction compared to the installation costs and ensuring sustainable utilization of the integrated system throughout its operational lifetime. Four scenarios were simulated considering winter and summer weather conditions. The proposed system aimed to reduce the actual energy cost, extend the ESSs lifetime, reduce energy losses, reduce CO_2 emissions, and maximize the financial returns from installing the PV, battery, and electric vehicle at home. The results revealed that the proposed system achieved the study's objectives and its capability to deal with varied seasonal conditions, energy price variations, user preferences, and sustain energy systems utilization. Additionally, the results encourage household consumers seeking to reduce their environmental impact and increase their financial returns associated with investing in PV, battery, and electric vehicle energy systems at home, resulting in promoting sustainable and efficient energy practices at the household level. In the future, the authors propose expanding the scope of the study by incorporating several homes in diverse geographical regions (energy demand patterns), considering monthly weather variations (seasonal dynamics), and investigating and optimizing various parameters of the integrated energy system to identify the most practical options for residential applications (scalability/replicability).

As the second outcome, Part 2 proposed three demand-side management strategies using PV, batteries, and electric vehicles connected to the grid. The proposed strategies achieved energy cost reduction, efficient energy systems utilization, energy saving, and carbon emissions reduction. Part 2 contributed to promoting demand side management, offering benefits for energy consumers by reducing energy costs and showing how their behavior changes in energy consumption contribute to preserving the environment and extending the lifetime of energy systems. In addition, it contributed toward encouraging the residential sector to be a part of the global efforts in moving toward sustainability and energy transition.

Part 3 carries out case studies for the energy sector and industry advancement, it focuses on providing **approaches** to raising awareness of energy issues for moving toward energy transition utilizing

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simulation game technology and educating/training future engineers utilizing the university's curricula. Three chapters are included:

- CHAPTER 8 presents an approach to examine the role of simulation games in raising social awareness of energy consumers' role in energy transition and sustainability. In line with the technological development in the energy sector and the increase in concerns about energy security and climate change, this study was carried out to examine how simulation games might affect Home Energy Consumers (HECs) awareness of their role in contributing to energy security, reducing the environmental impact of using energy, and reducing electricity prices. First, a questionnaire was carried out to measure the individuals' awareness, and then the game rules were explained, and the players started playing the game. After that, another questionnaire was carried out after playing the game to measure the effect of playing the game on increasing awareness. The Power the Grid game was chosen as a case study with the participation of ten players. The results showed a significant and remarkable role of playing this game in raising social awareness and educating HECs about energy issues compared with their awareness before playing the game. Accordingly, several options were proposed to be added to the game, which would enhance social awareness of their essential role in ensuring a secure energy future and a better environment, in addition to the accessibility of electrical power at reasonable prices. The content of these proposals revolves around the execution of the DR strategy, which has begun to be applied in several countries. This study recommends increasing the interest in supporting game designers and facilitating the marketing of such games to increase the number of their goers because of their positive impact.
- The "smart industrial revolution" with the "smart grid industry" contribute together to enhance the industrial production processes, resulting in sustainable economic and social development. Since engineers constitute a fundamental segment of this sector, well education and training for engineers contribute significantly to the industrial sector development and make them integrate easily into the job market. In CHAPTER 9, the focus shifts towards using educational strategies to equip future engineers with the necessary skills and mindset for addressing real-world challenges in manufacturing

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processes. This chapter seeks to empower students by providing them with a thorough comprehension of how their learning can be practically applied through the incorporation of theoretical knowledge and practical experiences into university curricula. It focuses on modernizing curricula in teaching industrial production principles and production processes, as well as the link between teachings in the classroom with practicing in reality. Students were equipped with the necessary skills by integrating theoretical instruction with practical applications, analyzing systems, and addressing problems mathematically. This holistic approach facilitated a deeper comprehension of the course and trained students to navigate real-world applications effectively. It effectively bridged the gap between theoretical study and practical application by introducing the students to prominent companies in their field and region. A feature of the course was visiting a manufacturing company, where both the teacher and industrialist experts facilitated a seamless link between classroom learning and real-world production processes. This experience enriched students' understanding of engineering processes and provided insights into their practical implementation. Moreover, students had the opportunity to engage with specialists from a renowned European company. Expert-led sessions were carried out in the classroom, fostering lively discussions and exchanges between students, experts, and the instructor. A feedback questionnaire was designed to assess the effectiveness of the teaching methodology, the overall student satisfaction, and identify potential areas for course improvement. The results demonstrate the efficacy of the course design in meeting its intended objectives. Besides, during the two academic years, the active participation, overall student satisfaction, and good grades underscore the students' appreciation and interest in the course.

- CHAPTER 10 presents a literature review focusing on recent studies in sustainability-related topics spanning from 2014 to 2023. The research framework implemented a selection process using the Web of Science database, refining criteria based on specific keywords in titles, abstracts, and topics. The literature review has three main sections including teaching optimization and simulation tools, energy flow management strategies, and battery manufacturing in terms of

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sustainability. CHAPTER 10 underscores the importance of educating future engineers, particularly in sustainability principles, optimization techniques, and software applications, where engineers significantly contribute in two key areas that have a strong correlation with sustainability. The first aspect is the role of engineers in the field of energy flow management, whether by carrying out research or projects on the ground. Where the literature shows that applying optimization techniques and modeling real-world systems in software are widely used in research. The second aspect involves the application of sustainability and optimization principles in manufacturing processes to ensure green manufacturing. This includes the selection of optimal materials and parameters for better performance and longevity, especially concerning batteries, due to their contribution to moving toward a secure and sustainable energy system.

As the third outcome, Part 3 proposed approaches to use simulation games technology and university curricula to raise awareness and train future engineers. The study found that immersion of individuals in simulation games of energy can increase the awareness of their key role in energy transition. Besides, modernizing curricula to be aligned with real-world technology development contributes in well future engineers' preparation. Part 3 revealed the potential of using technologies such as video games to make individuals understand how their role can contribute toward sustainability by adopting RESs and adjusting energy consumption. Likewise, it demonstrated that modernizing curricula, efficient teaching methods, teaching optimization and software tools, field visits, and lectures by experts can bridge the gap between theory and practice and bring students closer to real-world applications, which resulted in well-skilled future engineers.

Once the results of each of the three parts of the thesis are obtained, as previously and consecutively explained, specific objectives related to each of them are achieved, giving the following related conclusions:

1. The thesis **investigated** the key drivers for adopting efficient energy practices using HEMSs, which contribute to understanding the challenges and opportunities in sustainable energy practices adoption within the residential sector. It found that enhancing environmental awareness and family economic benefits significantly contributes to the

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use of HEMSs. This helps policymakers draw up policies to encourage energy consumers to use HEMSs, resulting in energy costs and carbon emissions reduction and enhancing energy security.

2. The thesis proposed innovative demand-side management **strategies** within SG delves into the application of advanced technologies and methodologies. The developed strategies considered electricity tariff incentives, energy consumers' preferences, preserving the environment, and energy systems life cycle. The thesis showed how these strategies provide benefits for energy consumers, the environment, and the overall electrical system by reducing energy usage costs, carbon emissions, and reliance on fossil fuels while simultaneously extending energy systems' lifetime and saving energy.

3. The thesis provided **approaches** to utilize technologies and curricula to prepare future engineers. It focused on utilizing technologies to raise awareness of energy consumers about their role in energy transition. It elucidated that simulation games of energy raise individuals' awareness and encourage active participation and responsible energy behavior leading to establishing a sustainable energy system. Besides, It highlighted the role of education in equipping future engineers by modernizing curricula, efficient teaching methods, teaching optimization and software tools, and on-site visits.

In conclusion, we can tell that the thesis provided practical solutions for moving toward energy sustainability and transition in terms of demand-side management in SG technology, raising awareness, and training future engineers. It proposed efficient demand side management strategies to integrate RESs and ESSs, raised society's awareness of energy consumers' role in energy sustainability, highlighted how the residential sector contributes to this endeavor, and underscored the importance of training future engineers to achieve efficient and sustainable tasks in scientific research and their professions, which are aligned with the objectives of the “European Green Deal”, “Paris Agreement”, “NZE scenario”, “EAP”, and “REPowerEU plan”. In other words, this work showed how the integration of clean energy systems, batteries, and electric vehicles drives sustainability and offers contributions to human wellbeing (reducing energy costs and independent self-consumption), preserving

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the environment (reducing carbon emission), and enhances overall energy systems (energy efficiency and energy security). It also showed how technologies and curricula play a key role in driving sustainability in terms of raising awareness and training future engineers. This thesis brought theory regulations, policies, and knowledge to real-world applications, offering a contribution for both individuals and policymakers in terms of moving toward sustainability and energy transition.

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RESUMEN

La sostenibilidad se ha convertido en un tema global en los últimos años debido principalmente a los recursos limitados y las preocupaciones entorno al cambio climático. Existe un reconocimiento cada vez mayor de la necesidad de adoptar prácticas sostenibles para garantizar el bienestar de las generaciones actuales y futuras. La promoción de la sostenibilidad ha ganado atención en varios sectores, como la energía, el transporte, la industria y la educación. En consecuencia, la sostenibilidad se ha convertido en una parte integral de los marcos políticos, la responsabilidad comunitaria y los planes de estudio educativos, lo que refleja un compromiso compartido para construir un futuro más resiliente y equitativo.

En cuanto a la sostenibilidad energética, la Unión Europea realiza esfuerzos en la transición energética y el reto de conseguir una emisión global neta cero, delineando políticas y proporcionando iniciativas para establecer un futuro sistema energético sostenible. El "Pacto Verde Europeo", el "Acuerdo de París", el escenario en 2050 de "cero emisiones netas", el "8º Programa europeo de acción medioambiental" y el "plan europeo REPowerEU", planean una sinergia conjunta para dar forma al panorama energético y alinearlo con el esfuerzo global en términos de desarrollo del sector de las energías renovables, reducción de la dependencia de los combustibles fósiles y descarbonización.

La integración de "sistemas de energía renovable" (*RESs*) es clave para mejorar la seguridad energética, reducir las emisiones y promover el crecimiento económico y tecnológico. El progreso en la penetración de *RESs* en la red eléctrica principal presenta desafíos debido a las variaciones de la demanda de energía y las fluctuaciones de la energía generada por los *RESs*, influenciadas por las condiciones climáticas, lo que genera problemas de equilibrio energético y en la estabilidad de la red. Además, el crecimiento continuo de la población y la tecnología ha llevado a un aumento notable en el consumo de energía, lo que subraya la necesidad de un futuro sistema energético fiable. Por lo tanto, abordar

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estos desafíos es imperativo para el avance sostenible. El sector residencial representa una parte sustancial del consumo total de energía, lo que indica su papel potencial en la adopción de prácticas energéticas eficientes alineadas con los esfuerzos globales hacia la transición energética y las cero emisiones netas.

La gestión del lado de la demanda es esencial para avanzar en la transición energética y el desarrollo del sector de las energías renovables. Implica optimizar y monitorear el consumo de energía y controlar las operaciones de la red de manera eficiente, permitiendo la integración perfecta de los *RESs* a la vez que se mantiene la estabilidad y fiabilidad de la red. Las estrategias de gestión del lado de la demanda pueden incluir la implementación de tecnologías energéticamente eficientes, sistemas domésticos inteligentes e iniciativas de cambio de comportamiento. En el ámbito del desarrollo de los *RESs*, la gestión del lado de la demanda facilita la integración de los *RESs* en la red principal, empleando técnicas como la "respuesta a la demanda" (*DR*) y los "sistemas de almacenamiento de energía" *(ESSs)* dentro de la tecnología de "red inteligente" (*SG)*, para adaptarse a las fluctuaciones inherentes en *RESs* como la eólica y la solar, y asegurar así un suministro energético fiable y estable. En línea con las políticas y regulaciones establecidas hacia un sistema energético sostenible, la gestión del lado de la demanda permite a los consumidores de energía cumplir con estos requisitos regulatorios mediante la adopción de tecnologías de energía limpia, la reducción de la huella de carbono y la mejora de la eficiencia energética. En resumen, la gestión del lado de la demanda tiene beneficios multifacéticos que incluyen la reducción de los costes de energía, la preservación del medio ambiente y la garantía de la seguridad energética.

Además, la "revolución industrial inteligente" enfatiza la necesidad de prácticas sostenibles en el consumo de energía, procesos de producción eficientes y la integración de los principios de sostenibilidad en la fabricación utilizando las "Tecnologías de la Información y la Comunicación". La Comisión Europea creó el grupo de trabajo "Uso sostenible y eficiente de la energía en la industria" en 2016 y lo revisó en 2021 para alinearlo con la investigación, la innovación y las políticas recientes como el Pacto Verde Europeo. Su objetivo es ayudar a las

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industrias a consumir menos energía. En este contexto, los ingenieros realizan muchas tareas en la industria, como la optimización de procesos, la recuperación de energía, la resolución de problemas y el análisis y la automatización de datos necesarios para realizar tareas sostenibles dentro del sector industrial.

El principal objetivo de esta tesis es investigar exhaustivamente la eficacia y el potencial de la gestión del lado de la demanda para fomentar prácticas energéticas sostenibles dentro del sector residencial utilizando tecnología de *SG*. Este enfoque se centra principalmente en mejorar la seguridad energética, la transición energética y la eficiencia energética, y se corresponde estrechamente con los objetivos establecidos en "Pacto Verde Europeo", el "Acuerdo de París", el escenario en 2050 de "cero emisiones netas", el "8º Programa europeo de acción medioambiental" y el "Plan europeo REPowerEU".

Los objetivos específicos son: **investigar** los principales impulsores para la implementación de "Sistemas de gestión de energía en el hogar" (*HEMSs*), incluyendo la evaluación de la capacidad de *HEMSs* para optimizar el consumo de energía, reducir los costes de energía, reducir las emisiones de carbono y mejorar la seguridad energética; explorar **estrategias** innovadoras para promover la gestión del lado de la demanda, considerando factores como los avances tecnológicos, los incentivos políticos y el comportamiento de los consumidores de energía (se hace hincapié en lograr objetivos ambientales, financieros, de consideración del ciclo de vida y de cambio de comportamiento); proporcionar **enfoques** para crear conciencia sobre el papel de la sociedad en el establecimiento de un sistema energético sostenible y dotar a los futuros ingenieros con la capacidad para la transferencia entre el conocimiento teórico y las aplicaciones del mundo real.

La metodología sigue tres partes conectadas con los tres objetivos específicos, con diversos capítulos cada una. En general, la metodología de investigación para cada capítulo implica una revisión exhaustiva de la literatura, un análisis de datos sobre la intención de los consumidores de energía hacia prácticas energéticas eficientes, el desarrollo de modelos matemáticos de estrategias de gestión del lado de la demanda y de utilización de tecnologías y enfoques para crear conciencia y

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educar y formar profesionales competentes en el ámbito de la energía para el desarrollo de los sectores industriales.

La Parte 1 incluye sólo un capítulo (CAPÍTULO 4). Se propone un modelo ampliado del "Modelo de Aceptación de Tecnología" (*TAM*) para investigar los factores que podrían afectar la intención de utilizar *HEMSs* y participar en los programas de *DR* una vez implantada la nueva tarifa eléctrica en España en 2021. Con base en la revisión de la literatura, la "conciencia ambiental percibida por el cliente" y los "beneficios económicos de la unidad familiar" se agregaron al *TAM*. El estudio se realizó en Galicia, noroeste de España. Después de recopilar los datos, se sometieron a un análisis utilizando el software de análisis de datos *Amos 20*. Los resultados cumplieron los objetivos de la investigación y proporcionaron información valiosa sobre la influencia de cada factor en la "intención de utilizar *HEMSs*". El estudio clarificó el impacto que ejercen diversos factores en la configuración de la "actitud" y la "intención de utilizar *HEMSs*". Los resultados muestran un impacto positivo de la "conciencia ambiental de los consumidores" y los "beneficios económicos de la familia" en su "actitud hacia el uso *HEMSs*". Además, los resultados muestran un efecto positivo directo de la "utilidad" y la "actitud hacia el uso" sobre "la intención de utilizar *HEMSs*". Se observa que cuanto mayores son los beneficios económicos y la conciencia ambiental, mayor es la actitud hacia el uso de *HEMSs*, lo que a su vez lleva a formular una intención positiva de utilizar *HEMSs*. El "beneficio económico percibido por la familia" se destaca como el factor más importante para mejorar la aceptación del consumidor, lo cual es consistente con la función de *HEMSs*; ahorrar energía y consumir energía en los periodos de precios bajos reduce la factura. Asimismo, la influencia de la "conciencia ambiental" sobre la "actitud hacia el uso de *HEMSs*" tiene una importancia notable. En otras palabras, los consumidores de energía están dispuestos a gestionar su consumo de energía para preservar el medio ambiente. Esta voluntad depende de que adquieran una conciencia adecuada sobre las cuestiones del cambio climático y se den cuenta de su papel esencial en la participación en los programas de *DR* encaminada a la mejora ambiental. Los resultados revelan que la "utilidad" tiene un impacto positivo y directo sobre la "intención de uso", y la "actitud" no media

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en la relación entre “utilidad” e “intención de uso”. Cuanto mayor sea la utilidad del uso de *HEMSs* para mejorar la calidad de vida, mayor será la intención de utilizarlos. Por el contrario, la “facilidad de uso” y la “utilidad” percibidas tienen efectos insignificantes en la “actitud hacia el uso”. A la luz de los hallazgos, los formuladores de políticas deberían tomar medidas que acentúen los beneficios económicos para los consumidores de energía y el impacto positivo en el medio ambiente de la adopción de *HEMSs* y elaborar políticas que respalden estos factores. Los investigadores pueden utilizar los hallazgos mencionados anteriormente como base para desarrollar aún más el modelo propuesto y explorar factores adicionales que potencialmente podrían afectar la aceptación del consumidor en España. Al hacerlo, pueden ofrecerles una comprensión más completa de los factores en juego, ayudando así a formular estrategias más efectivas destinadas a mejorar la aceptación de la nueva tarifa eléctrica por parte de los consumidores. Para obtener una comprensión más completa del tema en España, se recomienda ampliar el alcance de la investigación aumentando el tamaño de la muestra y realizando una encuesta a mayor escala que abarque varias ciudades del país. Un enfoque de este tipo produciría resultados más completos y sólidos, contribuyendo a una comprensión más profunda del comportamiento y las preferencias de los consumidores relacionados con el nuevo arancel.

Como primer resultado, la Parte 1 encontró que la “conciencia ambiental” y los “beneficios económicos familiares” impactan significativamente en la intención de adoptar prácticas eficientes de energía, utilizando *HEMSs* desde la adopción de la nueva tarifa eléctrica en España en 2021. Por otra parte, la “utilidad percibida del uso de *HEMSs*”, afecta directamente la “intención de los consumidores de energía de utilizar *HEMSs*”. La Parte 1 reveló el potencial del uso de *HEMSs* y exploró los principales impulsores clave de los consumidores de energía españoles que afectan sus hábitos de consumo de energía mediante el uso de *HEMSs*, lo que resulta en una reducción de los costes de energía y las emisiones de carbono.

La Parte 2 presenta **estrategias** innovadoras de *HEMSs* para lograr beneficios para los consumidores de energía, el medio ambiente y el sistema energético en general. Esta parte comprende tres capítulos:

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- El CAPÍTULO 5 propone una estrategia de gestión del flujo de energía. Se implementa un modelo de coste de utilización de energía combinando producción fotovoltaica (*PV*) y almacenamiento en baterías, considerando su coste de instalación. El modelo incluye el coste de almacenamiento de energía, los costes de operación y mantenimiento, y el coste de la energía comprada. El análisis de los resultados de la simulación muestra la distribución eficiente de la energía, enfocándose en lograr una reducción de costes reales y un funcionamiento óptimo de la batería. Durante los períodos de escasez de energía *PV*, la estrategia propuesta conserva estratégicamente las reservas de energía en las baterías, priorizando las operaciones de descarga cuando el precio de la energía de la red supera el precio de la energía de las baterías. Además, los hallazgos subrayan la ineficacia económica de vender el excedente de energía a la red, una práctica que a menudo produce menores retornos que el consumo doméstico. El trabajo propuesto muestra una reducción real del coste de energía asociada con los costes de instalación de baterías y *PV*, alentando a los consumidores a instalar sistemas de energía locales y administrar su consumo de energía. En consecuencia, estos hallazgos subrayan el papel de las soluciones energéticas descentralizadas en la mejora de la seguridad y la sostenibilidad energética.
- El CAPÍTULO 6 propone un método de optimización eficiente para programar electrodomésticos en conjunto con un sistema eficiente de gestión del flujo de energía que considera los ciclos de vida de la energía *PV* y de la batería, así como los costes de instalación. Se proponen y consideran modelos de fijación de precios del uso de energía *PV* y de baterías en la estrategia de optimización y el sistema de gestión del flujo de energía. Para la optimización, utilizamos el *Augmented Grey Wolf Optimization Algorithm* y el *Particle Swarm Optimization Algorithm*, que se implementan en el paquete de calculo numérico *MATLAB*. Se utilizaron datos reales de una vivienda en Vigo (España), para proporcionar resultados realistas que animen a los clientes nacionales a gestionar su consumo de energía con la nueva tarifa eléctrica en España implantada en 2021. Para mostrar la efectividad del sistema propuesto, se aplica una comparación con un modelo anterior de tarificación del uso de energía. El sistema propuesto

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logra una mejor reducción de costes y pérdidas de energía, una mayor extensión de la vida útil de la batería y alcanza el punto de equilibrio en poco tiempo. Alienta a los consumidores de energía a contribuir a la estabilidad de la red y la seguridad energética destacando los beneficios económicos y ambientales de programar electrodomésticos junto con el uso eficiente de la energía *PV* y las baterías durante su vida útil en comparación con sus costes de instalación. En el futuro, los autores proponen la posibilidad de estudiar el coste de reducción del consumo energético con la integración de vehículos eléctricos. Se recomienda también ampliar el alcance del estudio incorporando múltiples viviendas para estudiar el mecanismo de intercambio energético entre ellas, considerando las preferencias de cada usuario, e integrar cargas controladas termostáticamente al modelo de demanda de energía.

- EL CAPÍTULO 7 presenta un sistema eficaz de gestión de energía doméstica para hogares inteligentes que integra energía *PV*, baterías y vehículos eléctricos. Se desarrolló un algoritmo de gestión del flujo de energía para controlar los modos entre *PV*, baterías, vehículos eléctricos y la red. Además, introduce una estrategia de optimización utilizando *Particle Swarm Optimization Algorithm* para obtener parámetros óptimos para la batería (profundidad de descarga y tamaño) y la batería del vehículo eléctrico (profundidad de descarga) y programar los electrodomésticos. Se formularon e introdujeron en el proceso de optimización los modelos de costes de uso de energía *PV*, baterías y vehículos eléctricos, considerando los costes de instalación y el ciclo de vida de cada sistema, lo que resultó en una reducción de costes reales en comparación con los costes de instalación y garantizando la utilización sostenible del sistema integrado durante todo su proceso. vida operativa. Se simularon cuatro escenarios considerando condiciones climáticas de invierno y verano. El sistema propuesto tenía como objetivo reducir el coste energético real, extender la vida útil de *ESSs*, reducir las pérdidas de energía, reducir las emisiones de CO_2 y maximizar los retornos financieros de la instalación de la energía *PV*, la batería y el vehículo eléctrico en el hogar. Los resultados revelaron que el sistema propuesto logró los objetivos del estudio y su capacidad para hacer frente a diversas condiciones estacionales, variaciones del precio de la energía, preferencias de los

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usuarios y utilización sostenible de los sistemas energéticos. Además, los resultados alientan a los consumidores domésticos a buscar reducir su impacto ambiental y aumentar sus retornos financieros asociados con la inversión en sistemas de energía *PV*, baterías y vehículos eléctricos en el hogar, lo que resulta en la promoción de prácticas energéticas sostenibles y eficientes a nivel doméstico. En el futuro, los autores proponen ampliar el alcance del estudio incorporando varios hogares en diversas regiones geográficas (patrones de demanda de energía), considerando variaciones climáticas mensuales (dinámica estacional) e investigando y optimizando varios parámetros del sistema energético integrado para identificar las opciones más prácticas para aplicaciones residenciales (escalabilidad/ replicabilidad).

Como segundo resultado, la Parte 2 propuso tres estrategias de gestión del lado de la demanda utilizando energía *PV*, baterías y vehículos eléctricos conectados a la red. Las estrategias propuestas lograron la reducción de costes de energía, la utilización eficiente de sistemas energéticos, el ahorro de energía y la reducción de emisiones de carbono. La Parte 2 contribuyó a promover la gestión del lado de la demanda, ofreciendo beneficios a los consumidores de energía al reducir los costes de energía y mostrando cómo sus cambios de comportamiento en el consumo de energía contribuyen a preservar el medio ambiente y extender la vida útil de los sistemas energéticos. Además, contribuyó a incentivar al sector residencial a ser parte de los esfuerzos globales para avanzar hacia la sostenibilidad y la transición energética.

La Parte 3 lleva a cabo estudios de casos para el sector energético y el avance de la industria, se centra en proporcionar enfoques para crear conciencia sobre los problemas energéticos para avanzar hacia la transición energética utilizando tecnología de juegos de simulación y educar/capacitar a futuros ingenieros utilizando los planes de estudio de la universidad. Se incluyen tres capítulos:

- EL CAPÍTULO 8 presenta un enfoque para examinar el papel de los juegos de simulación en la sensibilización social sobre el papel de los consumidores de energía en la transición energética y la sostenibilidad. En línea con el desarrollo tecnológico en el sector energético y el aumento de las preocupaciones sobre la seguridad

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energética y el cambio climático, este estudio se llevó a cabo para examinar cómo los juegos de simulación podrían afectar la conciencia de los "consumidores de energía en el hogar" *(HECs)* sobre su papel a la hora de contribuir a la seguridad energética, reduciendo el impacto ambiental. del uso de energía y la reducción de los precios de la electricidad. Primero, se realizó un cuestionario para medir la conciencia de los individuos, luego se explicaron las reglas del juego y los jugadores comenzaron a jugar. Después de eso, se llevó a cabo otro cuestionario después de jugar el juego para medir el efecto de jugarlo en el aumento de la conciencia. Se eligió como caso de estudio el juego *Power the Grid* con la participación de diez jugadores. Los resultados mostraron un papel significativo y notable de este juego para aumentar la conciencia social y educar a *HECs* sobre cuestiones energéticas en comparación con su conciencia antes de jugar. En consecuencia, se propuso agregar al juego varias opciones que mejorarían la conciencia social sobre su papel esencial para garantizar un futuro energético seguro y un mejor medio ambiente, además de la accesibilidad a la energía eléctrica a precios razonables. El contenido de estas propuestas gira en torno a la ejecución de la estrategia de *DR*, que ha comenzado a aplicarse en varios países. Este estudio recomienda aumentar el interés en apoyar a los diseñadores de juegos y facilitar la comercialización de dichos juegos para aumentar el número de asistentes debido a su impacto positivo.

- La "revolución industrial inteligente" con la "industria de *SG*" contribuyen juntas a mejorar los procesos de producción industrial, lo que resulta en un desarrollo económico y social sostenible. Dado que los ingenieros constituyen un segmento fundamental de este sector, la educación y la formación de los ingenieros contribuyen significativamente al desarrollo del sector industrial y les permite integrarse fácilmente en el mercado laboral. En el CAPÍTULO 9, el enfoque cambia hacia el uso de estrategias educativas para equipar a los futuros ingenieros con las habilidades y la mentalidad necesarias para abordar los desafíos del mundo real en los procesos de fabricación. Este capítulo busca empoderar a los estudiantes brindándoles una comprensión profunda de cómo su aprendizaje puede aplicarse en la práctica mediante la incorporación de conocimientos teóricos y

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experiencias prácticas en los planes de estudio universitarios. Se centra en modernizar los planes de estudio en la enseñanza de los principios y procesos de producción industrial, así como en el vínculo entre la enseñanza en el aula y la práctica en la realidad. Los estudiantes recibieron las habilidades necesarias al integrar la instrucción teórica con aplicaciones prácticas, analizar sistemas y abordar problemas matemáticos. Este enfoque holístico facilitó una comprensión más profunda del curso y capacitó a los estudiantes para navegar eficazmente en aplicaciones del mundo real. Cerró efectivamente la brecha entre el estudio teórico y la aplicación práctica al presentar a los estudiantes empresas destacadas en su campo y región. Una característica del curso fue la visita a una empresa manufacturera, donde tanto el profesor como los expertos industriales facilitaron un vínculo perfecto entre el aprendizaje en el aula y los procesos de producción del mundo real. Esta experiencia enriqueció la comprensión de los estudiantes sobre los procesos de ingeniería y proporcionó información sobre su implementación práctica. Además, los estudiantes tuvieron la oportunidad de interactuar con especialistas de una reconocida empresa europea. Se llevaron a cabo sesiones dirigidas por expertos en el aula, fomentando animados debates e intercambios entre estudiantes, expertos y el instructor. Se diseñó un cuestionario de retroalimentación para evaluar la efectividad de la metodología de enseñanza, la satisfacción general de los estudiantes e identificar áreas potenciales de mejora del curso. Los resultados demuestran la eficacia del diseño del curso para alcanzar los objetivos previstos. Además, durante los dos años académicos, la participación activa, la satisfacción general de los estudiantes y las buenas calificaciones subrayan el aprecio y el interés de los estudiantes por el curso.

- El CAPÍTULO 10 presenta una revisión de la literatura centrada en estudios recientes sobre temas relacionados con la sostenibilidad que abarcan desde 2014 hasta 2023. El marco de investigación implementó un proceso de selección utilizando la base de datos *Web of Science*, refinando los criterios basados en palabras clave específicas en títulos, resúmenes y temas. La revisión de la literatura tiene tres secciones principales que incluyen la enseñanza de herramientas de simulación y optimización, estrategias de gestión del flujo de energía y fabricación

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de baterías en términos de sostenibilidad. El CAPÍTULO 10 subraya la importancia de educar a los futuros ingenieros, particularmente en principios de sostenibilidad, técnicas de optimización y aplicaciones de software, donde los ingenieros contribuyen significativamente en dos áreas clave que tienen una fuerte correlación con la sostenibilidad. El primer aspecto es el papel de los ingenieros en el campo de la gestión del flujo de energía, ya sea mediante la realización de investigaciones o proyectos sobre el terreno. Donde la literatura muestra que la aplicación de técnicas de optimización y modelado de sistemas del mundo real en software son ampliamente utilizados en la investigación. El segundo aspecto implica la aplicación de principios de sostenibilidad y optimización en los procesos de fabricación para garantizar una fabricación ecológica. Esto incluye la selección de materiales y parámetros óptimos para un mejor rendimiento y longevidad, especialmente en lo que respecta a las baterías, debido a su contribución a avanzar hacia un sistema energético seguro y sostenible.

Como tercer resultado, la Parte 3 propone enfoques para utilizar la tecnología de los juegos de simulación y los planes de estudio universitarios para crear conciencia y educar a los futuros ingenieros. El estudio encontró que la inmersión de las personas en juegos de simulación de energía puede aumentar la conciencia de su papel clave en la transición energética. Además, modernizar los planes de estudio para alinearlos con el desarrollo tecnológico del mundo real contribuye a la preparación de los futuros ingenieros. La parte 3 reveló el potencial del uso de tecnologías como los juegos de simulación para hacer que las personas comprendan cómo su papel puede contribuir a la sostenibilidad mediante la adopción de *RESs* y el ajuste del consumo de energía. Asimismo, demostró que la modernización de los planes de estudio, los métodos de enseñanza eficientes, la optimización de la enseñanza y las herramientas de software, las visitas de campo y las conferencias de expertos pueden cerrar la brecha entre la teoría y la práctica y acercar a los estudiantes a las aplicaciones del mundo real, lo que resultó en futuros bien capacitados. ingenieros.

Una vez obtenidos los resultados de cada una de las tres partes de la tesis, tal y como se explicó anterior y consecutivamente, se alcanzan

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objetivos específicos relacionados con cada una de ellas, dando las siguientes conclusiones relacionadas:

1. La tesis investigó los impulsores clave para la adopción de prácticas energéticas eficientes utilizando *HEMSs*, que contribuyen a comprender los desafíos y oportunidades en la adopción de prácticas energéticas sostenibles dentro del sector residencial. Encontró que mejorar la conciencia ambiental y los beneficios económicos familiares contribuye significativamente al uso de *HEMSs*. Esto ayuda a los formuladores de políticas a elaborar políticas para alentar a los consumidores de energía a utilizar *HEMSs*, lo que resulta en una reducción de los costes de energía y de las emisiones de carbono y mejora de la seguridad energética.
2. La tesis propone estrategias innovadoras de gestión del lado de la demanda dentro de *SG* profundiza en la aplicación de tecnologías y metodologías avanzadas. Las estrategias desarrolladas consideraron incentivos tarifarios de electricidad, preferencias de los consumidores de energía, preservación del medio ambiente y ciclo de vida de los sistemas energéticos. La tesis mostró cómo estas estrategias brindan beneficios para los consumidores de energía, el medio ambiente y el sistema eléctrico en general al reducir los costes de uso de energía, las emisiones de carbono y la dependencia de combustibles fósiles, al mismo tiempo que extienden la vida útil de los sistemas energéticos y ahorran energía.
3. La tesis propuso enfoques para utilizar tecnologías y planes de estudio para preparar a futuros ingenieros. Se centró en la utilización de tecnologías para concienciar a los consumidores de energía sobre su papel en la transición energética. Se aclaró que los juegos de simulación de energía aumentan la conciencia de las personas y fomentan la participación activa y un comportamiento energético responsable que conduzca al establecimiento de un sistema energético sostenible. Además, destacó el papel de la educación en la preparación de los futuros ingenieros mediante la modernización de los planes de estudio, métodos de enseñanza eficientes, optimización de la enseñanza y herramientas de software, y visitas *in situ*.

En conclusión, podemos decir que la tesis proporcionó soluciones prácticas para avanzar hacia la sostenibilidad energética y la transición

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en términos de gestión del lado de la demanda en tecnología de *SG*, crear conciencia y educar a los futuros ingenieros. Propuso estrategias eficientes de gestión del lado de la demanda para integrar *RESs* y *ESSs*, aumentó la conciencia de la sociedad sobre el papel de los consumidores de energía en la sostenibilidad energética, destacó cómo el sector residencial contribuye a este esfuerzo y subrayó la importancia de educar a los futuros ingenieros para lograr sistemas eficientes. y tareas sostenibles en la investigación científica y sus profesiones, que estén alineadas con los objetivos del "Pacto Verde Europeo", el "Acuerdo de París", el escenario en 2050 de "cero emisiones netas", el "8º Programa europeo de acción medioambiental" y el "plan europeo REPowerEU". En otras palabras, este trabajo mostró cómo la integración de sistemas de energía limpia, baterías y vehículos eléctricos impulsa la sostenibilidad y ofrece contribuciones al bienestar humano (reduciendo los costes de energía y el autoconsumo independiente), preservando el medio ambiente (reduciendo las emisiones de carbono) y mejorando Sistemas energéticos globales (eficiencia energética y seguridad energética). También mostró cómo las tecnologías y los planes de estudios desempeñan un papel clave a la hora de impulsar la sostenibilidad en términos de sensibilización y formación de futuros ingenieros. Esta tesis llevó las regulaciones teóricas, las políticas y el conocimiento a aplicaciones del mundo real, ofreciendo una contribución tanto para los individuos como para los formuladores de políticas en términos de avanzar hacia la sostenibilidad y la transición energética.

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RESUMO

A sostibilidade converteuse nun problema global nos últimos anos debido principalmente aos recursos limitados e ás preocupacións sobre o cambio climático. Hai un recoñecemento crecente da necesidade de adoptar prácticas sostibles para garantir o benestar das xeracións actuais e futuras. A promoción da sostibilidade gañou atención en diversos sectores, como a enerxía, o transporte, a industria e a educación. En consecuencia, a sostibilidade converteuse nunha parte integrante dos marcos políticos, da responsabilidade comunitaria e dos currículos educativos, o que reflicte un compromiso compartido para construír un futuro máis resistente e equitativo.

En canto á sostibilidade enerxética, a Unión Europea está a facer esforzos na transición enerxética e no reto de acadar cero emisións mundiais netas, delineando políticas e proporcionando iniciativas para establecer un futuro sistema enerxético sustentable. O "Pacto Verde Europeo", o "Acordo de París", "8o Programa Europeo de Acción Ambiental", o "Escenario Cero Emisións Netas para 2050" e o "plan REPowerEU", planifican unha sinerxía conxunta para dar forma ao panorama enerxético e aliñarse. co esforzo global en materia de desenvolvemento do sector das enerxías renovables, redución da dependencia dos combustibles fósiles e descarbonización.

A integración de "sistemas de enerxía removable" (*RESs*) é clave para mellorar a seguridade enerxética, reducir as emisións e promover o crecemento económico e tecnolóxico. Os avances na penetración dos sistemas de enerxías renovables na rede eléctrica principal presentan retos debido ás variacións na demanda de enerxía e ás flutuacións da potencia xerada polos sistemas de enerxías renovables, influenciadas polas condicións meteorolóxicas, o que orixina problemas de balance enerxético e de estabilidade da rede. Ademais, o continuo crecemento da poboación e da tecnoloxía levou a un notable aumento do consumo de enerxía, o que subliña a necesidade dun futuro sistema enerxético fiable. Polo tanto, abordar estes desafíos é imprescindible para o avance

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sostible. O sector residencial representa unha parte substancial do consumo total de enerxía, o que indica o seu papel potencial na adopción de prácticas enerxéticas eficientes aliñadas cos esforzos mundiais para a transición enerxética e as emisións netas cero.

A xestión da demanda é esencial para avanzar na transición enerxética e no desenvolvemento do sector das enerxías renovables. Implica optimizar e supervisar o consumo de enerxía e controlar as operacións da rede de forma eficiente, permitindo a integración perfecta dos *RESs* mantendo a estabilidade e fiabilidade da rede. As estratexias de xestión da demanda poden incluír a implementación de tecnoloxías eficientes enerxéticamente, sistemas domésticos intelixentes e iniciativas de cambio de comportamento. No ámbito do desenvolvemento de *RESs*, a xestión da demanda facilita a integración de *RESs* na rede principal, utilizando técnicas como a "resposta á demanda" (*DR*) e os "sistemas de almacenamento de enerxía" (*ESSs*) dentro da tecnoloxía de "rede intelixente" (*SG*), para adaptarse ás flutuacións inherentes ás enerxías renovables. sistemas como eólico e solar, garantindo así un abastecemento de enerxía fiable e estable. De acordo coas políticas e regulamentos establecidos para un sistema enerxético sostible, a xestión da demanda permite aos consumidores de enerxía cumprir estes requisitos regulamentarios adoptando tecnoloxías de enerxía limpa, reducindo a pegada de carbono e mellorando a eficiencia enerxética. En resumo, a xestión da demanda ten beneficios multifacéticos, incluíndo a redución dos custos enerxéticos, a preservación do medio ambiente e a garantía de seguridade enerxética.

Ademais, a "revolución industrial intelixente" enfatiza a necesidade de prácticas sostibles no consumo de enerxía, procesos de produción eficientes e a integración de principios de sostibilidade na fabricación utilizando "Tecnoloxías da Información e da Comunicación". A Comisión Europea creou o grupo de traballo "Uso sustentable e eficiente da enerxía na industria" en 2016 e revisouno en 2021 para aliñalo coa investigación, innovación e políticas recentes como o Pacto Verde Europeo. O seu obxectivo é axudar ás industrias a consumir menos enerxía. Neste contexto, os enxeñeiros realizan moitas tarefas na industria, como a optimización de procesos, a recuperación de enerxía, a resolución de problemas e a análise e automatización de

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datos necesarios para realizar tarefas sostibles dentro do sector industrial.

O obxectivo principal desta tese é investigar exhaustivamente a eficacia e o potencial da xestión da demanda na promoción de prácticas enerxéticas sostibles no sector residencial mediante a tecnoloxía *SG*. Este enfoque céntrase principalmente na mellora da seguridade enerxética, a transición enerxética e a eficiencia enerxética, e correspóndese estreitamente cos obxectivos establecidos no "Pacto Verde Europeo", o "Acordo de París", "8º Programa Europeo de Acción Ambiental", o "Escenario Cero Emisións Netas para 2050" e o "plan REPowerEU".

Os obxectivos específicos son: **investigar** os principais motores para a implantación dos "Sistemas de Xestión da Enerxía Doméstica" (*HEMS*), incluíndo a avaliación da capacidade dos *HEMS* para optimizar o consumo de enerxía, reducir os custos enerxéticos, reducir as emisións de carbono e mellorar a seguridade enerxética; explorar **estratexias** innovadoras para promover a xestión da demanda, tendo en conta factores como os avances tecnolóxicos, os incentivos políticos e o comportamento dos consumidores de enerxía (féntase na consecución de obxectivos ambientais, financeiros, de ciclo de vida e de cambio de comportamento). proporcionar **enfoques** para concienciar sobre o papel da sociedade no establecemento dun sistema enerxético sostible e dotar aos futuros enxeñeiros da capacidade de transferencia entre coñecementos teóricos e aplicacións do mundo real.

A metodoloxía segue tres partes conectadas cos tres obxectivos específicos, con varios capítulos cada unha. En xeral, a metodoloxía de investigación para cada capítulo implica unha revisión exhaustiva da literatura, análise de datos sobre a intención dos consumidores de enerxía cara a prácticas enerxéticas eficientes, desenvolvemento de modelos matemáticos de estratexias de xestión da demanda e uso de tecnoloxías e enfoques para concienciar, educar e formar. profesionais competentes no ámbito da enerxía para o desenvolvemento dos sectores industriais.

A parte 1 inclúe só un capítulo (CAPÍTULO 4). Proponse un modelo ampliado do "Modelo de Aceptación de Tecnoloxía" (*TAM*) para **investigar** os factores que poderían afectar a intención de utilizar

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HEMS e participar en programas de *DR* unha vez implantada a nova tarifa eléctrica en España en 2021. En base á revisión da literatura, "a conciencia ambiental percibida polo cliente" e "beneficios económicos da unidade familiar" engadíronse ao *TAM*. O estudo realizouse en Galicia, no noroeste de España. Despois de recoller os datos, sometéronse a análise mediante o software de análise de datos *Amos 20*. Os resultados cumpriron os obxectivos da investigación e proporcionaron información valiosa sobre a influencia de cada factor na "intención de usar *HEMS*". O estudo aclarou o impacto de varios factores na configuración da "actitude" e a "intención de usar *HEMS*". Os resultados mostran un impacto positivo da "conciencia ambiental dos consumidores" e dos "beneficios económicos familiars" na súa "actitude cara ao uso dos *HEMS*". Ademais, os resultados mostran un efecto positivo directo da "utilidade" e da "actitude cara ao uso" na "intención de usar *HEMS*". Obsérvase que cantos maiores son os beneficios económicos e a conciencia ambiental, maior é a actitude cara ao uso dos *HEMS*, o que leva á súa vez a formular unha intención positiva de utilizar os *HEMS*. Destácase o "beneficio económico percibido pola familia" como o factor máis importante para mellorar a aceptación dos consumidores, coherente coa función dos *HEMS*; Aforrar enerxía e consumir enerxía durante períodos de baixo prezo reduce a túa factura. Así mesmo, a influencia da "conciencia ambiental" na "actitude cara ao uso dos HEMS" é de notable importancia. Noutras palabras, os consumidores de enerxía están dispostos a xestionar o seu consumo de enerxía para preservar o medio ambiente. Esta vontade depende de que adquiran unha conciencia adecuada sobre os problemas do cambio climático e se dean conta do seu papel esencial na participación en programas de *DR* destinados á mellora ambiental. Ademais, os resultados revelan que a "utilidade" ten un impacto positivo e directo na "intención de usar", e a "actitude" non media na relación entre "utilidade" e "intención de usar". Canto maior sexa a utilidade do uso dos *HEMS* para mellorar a calidade de vida, maior será a intención de utilizalos. Pola contra, a "facilidade de uso" e a "utilidade" percibidas teñen efectos insignificantes na "actitude cara ao uso". Á luz dos resultados, os responsables políticos deberían adoptar medidas que acentúen os beneficios económicos para os consumidores

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de enerxía e o impacto positivo sobre o medio ambiente da adopción de *HEMS* e desenvolver políticas que apoien estes factores. Os investigadores poden utilizar os resultados mencionados anteriormente como base para desenvolver aínda máis o modelo proposto e explorar factores adicionais que poidan afectar a aceptación dos consumidores en España. Con iso, poden ofrecerlles unha comprensión máis completa dos factores en xogo, contribuíndo así a formular estratexias máis eficaces destinadas a mellorar a aceptación dos consumidores da nova tarifa eléctrica. Para obter unha comprensión máis completa do tema en España, recoméndase ampliar o alcance da investigación aumentando o tamaño da mostra e realizando unha enquisa a maior escala que abarque varias cidades do país. Este enfoque produciría resultados máis completos e robustos, contribuíndo a unha comprensión máis profunda do comportamento e das preferencias dos consumidores relacionadas coa nova tarifa.

Como primeiro resultado, a Parte 1 constatou que a "concienciación ambiental" e os "beneficios económicos familiars" inciden significativamente na intención de adoptar prácticas de eficiencia enerxética, utilizando *HEMS* desde a adopción da nova tarifa eléctrica en España en 2021. Ademais, a "utilidade percibida do uso de *HEMS*" afecta directamente "a intención dos consumidores de enerxía de usar *HEMS*". A parte 1 revelou o potencial do uso de *HEMS* e explorou os principais motores dos consumidores españois de enerxía que afectan os seus hábitos de consumo enerxético mediante o uso de *HEMS*, o que resulta nunha redución dos custos enerxéticos e das emisións de carbono.

A parte 2 presenta **estratexias** innovadoras de *HEMS* para conseguir beneficios para os consumidores de enerxía, o medio ambiente e o sistema enerxético en xeral. Esta parte inclúe tres capítulos:

- O CAPÍTULO 5 propón unha estratexia de xestión do fluxo de enerxía. Impléntase un modelo de custo de utilización da enerxía que combina a produción fotovoltaica (*PV*) e o almacenamento de baterías, tendo en conta o seu custo de instalación. O modelo inclúe o custo do almacenamento de enerxía, os custos de operación e mantemento e o custo da enerxía adquirida. A análise dos resultados da simulación

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mostra unha distribución eficiente da enerxía, centrándose en conseguir unha redución de custos reais e un rendemento óptimo da batería. Durante os períodos de escaseza de enerxía *PV*, a estratexia proposta conserva estratexicamente as reservas de enerxía nas baterías, priorizando as operacións de descarga cando o prezo da enerxía da rede supera o prezo da batería. Ademais, os resultados destacan a ineficiencia económica da venda de enerxía excedente á rede, unha práctica que adoita producir menores retornos que o consumo doméstico. O traballo proposto mostra unha redución real do custo enerxético asociado aos custos de instalación de baterías e *PV*, animando aos consumidores a instalar sistemas de enerxía locais e xestionar o seu consumo enerxético. En consecuencia, estes achados subliñan o papel das solucións enerxéticas descentralizadas na mellora da seguridade enerxética e da sostibilidade.

- O CAPÍTULO 6 propón un método de optimización eficiente para a programación de electrodomésticos xunto cun sistema de xestión de fluxo de enerxía eficiente que teña en conta os ciclos de vida das baterías e *PV*, así como os custos de instalación. Propóñense modelos de prezos do uso da enerxía *PV* e da batería e considéranse na estratexia de optimización e no sistema de xestión do fluxo de enerxía. Para a optimización, usamos o *Augumented Grey Wolf Optimization Algorithm* e o *Particle Swarm Optimization Algorithm*, que se implementan no paquete de cálculo numérico de *MATLAB*. Utilizáronse datos reais dunha vivenda de Vigo (España) para ofrecer resultados realistas que incentiven aos clientes nacionais a xestionar o seu consumo enerxético coa nova tarifa eléctrica implantada en España en 2021. Para mostrar a eficacia do sistema proposto, aplícase unha comparación. cun modelo de prezos de consumo de enerxía anterior. O sistema proposto consegue unha mellor redución de custos e perdas enerxéticas, unha maior prolongación da duración da batería e chega ao punto de equilibrio en pouco tempo. Anima aos consumidores de enerxía a contribuír á estabilidade da rede e á seguridade enerxética destacando os beneficios económicos e ambientais da programación de aparellos xunto co uso eficiente da enerxía *PV* e das baterías ao longo da súa vida útil en comparación cos seus custos de instalación. No futuro, os autores propoñen a posibilidade de estudar o custo da

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redución do consumo enerxético coa integración dos vehículos eléctricos. Ademais, recoméndase ampliar o alcance do estudo incorporando varias vivendas para estudar o mecanismo de intercambio enerxético entre elas, tendo en conta as preferencias de cada usuario, e integrar as cargas controladas termostáticamente no modelo de demanda enerxética.

- O CAPÍTULO 7 presenta un sistema eficaz de xestión da enerxía doméstica para fogares intelixentes que integra enerxía *PV*, baterías e vehículos eléctricos. Desenvolveuse un algoritmo de xestión de fluxo de enerxía para controlar os modos entre a *PV*, as baterías, os vehículos eléctricos e a rede. Ademais, introduce unha estratexia de optimización mediante o *Particle Swarm Optimization Algorithm* para obter os parámetros óptimos da batería (profundidade e tamaño de descarga) e da batería do vehículo eléctrico (profundidade de descarga) e programar os electrodomésticos. Formuláronse e introducíronse no proceso de optimización modelos de custos de uso de vehículos eléctricos, *PV*, e baterías, tendo en conta os custos de instalación e o ciclo de vida de cada sistema, resultando nunha redución dos custos reais en comparación cos custos de instalación e garantindo o uso sostible do sistema integrado en todo o tempo. o seu proceso. vida operativa. Simuláronse catro escenarios tendo en conta as condicións climáticas de inverno e verán. O sistema proposto tiña como obxectivo reducir o custo enerxético real, estender a vida útil dos *ESS*, reducir as perdas enerxéticas, reducir as emisións de CO_2 e maximizar o rendemento económico da instalación de vehículos *PV*, baterías e eléctricos no fogar. Os resultados revelaron que o sistema proposto acadou os obxectivos do estudo e a súa capacidade para facer fronte a diversas condicións estacionais, variacións de prezos da enerxía, preferencias dos usuarios e utilización sostible dos sistemas enerxéticos. Ademais, os resultados incentivan aos consumidores domésticos a buscar reducir o seu impacto ambiental e aumentar os seus retornos financeiros asociados ao investimento en sistemas de enerxía *PV*, de baterías e de vehículos eléctricos domésticos, o que resulta na promoción de prácticas enerxéticas sostibles e eficientes a nivel doméstico. No futuro, os autores propoñen ampliar o alcance do estudo incorporando varios fogares en varias rexións xeográficas (patróns de demanda enerxética),

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considerando as variacións climáticas mensuais (dinámicas estacionais) e investigando e optimizando varios parámetros do sistema enerxético integrado para identificar as opcións máis adecuadas para aplicacións residenciais (escalabilidade/replicabilidade).

Como segundo resultado, a Parte 2 propuxo tres estratexias de xestión do lado da demanda utilizando *PV*, baterías e vehículos eléctricos conectados á rede. As estratexias propostas lograron a redución dos custos enerxéticos, o uso eficiente dos sistemas enerxéticos, o aforro enerxético e a redución das emisións de carbono. A segunda parte contribuíu a promover a xestión da demanda, ofrecendo beneficios aos consumidores de enerxía reducindo os custos enerxéticos e mostrando como os seus cambios de comportamento no consumo de enerxía contribúen a preservar o medio ambiente e prolongar a vida útil dos sistemas enerxéticos. Ademais, contribuíu a fomentar que o sector residencial forme parte dos esforzos globais para avanzar cara á sostibilidade e á transición enerxética.

A parte 3 realiza estudos de caso para o sector enerxético e o avance da industria, céntrase en ofrecer **enfoques** para concienciar sobre os problemas enerxéticos para avanzar cara á transición enerxética mediante a tecnoloxía de xogos de simulación e educar/formar futuros enxeñeiros utilizando os plans de estudo universitarios. Inclúense tres capítulos:

- O CAPÍTULO 8 presenta un enfoque para examinar o papel dos xogos de simulación na concienciación social sobre o papel dos consumidores de enerxía na transición enerxética e na sostibilidade. En liña co desenvolvemento tecnolóxico do sector enerxético e as crecentes preocupacións sobre a seguridade enerxética e o cambio climático, este estudo realizouse para examinar como os xogos de simulación poden afectar a concienciación dos "consumidores domésticos de enerxía" (*HECs*) sobre o seu papel na contribución á enerxía seguridade, reducindo o impacto ambiental. do uso da enerxía e a redución dos prezos da electricidade. En primeiro lugar, realizouse un cuestionario para medir a conciencia dos individuos, despois explicáronse as regras do xogo e os xogadores comezaron a xogar. Despois diso, realizouse outro cuestionario despois de xogar ao xogo para medir o efecto de xogar ao xogo no aumento da conciencia. Como caso práctico

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escolleuse o xogo *Power the Grid* coa participación de dez xogadores. Os resultados mostraron un papel significativo e notable deste xogo para aumentar a conciencia social e educar aos *HECs* sobre os problemas enerxéticos en comparación coa súa conciencia antes de xogar. En consecuencia, propúxose engadir ao xogo varias opcións que melloren a concienciación social sobre o seu papel esencial para garantir un futuro enerxético seguro e un mellor medio ambiente, ademais da accesibilidade á enerxía eléctrica a prezos razoables. O contido destas propostas xira arredor da execución da estratexia de *DR*, que se comezou a aplicar en varios países. Este estudo recomenda aumentar o interese por apoiar aos deseñadores de xogos e facilitar a comercialización deste tipo de xogos para aumentar o número de asistentes polo seu impacto positivo.

- A "revolución industrial intelixente" coa "industria *SG*" conxuntamente contribúen a mellorar os procesos de produción industrial, resultando nun desenvolvemento económico e social sostible. Dado que os enxeñeiros constitúen un segmento vital deste sector, a formación e a formación dos enxeñeiros contribúen significativamente ao desenvolvemento do sector industrial e permítelles integrarse facilmente no mercado laboral. No CAPÍTULO 9, o foco cambia ao uso de estratexias educativas para equipar aos futuros enxeñeiros coas habilidades e a mentalidade necesarias para afrontar os desafíos do mundo real nos procesos de fabricación. Este capítulo busca capacitar aos estudantes proporcionándolles unha comprensión profunda de como se pode aplicar a súa aprendizaxe na práctica incorporando coñecementos teóricos e experiencias prácticas aos currículos universitarios. Céntrase na modernización dos currículos no ensino dos principios e procesos de produción industrial, así como na vinculación entre o ensino na aula e a práctica do mundo real. Os estudantes recibiron as habilidades necesarias integrando a instrución teórica con aplicacións prácticas, analizando sistemas e abordando problemas matemáticos. Este enfoque holístico facilitou unha comprensión máis profunda do curso e permitiu aos estudantes navegar eficazmente polas aplicacións do mundo real. Salvou eficazmente a brecha entre o estudo teórico e a aplicación práctica ao presentar aos estudantes a empresas líderes no seu campo e rexión. Unha

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característica do curso foi a visita a unha empresa de fabricación, onde tanto o profesor como os expertos industriais facilitaron un vínculo perfecto entre a aprendizaxe na aula e os procesos de produción do mundo real. Esta experiencia enriqueceu a comprensión dos estudantes dos procesos de enxeñería e proporcionou información sobre a súa implementación práctica. Ademais, o alumnado tivo a oportunidade de relacionarse con especialistas dunha recoñecida empresa europea. Realizáronse sesións dirixidas por expertos na aula, fomentando animadas discusións e intercambios entre estudantes, expertos e profesor. Deseñouse un cuestionario de retroalimentación para avaliar a eficacia da metodoloxía docente, a satisfacción global do alumnado e identificar posibles áreas de mellora do curso. Os resultados demostran a eficacia do deseño do curso para acadar os obxectivos previstos. Ademais, durante os dous cursos académicos, a participación activa, a satisfacción global dos estudantes e as boas calificacións subliñan a apreciación e o interese dos estudantes polo curso.

- O CAPÍTULO 10 presenta unha revisión da literatura centrada en estudos recentes sobre temas relacionados coa sostibilidade que abarcan desde 2014 ata 2023. O marco de investigación implementou un proceso de selección mediante a base de datos *Web of Science*, refinando os criterios en función de palabras clave específicas en títulos, resumos e temas. A revisión da literatura ten tres seccións principais que inclúen: ferramentas de simulación e optimización do ensino, estratexias de xestión do fluxo de enerxía e fabricación de baterías en termos de sostibilidade. O CAPÍTULO 10 destaca a importancia de formar aos futuros enxeñeiros en principios de sostibilidade, técnicas de optimización e aplicacións de software, onde contribúen significativamente en dúas áreas clave que teñen unha forte correlación coa sostibilidade. A primeira é o papel dos enxeñeiros no campo da xestión do fluxo de enerxía, xa sexa realizando investigacións ou proxectos na materia. Onde a literatura mostra que a aplicación de técnicas de optimización e modelado de sistemas do mundo real en software son moi utilizados na investigación. A segunda área clave de actuación dos enxeñeiros implica a aplicación de principios de sostibilidade e optimización nos procesos de fabricación para garantir unha fabricación ecolóxica. Isto inclúe a selección de materiais e

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parámetros óptimos para un mellor rendemento e lonxevidade, especialmente no que se refire ás baterías, pola súa contribución a avanzar cara a un sistema enerxético seguro e sostible.

Como terceiro resultado, a Parte 3 propón enfoques para usar a tecnoloxía dos xogos de simulación e os currículos universitarios para concienciar e educar aos futuros enxeñeiros. O estudo descubriu que mergullar ás persoas en xogos de simulación enerxéticos pode aumentar a conciencia do seu papel clave na transición enerxética. Ademais, modernizar os currículos para aliñarse co desenvolvemento tecnolóxico do mundo real contribúe á preparación dos futuros enxeñeiros. A parte 3 revelou o potencial do uso de tecnoloxías como os xogos de simulación para que as persoas comprendan como o seu papel pode contribuír á sostibilidade adoptando *RESs* e axustando o consumo de enerxía. Ademais, demostrou que a modernización dos currículos, os métodos de ensino eficientes, a optimización das ferramentas didácticas e de software, as visitas de campo e as conferencias de expertos poden pechar a brecha entre a teoría e a práctica e achegar aos estudantes ás aplicacións do mundo real, dando como resultado futuros estudantes ben adestrados enxeñeiros.

Unha vez obtidos os resultados de cada unha das tres partes da tese, tal e como se explicou anteriormente e de forma consecutiva, conséguense obxectivos específicos relacionados con cada unha delas, dando as seguintes conclusións relacionadas:

1. A tese investigou os principais motores para a adopción de prácticas enerxéticas eficientes mediante *HEMS*, que contribúen a comprender os desafíos e oportunidades na adopción de prácticas enerxéticas sostibles no sector residencial. Descubriu que a mellora da concienciación ambiental e os beneficios económicos familiares contribúen significativamente ao uso dos *HEMS*. Isto axuda aos responsables políticos a desenvolver políticas para animar aos consumidores de enerxía a utilizar *HEMS*, o que resulta en custos enerxéticos reducidos e emisións de carbono e mellora da seguridade enerxética.

2. A tese propón estratexias innovadoras de xestión da demanda dentro de *SG* e afonda na aplicación de tecnoloxías e metodoloxías avanzadas. As estratexias desenvolvidas consideraron incentivos da

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tarifa eléctrica, preferencias dos consumidores de enerxía, preservación do medio ambiente e ciclo de vida dos sistemas enerxéticos. A tese mostrou como estas estratexias proporcionan beneficios aos consumidores de enerxía, ao medio ambiente e ao sistema eléctrico en xeral ao reducir os custos de uso da enerxía, as emisións de carbono e a dependencia dos combustibles fósiles, ao tempo que prolongan a vida útil dos sistemas enerxéticos e aforran enerxía.

3. A tese propuxo enfoques para utilizar tecnoloxías e currículos para preparar os futuros enxeñeiros. Centrouse no uso das tecnoloxías para concienciar aos consumidores de enerxía sobre o seu papel na transición enerxética. Aclarouse que os xogos de simulación enerxéticos aumentan a concienciación da xente e fomentan a participación activa e un comportamento enerxético responsable que conduce ao establecemento dun sistema enerxético sostible. Ademais, destacou o papel da educación na preparación dos futuros enxeñeiros mediante a modernización dos currículos, os métodos de ensino eficientes, a optimización das ferramentas didácticas e de software e as visitas presenciais.

En conclusión, podemos dicir que a tese proporcionou solucións prácticas para avanzar cara á sostibilidade enerxética e a transición en termos de xestión da demanda en tecnoloxía *SG*, crear conciencia e formar aos futuros enxeñeiros. Propuxo estratexias eficientes de xestión da demanda para integrar *RESs* e *ESSs*, aumentou a conciencia da sociedade sobre o papel dos consumidores de enerxía na sostibilidade enerxética, destacou como o sector residencial contribúe a este esforzo e subliñou a importancia de educar aos futuros enxeñeiros para lograr sistemas eficientes e tarefas sostibles na investigación científica e nas súas profesións, que están aliñadas cos obxectivos do "Pacto Verde Europeo", o "Acordo de París", o escenario de "emisións netas cero" en 2050, o "8o Programa Europeo de Acción Ambiental" e o "Plan Europeo REPowerEU". Noutras palabras, este traballo mostrou como a integración de sistemas de enerxía limpa, baterías e vehículos eléctricos impulsa a sostibilidade e ofrece contribucións ao benestar humano (reducindo custos enerxéticos e autoconsumo independente), preservando o medio ambiente (reducindo as emisións de carbono) e mellora dos sistemas enerxéticos globais (eficiencia enerxética e

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seguridade enerxética). Tamén mostrou como as tecnoloxías e os currículos xogan un papel fundamental para impulsar a sostibilidade en termos de concienciación e formación de futuros enxeñeiros. Esta tese achegou normativas, políticas e coñecementos teóricos a aplicacións do mundo real, ofrecendo unha contribución tanto aos individuos como aos responsables políticos en canto á sostibilidade e á transición enerxética.

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CHAPTER 1. INTRODUCTION

The European Union (EU) introduced the European Green Deal in December 2019, which represents a comprehensive and ambitious initiative to transition towards a sustainable and climate-neutral economy [European Commission, 2021]. At its core, the European Green Deal targets the EU to achieve net-zero Greenhouse Gas emissions (GHG) by 2050, emphasizing a holistic approach that spans various sectors. The deal includes the Just Transition Mechanism, designed to support regions heavily dependent on fossil fuels in their transition to cleaner alternatives.

The International Energy Agency (IEA) launched The Net Zero Emissions by 2050 Scenario (NZE Scenario) in 2021, which aims to present a pathway for cutting Carbon Dioxide (CO_2) emissions and reducing growth in energy demand [IEA, 2021].

Moreover, the European Commission introduced the REPowerEU plan in May 2022, which presents a comprehensive strategy to diminish Europe's dependence on fossil fuels and expedite the shift to a sustainable energy system [European Commission, 2022a]. It seeks to hasten the green transition through the increased deployment of renewable energy sector and energy efficiency measures while promoting energy security and solidarity among EU Member States. To realize these objectives, the plan proposes substantial investments in renewable energy, energy efficiency, and alternative gas supplies, along with a review of EU energy legislation and establishing a new EU Energy Platform for coordinated energy policy. The REPowerEU plan signifies a stride in Europe's pursuit of energy independence and climate neutrality, offering a strategic response to geopolitical challenges and fostering a more secure and sustainable energy future. In terms of the residential sector, the REPowerEU plan launched short-term intervention measures such as accelerating the use of DR.

In line with the current efforts for sustainability advancement, the EU launched the 8th Environment Action Programme (EAP) in 2022

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[European Commission, 2022b]. EAP aims to guide policies and actions for addressing environmental challenges and ensuring a sustainable future in Europe. This delves into reducing greenhouse emissions, advancing towards regenerative growth, pursuing zero pollution, and reducing the environmental impact of production and consumption in several sectors, such as energy, building, and industry.

Besides, the smart industrial revolution (Industry 4.0) emphasizes the need for sustainable practices in energy consumption, efficient production processes, and integration of the principles of sustainability in manufacturing utilizing the Information and Communication Technologies (ICTs). The European Commission established the "Sustainable and Efficient Energy Use in Industry" working group in 2016 and revised it in 2021 to be aligned with recent research, innovation, and policies such as the EU Green Deal. It aims to help industries become less energy, resources, and emissions intensive and more competitive [European Commission, 2024a]. In this context, engineers perform many tasks in industry, such as process optimization, energy recovery, solving problems, and data analytics and automation. Consequently, it's important to prepare future engineers with the knowledge and skills required to perform sustainable tasks within the industry sector.

1.1. ENERGY SYSTEM

Energy systems are the lifeblood that keeps our modern world running. They provide the power needed for homes, businesses, cars, and factories. The energy grid comprises a mix of different energy sources, such as fossil fuels, renewables, and nuclear power. They all work together to ensure meeting the energy demand, which seems to be increasing more and more [Ahmad et al., 2020].

The world's shift towards sustainability, environmental responsibility, and raising awareness of resource limitations drives innovations in cleaner energy production, energy efficiency, and eco-friendly practices, leading the way toward a greener and more sustainable future [Halkos et al., 2020]. Energy systems have become at the forefront of technological and policy advancements including the development of Renewable Energy Systems (RESs) such as solar and

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wind power, the electrification of transportation, and advancements in energy storage. The complexity of energy systems goes beyond mere generation; that is where transmission, distribution, and the integration of SG technologies come in.

1.1.1. Energy security

Energy security is reliable, affordable, and sustainable access to energy resources and services that meet the needs of individuals, communities, and nations [IEA, 2014; APERC, 2007]. It involves ensuring a stable energy supply to support countries' development, economic activities, and well-being. The energy security aspects include ensuring the diversification of energy sources in the energy system, the development of local energy resources, investment in resilient energy infrastructure, and international cooperation to address shared challenges. The goal is to establish a robust and resilient energy system that can withstand potential risks, such as geopolitical tensions, natural disasters, or supply disruptions, and to promote long-term stability in energy markets. Achieving a reliable and sustainable energy future requires considering the complex interplay among energy, economic, environmental, and geopolitical factors [Strojny et al., 2023].

The background of this issue is rooted in the reliance on conventional fossil fuels. Countries that rely mainly on a fixed energy source and import energy fuels are exposed to supply disruptions and price fluctuations risks [British Petroleum, 2019]. The Integration of diverse energy resources, such as solar, wind, and hydropower, reduces the possibility of these risks. The development of local energy resources and investing in resilient energy infrastructure are effective strategies to enhance countries' energy security, contribute to a diversified energy system, and reduce the reliance on external suppliers, resulting in mitigating energy security risks [Trifonov et al., 2021; Azzuni et al., 2018]. Robust transmission and distribution networks, advanced grid technologies, and storage solutions are essential components of infrastructure that can withstand disruptions and mitigate the impact of unforeseen events on their energy systems. Besides, international cooperation plays a significant role in addressing shared energy security challenges [Liu et al., 2022]. Collaborative efforts, such as regional

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energy partnerships and agreements, contribute to the stability of global energy markets. These initiatives promote mutual support during times of crisis, facilitate the sharing of technology and expertise, and foster a collective commitment to securing the world's energy future.

The role of the residential sector is taken under consideration in terms of energy security enhancement, which holds the third sector in consuming energy. It includes several aspects such as energy consumption, efficiency measures, decentralization by installing local energy systems, energy demand patterns, and DR programs [EEA, 2022]. The daily energy consumption activities including electricity, heating, cooling, and various appliances, contribute substantially to the total country's energy production. The energy demand patterns are dynamic and affected by factors such as seasonal variations and lifestyle. Household Energy Consumers (HECs) have a direct effect on energy security regarding efficient energy practices. Policies and awareness initiatives about household consumers' role and responsible energy consumption for energy-efficient practices, promoting smart homes, and education contribute to fostering energy security and raising awareness about climate change [Cornago, 2021]. Moreover, encouraging the adoption of local renewable energy such as Photovoltaic (PV) and Energy Storage Systems (ESSs) such as batteries and the utilization of Electrical vehicles (EVs) contributes to establishing a diverse energy system, making it more robust against disruptions. This decentralized approach can enhance energy security by reducing dependence on centralized power grids. Furthermore, DR programs make energy consumption flexible by scheduling energy consumption according to the main grid stats expressed by energy usage price.

In addressing the worldwide energy security challenges, the European Commission introduced the Regulation (EU) 2018/1999 concerning the Governance of the Energy Union and Climate in Action. It seeks to guarantee the consistent implementation and coordination of the EU's Energy Union Strategy. This encompasses key areas such as energy security, the internal energy market, energy efficiency, decarbonization, and research and innovation. It specifically addresses the objectives outlined in the 2030 policy framework for climate and

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energy [IEA, 2022a; EU, 2023a]. The Spanish government introduced the More Energy Security Plan (+SE) in October 2022. It aims to enhance long-term energy security and energy savings and efficiency, transformation of the energy system, transition to renewable energies and hydrogen, and collaboration with the rest of the European countries [IEDA, 2022]. Furthermore, in response to the United Nations Sustainable Development Goal 13 (Climate Action), the Spanish electricity company Endesa began installing three photovoltaic plants and a wind farm, totalling 645 MW in 2021, to the end diversify energy production, improve the security of supply, and fulfil the renewable energy targets of Spain [EIB, 2021].

1.1.2. Managing demand and emissions

The management of both demand side and emissions has emerged as a challenge due to energy and environmental concerns. In line with global population growth, urbanization, and industrialization advancement, the need to optimize energy utilization, curb GHG emissions, and promote energy efficiency across sectors has been a priority to consider [Wang et al., 2017]. Balancing the energy demand with sustainability imperatives requires strategic policy interventions, technological innovations, and widespread behavioural changes [Zohuri, 2023; Rae et al., 2012]. This sets the stage for exploring the intricate interplay between demand management and emissions reduction, underscoring the imperative to find comprehensive solutions for a more sustainable and resilient future. Smart technologies, such as SG and DR programs, are also being integrated to enhance real-time monitoring and control, enabling a more responsive and efficient energy infrastructure.

Governments are implementing stringent regulations and standards for appliances, buildings, and industrial processes to optimize energy use, thereby reducing overall energy demand, whereas policies targeting emissions reduction are paramount. Many nations are setting ambitious targets for transitioning to RESs, such as wind, solar, and hydropower, while phasing out reliance on fossil fuels, resulting in curbing GHG emissions. Furthermore, international agreements, such as the Paris Agreement, provide a framework for collaborative efforts to mitigate global emissions [United Nations Climate Change, 2016].

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1.1.2.1. Behavioural change

Behavioural change stands as a main aspect in addressing contemporary societal challenges, particularly in the context of energy sustainability and environmental concerns. Statistics underscore the magnitude of the challenge, revealing the substantial carbon footprint associated with daily activities, ranging from transportation choices to household energy use [IEA, 2023a]. The global CO_2 per capita has increased from 3.9 to 4.3 tCO_2 between 1990 and 2021, resulting in a total CO_2 emission of 33,572 Mt in 2021 compared to 20,540 Mt of CO_2 in 1990, with an increase of 63.447%. In Spain, the CO_2 emissions produced by the residential sector have increased by 26.426% between 1990 and 2021. The background of this issue lies in the realization that human behaviour significantly influences resource consumption patterns. Therefore, by fostering energy-efficient practices, such as using energy-saving appliances, adjusting daily habits, and adopting energy-efficient technologies, society can contribute to reducing GHG emissions associated with energy production and consumption. Besides, behavioural changes can lead to a more conscientious use of resources, promoting a shift towards cleaner energy sources and sustainable practices. Educational initiatives, public awareness campaigns, and incentivization programs contribute to fostering a paradigm shift towards more responsible and sustainable lifestyles [Lubowiecki-Vikuk et al., 2021].

The NZE Scenario indicated that behavioural changes can contribute to around 15% of the emissions reductions by 2050, which could be directly incentivized or mandated by government policies [IEA, 2021]. In response, policies are being formulated worldwide to promote sustainable behaviour and reduce society's environmental impacts. The European Commission provides funding and tender opportunities in terms of behavioural, social, and cultural change, aligning with the Green Deal. The Horizon 2020 Framework Programme was proposed, aimed to implement research and experimentation on behavioural, social, and cultural change across Europe, founded on transdisciplinary expertise and strong ethical and methodological standards [European Commission, 2024b].

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1.1.2.2. Energy efficiency

Energy efficiency expresses optimizing the use of energy resources in a less wasteful manner to accomplish a specific task. This approach contributes to reducing GHG emissions, conserving natural resources, enhancing energy security, and reducing energy costs, which is fundamental in the realm of sustainable energy practices [United Nations Environment Programme, 2024]. Energy efficiency enhancement measures involve various sectors, encompassing residential (efficient appliances, building design, installing local renewable and storage energy systems, and end-user consumption behaviour), transportation, and industrial processes. In the realm of the energy transition, even though the share of RESs has increased, CO_2 emissions have also increased, underscoring the importance of saving energy and reducing energy consumption [Erdogan et al., 2023].

Efficiency, electrification, behavioural change, and digitalization influence global energy intensity, serving as a metric for evaluating economic energy efficiency. Over the last decade, there has been a modest decline of 1.7% in global energy intensity. The statistics for 2023 indicate a reduction of 1.3%, which is supposed to fall by 4.1%, according to the NZE Scenario [IEA, 2023b]. The slowed pace of global energy intensity improvements requires taking measures of energy efficiency progress, where the slow progress on energy efficiency, results in higher global economy's levels of energy consumption and CO_2 emissions, which is not aligned with the NZE Scenario. Therefore, achieving alignment with the NZE Scenario demands a consistent enhancement, necessitating an increase in annual progress from the 2% attained in 2022, to approximately 4% per year until 2030 [IEA, 2023c].

Regarding energy consumed by appliances and equipment, it should be reduced by 25% in 2030 compared to 2020 to align with the NZE Scenario, where energy performance standards and labels are applied to many appliances in various sectors [IEA, 2023d]. However, the EVs are not well addressed, and around 50% of global energy use is not covered by any scheme [IEA, 2023d]. In 2022, global energy efficiency investment surged by 16% to reach USD 600 billion, driven by government stimulus programs focusing on efficient buildings and

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the increasing popularity of electric cars. EVs stand out as 14% of global car sales, expected to grow more in 2023 [IEA, 2023d]. However, keeping progress in energy efficiency might face challenges, including higher interest rates and inflation, which hinder efficiency investments, leading to affect consumers' ability to buy new efficient equipment. This underscores the importance of government interventions that increase the rate of deployment of more efficient technologies.

In response to energy crises and the abovementioned challenges, considerable efforts are underway by countries to reassess energy efficiency targets and policies, aiming to minimize reliance on fossil fuels and protect energy consumers from high energy prices. In Europe, the European Parliament and the Council of the EU established the Energy Efficiency Directive (2012/27/EU) for the first time in 2012 [European Commission, 2012]. It forms a part of the EU's broader efforts to enhance energy efficiency and achieve its energy and climate goals. The Energy Efficiency Directive outlines measures to promote energy efficiency in various sectors, including buildings, industry, and transportation, to reduce energy consumption and GHG emissions across the EU member states. In line with the energy challenges and climate change, the Energy Efficiency Directive was updated in 2018. In March 2023, the revised directive (EU/2023/1791) was published to deliver the European Green Deal and the REPowerEU Plan. The notable thing in this revised directive is establishing "energy efficiency first" as a fundamental principle of EU energy policy, giving it legal standing for the first time [European Commission, 2012]. One of "the Energy Efficiency First" principles aims to reduce energy demand and manage it cost-effectively. The revised directive sets a robust energy efficiency target of 11.7% for 2030, exceeding the initial "Fit for 55" proposal. EU countries are obligated to collectively achieve additional reductions in final and primary energy consumption compared to 2020 and achieve double energy savings annually compared to the current reduction (0.8%), starting from 1.49% in 2024 and reaching 1.9% by 2030 [IEA, 2023d]. This is an important instrument to drive energy savings in end-use sectors such as the residential sector. Moreover, energy management systems in companies will become a default

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obligation for large energy consumers [Díaz et al., 2022]. Heating and cooling plans have to be enhanced in large regions that exceed a population of 45,000, where no natural gas will be used for heating and cooling systems by 2023 [EU, 2023b].

1.1.2.3. Demand response

DR is defined as "Changes in electric usage by end-use consumers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" [Qdr, 2006].

DR is an effective strategy within the realm of energy management; this innovative concept involves adjusting electricity usage in response to signals from grid operators during peak periods, emergencies, and high electricity prices. DR programs allow energy consumers to take part in balancing the electricity grid and energy system flexibility [Gelazanskas et al., 2014]. The core principle of DR lies in the flexibility of behavioral changes in energy consumption, without compromising consumers' comfort. DR programs are generally classified into two basic categories: incentive-based DR (incentive-based DR, curtail-able load, and demand-side bidding, capacity, and ancillary services) and price-based DR (time-of-use tariffs, critical peak pricing, and real-time pricing), supported by advanced technologies such as smart meters and home automation systems [Zhang et al., 2012]. Besides, DR enhances grid reliability and stability by reducing the need for additional, often fossil fuel, to meet peak demand. It also contributes to energy efficiency and sustainability goals by optimizing the use of energy resources.

In this context, Home Energy Management Systems (HEMSs) take part in achieving the NZE Scenario's objectives, contributing to a sustainable and energy-efficient future. HEMSs activities involve shifting the operation time of controllable appliances to off-peak hours, such as the dishwasher and washing machine. Another scenario could be followed, shifting the controllable appliances to the high power generation periods of local RESs with an auxiliary energy system collaboration, such as installing a battery storage system and taking

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advantage of the EV's battery energy [Lee et al., 2011]. In addition to the benefits DR provides to energy system stability and security, it also provides benefits for energy consumers by offering them to operate non-essential appliances in the off-peak periods at a low price, resulting in electricity bill reduction [Zafar et al., 2020]. This approach based on the behavioral changes in energy consumption, helps in the long term in integrating RESs by aligning energy consumption with periods of abundant renewable generation, leading to establishing more RESs plants and avoiding energy balance problems. In summary, adopting HEMS based on DR programs aligns with the NZE Scenario's goals of drastically reducing GHG emissions, maximizing the use of RES, and enhancing overall energy efficiency.

Countries are making notable innovation progress in advancing DR adoption. In July 2023, the South Australian government implemented new regulations for air conditioner operation for heating and cooling processes needs [Government of South Australia, 2023]. The new regulations aim to reduce grid demand when air conditioners operate at their highest during hot and cold periods, assisting in avoiding blackouts. Energy operators send a signal to air conditioners that have DR capability. The air conditioners then adjust their energy consumption (turning off or using an efficient operation mode), contributing to ensuring grid stability and improving energy efficiency. For this purpose, no air conditioners will be connected to the electricity system, if they don't meet the new DR capability requirements from July 2023 onwards. In Europe, an action plan was proposed in 2022, to deliver the European Green Deal [EU, 2022; European Commission, 2023a]. In terms of the energy system, the proposed action plan includes supporting the use of DR programs through efficient electricity grid utilization with enhanced transparency, improved network tariffs for SG, and project finance support for SG and modernization of distribution grids. Aligning with the NZE Scenario, around 250 GW of DR capacity will be in buildings by 2030, standing out of 50% of the required DR capacity, and another 50 GW will come from EVs [IEA, 2023e]. This indicates the importance of the residential sector in achieving the NZE scenario goals, highlighting HEMS's role. In response, many approaches are being tested and applied to increase

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residential participation in DR. Experiments for exporting electricity from EVs to the grid (EV2G) are being within some countries, such as France, the Netherlands, and the United Kingdom. In France, the Electricity Transmission Network (RTE) authorized the integration of EVs into the electricity system balance for the first time in 2022 [RTE, 2022]. In the Netherlands, the Hyundai EV2G project in Utrecht with Ioniq 5 began in April 2022, under the collaboration between Hyundai Motor and We Drive Solar companies [Electrive, 2022]. The goal of the project is to demonstrate the feasibility of EV2G technology. The project involves deploying a fleet of 25 Hyundai Ioniq 5 EVs with EV2G capability in Utrecht. The vehicles are used to store excess solar energy generated by local homes and businesses, and then discharge that energy back to the grid when needed. This will help to reduce the city's reliance on fossil fuels and improve the stability of the electricity grid. In 2022, the Interoperable Demand Side Response program was launched in the UK [GOV.UK, 2022]. It is a government-backed initiative that includes developing and testing interoperable DR protocols and standards, developing and deploying interoperable DR applications, and evaluating the impact of interoperable DR on the electricity grid, through smart meters and energy management systems. The main objective is to make household energy customers and businesses adjust their energy consumption in response to signals from the electricity grid, leading to peak demand reduction and the grid's stability improvement.

Due to the current energy crisis, accelerating the establishment of policy and regulation is needed for DR capacity advancement aligning with the NZE Scenario. In response, various measures have been implemented globally. In Europe, enhancing the DR capacity, in terms of facilitating data access and adopting smart appliances was considered in the framework of the action plan for the digitalization of the energy system that was approved by the European Commission in 2022 [EU, 2022]. Besides, in 2023, the European Commission has proposed to reform the EU's electricity market design to accelerate the green transition and offer energy consumers access to affordable renewable electricity, bring flexible solutions, such as DR and energy storage, and protect consumers from price spikes [European Commission, 2023b].

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The proposed reform includes revisions to several parts of EU legislation, especially the Electricity Regulation, the Electricity Directive, and the Regulation on Wholesale Energy Market Integrity and Transparency Regulation. In Spain, in April 2014, a new tariff price for energy usage was established. The Voluntary Price for the Small Consumer (PVPC) includes three tariffs: 2.0 A (default tariff), 2.0 DHA (2-period tariff), and 2.0 DHS (EVs). Subsequently, in June 2021, the government implemented a revised electricity tariff for small consumers, featuring a single tariff with three periods, to advance DR. The first period, considered off-peak, offers lower electricity prices on weekdays, weekends, and national holidays. The second period has intermediate prices. The third period, on-peak, has the highest electricity prices [REE, 2022a]. In the USA, the Load management rulemaking in California was approved. It is a comprehensive set of regulations, that govern the energy management mechanisms to improve the reliability and efficiency of the state's electricity grid. These regulations are designed to balance the needs of consumers, utilities, and the environment [California Energy Commission, 2022]. On the international collaboration aspect in accelerating demand-side flexibility advancement, several international initiatives have been launched, including the IEA Digital Demand Driven Electricity Networks Initiative and Mission Innovation Green Powered Future Mission [IEA, 2019; Mission Innovation, 2023]. These initiatives are exchanging best practices, providing policy guidance, and launching demonstration projects to promote the effective integration of RESs.

1.1.3. Energy supply and transformation

Energy supply and transformation refers to the energy production, distribution, and conversion processes to meet nations' needs. This involves producing energy from various sources, such as fossil fuels and RESs, and transforming it into usable forms such as electricity and heat. Due to energy security and climate change concerns, the transition to clean energy, the development of SG, and the integration of ESSs are needed.

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1.1.3.1. Electrification

Electrification refers to the process of expanding electricity consumption in various applications at the expense of fossil fuel. It involves substituting devices, equipment, and devices powered by fossil fuels with electrical alternatives, such as EVs instead of gasoline cars [Gold, 2021]. In addition to harnessing RESs by modernizing and digitizing the electricity grid, to manage the energy demand growth and integrate more RESs into the main grid. This approach contributes to reducing CO_2 emissions, promoting energy efficiency, enhancing energy security, and clean energy transition advancement [Farnsworth et al., 2018]. As we step near 2030, an aspect of our energy landscape demands immediate attention, the share of electricity in final energy consumption, which has a direct relation to CO_2 emissions stands at 20% in 2022, while the share of electricity percentage is set to be 27% for 2030 in alignment with the NZE Scenario [IEA, 2023f]. This disparity underscores the pressing need for substantial investments, robust policy frameworks, and strategic regulations. Addressing this issue becomes a priority, as we navigate the path towards a sustainable and net-zero emissions future, focusing on the efforts across sectors and stakeholders.

In the realm of electrification technologies development, the primary focus revolves around two key domains: homes and cars. In the residential sector, the development includes electric heating, cooling, and appliances, and in the automotive sector, expanding the replacement of traditional cars with EVs, leading to a cleaner and more energy-efficient future. In 2022, heat pump sales increased by 11% globally compared to the previous year, where Europe presented the highest increment of 40% [IEA, 2023g]. On the transport front, a growth of 58% in electrical car sales in 2022 compared to 2021 [IEA, 2023h]. Besides, heavy-duty car sales in 2022 increased by double in Europe compared to 2021, however, it witnessed a slow development [IEA, 2023f].

Many countries are addressing electrification with different strategies, focusing on either an increase in the consumption of energy from electricity or enhancing the proportion of (renewable) electricity within the overall produced energy. In addition to developing policy

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and regulation measures. In 2019, the European Commission set regulations for new passenger cars and new light commercial vehicles (Regulation (EU) 2019/631), to align with the EU's GHG reduction goals set in Regulation (EU) 2018/842, contribute to the objectives of the Paris Agreement, and support the smooth functioning of the internal market [EU, 2023c]. In 2022, the regulations were amended to set more ambitious standards for reducing the CO_2 emissions of new cars and vans. A reduction of 100% in CO_2 emissions from new passenger cars and fans target is targeted to be achieved by 2035.

Financial support or incentive programs aimed at encouraging investments in global heavy industry electrification are undertaken in several regions. The Council and European Parliament have agreed on the second iteration of the Connecting Europe Facility to be run from 2021 to 2027, which keeps supporting projects in transport, digital, and energy [The Council of the EU et al., 2021]. The REPowerEU plan in Europe has significantly increased the budget within the Innovation Fund, focusing on electrification in industry and hydrogen [European Commission, 2022c; IEA, 2022b]. Similarly, in Finland, the government introduced a subsidy fund dedicated to facilitating the electrification of heavy industries [Finnish Government, 2022]. These initiatives underscore a growing commitment to fostering sustainable practices and reducing the environmental impact of industrial operations on a global scale.

1.1.3.2. Smart grid

The increasing electricity demand, coupled with the integration of intermittent RESs, led to flexibility and stability challenges in the traditional grid [Liserre et al., 2010]. Additionally, the susceptibility of the grid to physical disruptions, such as natural disasters, and the emerging threat of cybersecurity risks underscored the need for a resilient and secure energy infrastructure. As a result, the SG emerged as a transformative solution, it is an electricity network characterized by bidirectional flows of electricity and information, facilitated by digital communication technology [Gharavi et al., 2011]. Unlike traditional grids, SG is electronically controlled, aiming to enhance efficiency and minimize outages. The components of an SG include the

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utility sector encompassing generation, transmission, and distribution, along with RESs such as PV and wind turbines, auxiliary resources such as diesel generators and ESSs, and consumers, including households and businesses. Operational and energy measures, such as smart meters, contribute to the intelligent control of electricity production and distribution [Abrahamsen et al., 2021; Shahzad, 2020]. The main objective is to optimize the efficiency of every system component, minimizing both costs and environmental impacts, while concurrently maximizing the reliability, resilience, flexibility, and stability of the electricity system.

Significant progress in SG technology advancement is being observed across various regions. The European Commission introduced the EU action plan "Digitalisation of the energy system", with EUR 584 billion in investments by 2030, including EUR 170 billion dedicated to digitalization initiatives such as smart meters [European Commission, 2022d]. China committed USD 442 billion to modernize its power grids from 2021 to 2025 [Transformers, 2023], while Japan allocated USD 155 billion to boost investments in smart power grids [Nikkei Asia, 2022]. India allocated USD 38 billion to support power distribution companies and enhance distribution infrastructure [Financial Express, 2022]. In the United States, the Grid Resilience Innovative Partnership Program was initiated, offering a funding opportunity of USD 10.5 billion for upgrading and expanding the electric grids [Grid Deployment Office, 2023]. Additionally, Canada is investing USD 100 million through its Green Infrastructure Smart Grid Program to promote the deployment of SG technologies and integrated systems [Government of Canada, 2023]. These global initiatives underscore a collective commitment to advancing digitalization and resilience in energy systems. However, the investments in the electricity grid need to be doubled through to 2030 according to the NZE Scenario.

At the international level, many collaboration programs for SG advancement are being taken. These initiatives aim to share knowledge and best practices, highlight the advantages of SG implementation, foster cooperation on international standards, encourage manufacturers, and enhance user acceptance to be part of the energy system. The International Smart Grid Action Network (ISGAN) was established in

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2011 and operates as a joint initiative between the Clean Energy Ministerial (CEM) and IEA. ISGAN is a global platform dedicated to accelerating the development and deployment of smarter, cleaner, and more flexible electricity grids [ISGAN, 2011]. The Global Smart Energy Federation (GSEF) is a global organization that brings together public-private stakeholders in the energy sector to collaborate and tackle challenges regarding the energy transition and support the rapid deployment of SG technologies. It was established in 2011 and boasts a diverse membership, encompassing 16 partners from Africa, America, Asia, and Europe [GSEF, 2010]. The Smart Grids Task Force (SGTF) is an expert group established by the European Commission in 2019 to advise on policy and regulatory directions in the EU to coordinate at the European level the implementation of Smart Grids under the provisions of the Directive 2009/72/EC, Directive 2009/73/EC and Directive 2012/27/EU [European Commission, 2019]. It finished its work in 2022, providing recommendations involving standards and protocols to enhance SG technologies implementation, cybersecurity risks associated with SG, regulations to support the deployment of SG, and challenges and opportunities. The Trans-European Networks for Energy (TEN-E) is a policy established by the EU in 1996 to create a modern, interconnected energy infrastructure across member states. It was revised and entered into force in June 2022, introducing new rules aimed at modernizing the existing infrastructure, decarbonizing the energy system, and interconnecting the EU member states more effectively towards the EU's 2050 climate neutrality objectives [IEA, 2022c].

1.1.3.3. Grid scale storage

Grid-scale storage refers to large-scale ESSs designed to store and release electricity on a massive scale within an electrical grid. These systems contribute to enhancing grid reliability, managing peak demand, and integrating intermittent RESs, such as wind and solar, into the grid [Tan et al., 2021]. Grid-scale storage solutions include technologies such as Battery Energy Storage Systems (BESSs), pumped storage hydroelectricity, Compressed Air Energy Storage (CAES), and other advanced energy storage technologies. The primary

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objective is to balance supply and demand, improve grid reliability, and integrate more RESs into the grid. Aligning with the NZE Scenario, ESSs technologies, particularly batteries, are essential to handle the hourly and seasonal variations in RESs electricity generation while ensuring the grids' stability and reliability in the face of growing demand and massive deployment of RESs. From small-scale homes to large utility grids, batteries' versatile range and adaptable capacity are making them a key player in the energy landscape [Rezaeimozafar et al., 2022; Aneke et al., 2016]. Besides, EVs are revolutionizing the electricity landscape and play a multifaceted role in modern electricity grids. EVs can serve as a valuable unit for grid management through V2G and grid to EV (G2EV) technologies, enabling EVs to import electricity from the grid and export energy to the grid when needed [Hussain et al., 2021]. Through smart charging technologies and DR programs, EVs can be charged in periods of low demand where the price is low, and discharged to the grid in periods of high demand where the price is high. This approach enhances grids' stability and reliability and has benefits for owners by earning money from selling energy.

During previous years, the world has seen great progress in installing grid-scale batteries, where Lithium-ion batteries remained the predominant choice, constituting the majority of newly installed capacity for grid-scale storage and home energy storage systems [IEA, 2023i]. The total capacity of installed grid-scale battery storage reached around 28 GW in 2022 compared to 0.8 GW in 2017. In Europe, there was a 100% increment in 2022 compared to 2021 [IEA, 2023k].

To keep aligned with the NZE Scenario, a significant growth in grid-scale battery capacity is needed. Where the total capacity is planned to be 970 GW in 2030, which means that the current capacity should be increased by 35 times within an annual increment of 170 GW. This expansion is necessary to address the rapid increase in the share of RES and its output power variations [IEA, 2023l]. However, according to the Tracking Clean Energy Progress 2023 report, the projected growth in grid-scale storage capacity is currently falling short of what's needed to achieve the NZE Scenario’s target, demanding concerted efforts to accelerate its development [IEA, 2023i].

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Dealing with the issue, several policies, subsidies, and regulatory reforms are put in place worldwide. China has set its sights on becoming a global leader in energy storage, announcing plans in July 2021 to install over 30 gigawatts of non-pumped hydropower energy storage by 2025, within a three-fold increment compared to 2022's capacity [Reuters, 2023]. The main objective is to enhance RES integration, peak demand management, and grid stability. The Inflation Reduction Act, signed in the USA in August 2022, marks a significant stride toward energy storage advancement (stand-alone and grid-scale), which includes tax incentives and other measures [Colthorpe, 2022]. It addresses various issues, such as reducing GHG emissions, promoting EVs, and advancing clean energy technologies. In March 2023, the European Commission published a Recommendation on Energy Storage, outlining several key recommendations to accelerate the widespread deployment of energy storage across the EU and achieve their clean energy goals [EU, 2023d]. It focused on streamlining permitting procedures to speed up project development, facilitating access to finance for energy storage projects, and establishing national strategies for energy storage deployment. In addition to, fostering a supportive regulatory environment, creating investment for the private sector, supporting research and innovation, reviewing and updating existing regulations, enhancing data sharing and transparency, and raising public awareness.

1.2. THE STUDY MOTIVATION

In the wake of the ongoing energy crises, caused by depleting fossil fuel reserves and the quest for advancing towards a secure energy system and net zero-emission future, it becomes increasingly evident that the residential sector contributes to shaping the trajectory towards sustainable energy practices and energy transition. As nations worldwide commit to ambitious targets outlined in initiatives such as the NZE Scenario, alongside the European Green Deal, EAP, and the REPowerEU plan, for emissions reduction and renewable energy integration, the demand side management under DR programs and SG technologies emerges as a primary element to revolutionize residential

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energy consumption and contribute to moving towards secure and clean energy system.

The motivation behind studying HEMSs lies in their potential to change the way of energy consumption and management within homes. HEMSs encompass integrating advanced technology, data analytics, and RESs, which empower homeowners to monitor, control, and optimize their energy usage in real-time. In addition to enhancing energy security, HEMSs contribute to electricity cost reduction and environmental benefits.

Understanding the factors that might affect HEMSs adoption is essential for unlocking its full potential. Motivations for adopting HEMSs are widespread and may include financial savings, climate change, and energy independence. Conversely, barriers such as high upfront costs, lack of awareness, or concerns about privacy and data security can hinder widespread adoption.

Delving into developing HEMSs strategies and highlighting the benefits to HECs can provide valuable insights for policymakers, energy providers, and technology developers. Identifying the factors that influence consumer decision-making can inform the design of targeted incentives, educational campaigns, and innovations aimed at overcoming barriers and promoting HEMSs adoption. Moreover, studying HEMSs can shed light on behavior change impacts and implications for the transition to a sustainable energy future, assessing the effectiveness of HEMS in reducing carbon emissions, alleviating strain on the grid, and promoting flexibility and resilience of the energy system.

Besides, recognition of the role of society in moving towards sustainability and engineers' impact in promoting sustainable and efficient practices in their profession, particularly in energy and industry, necessitates the exploration of technologies and approaches to raise social awareness and well preparation of future engineers.

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CHAPTER 2. OBJECTIVES

The main objective of this thesis is to comprehensively investigate the efficacy and potential of demand side management in fostering sustainable energy practices within the residential sector using SG technology. Specifically, the research aims to investigate the main drivers for HEMS implementation, evaluating HEMS capacity to optimize energy consumption, reduce energy costs, reduce carbon emissions, and enhance energy security. The thesis seeks to explore innovative strategies for promoting demand-side management, considering factors such as technological advancements, policy incentives, and energy consumers' behavior. Emphasis is placed on achieving environmental, financial, lifecycle consideration, and behavior change objectives. Additionally, it seeks to raise awareness regarding society's role in establishing a sustainable energy system and equipping future engineers to bridge the gap between theoretical knowledge and real-world advancement. This approach is mainly focused on enhancing energy security, energy transition, and energy efficiency, corresponding closely with the goals set forth in the European Green Deal, Paris Agreement, the NZE Scenario, EAP, and the REPowerEU plan.

The structure provided guides the implementation of the thesis parts (Figure 2.1). In Part 1, a systematic literature review is carried out to explore the factors that might affect consumers adopting new technologies, particularly in terms of adopting efficient energy practices. Then, drawing upon insights obtained from the literature, factors are identified to investigate the potential of adopting HEMS within DR programs and SG technologies. This study seeks to highlight the factors that might affect HECs to adopt HEMS, to help policymakers draw up policies to effectively disseminate strategies to encourage home consumers to contribute to energy transition. Additionally, assisting energy management researchers in incorporating key factors that affect energy consumers into their

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proposed models. By doing so, these models can clarify the financial and environmental benefits of effective energy consumption management, thereby encouraging energy consumers to adopt more sustainable practices. Ultimately, this approach culminates in offering a solution pathway to issues such as the difficulty of behavior changes, lack of policies, and lack of knowledge of the significant factors. Consequently, it fosters the development of HEMS adoption and empowers households to contribute to the transition towards a more sustainable energy future.

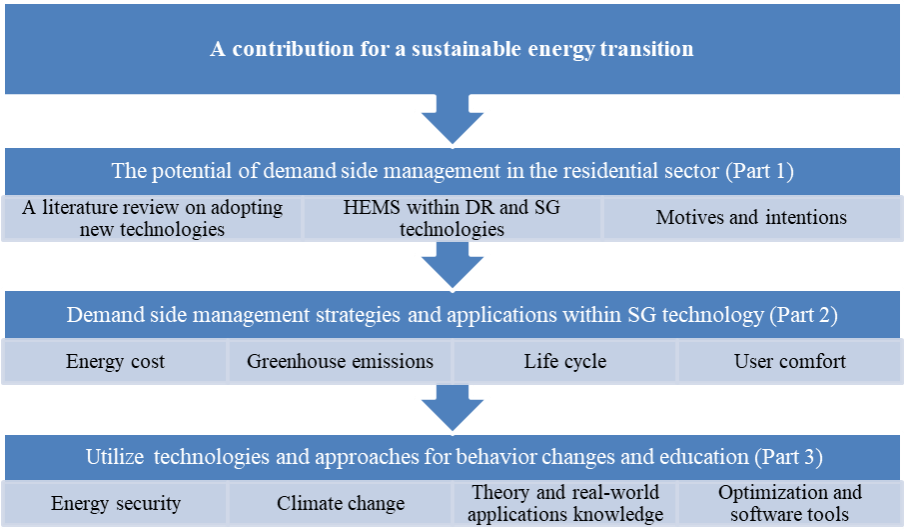

Figure 2.1: Objectives overview

Then, based on the identified factors that affect HECs to adopt HEMSs, effective demand side management strategies are suggested in Part 2. The suggested strategies consider various aspects, such as energy usage costs, environmental benefits, life cycle principles of the integrated energy system, the installation cost of the local energy systems such as PV and ESSs, and household preferences. This approach seeks to investigate the benefits of adopting HEMS for households and operators, aligning with the current global efforts towards energy transition and net zero emission. Highlighting the benefits encourages HECs to change their patterns in consuming energy and install local energy systems, contributing to a future secure energy

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system. Similarly, for operators, it ensures a stable energy system and increases the capacity of integrating more RES plants into the grid, which helps policymakers draw up policies and raise awareness.

In Part 3, the thesis keeps focusing on smart systems, especially, behavior changes among households to optimize energy utilization, thereby facilitating the transition towards sustainable energy practices and energy transition. Keeping track of the latest advancements in global and EU policies and frameworks regarding renewable energy sector development and energy transition, the study seeks to utilize technologies and tools essential to foster moving towards sustainable energy practices. Besides, aligning with the smart industrial revolution and recognizing the importance of education in bridging the gap between theory and real-world application, the thesis underscores the role of education in empowering individuals to implement sustainable solutions in their daily lives. The study aims to equip future engineers with the necessary skills to contribute to the efficiency of real-world manufacturing processes. Furthermore, a discussion about the role of optimization and software principles and applications is carried out to highlight their contribution to sustainability development.

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CHAPTER 3. METHODOLOGY

To accomplish the objectives described in the previous chapter, the Doctoral Thesis is organized into self-contained chapters, each developed independently. Each chapter carries out a comprehensive review of the current literature, delineates the objectives, outlines the methodology implemented, details the research development, discusses the results, and draws conclusions.

In CHAPTER 1, an introduction is provided, where it contextualizes and justifies the work. CHAPTER 2 identifies the study objectives, whereas CHAPTER 3 outlines the methodology undertaken in developing the thesis. Figure 3.1 summarizes the process followed.

To achieve the objectives of the thesis, which focus on optimal energy patterns consumption, optimal energy systems utilization within the context of SG technology and DR programs, and education and awareness-raising for advancements in the energy sector and industry, the structure follows three main parts:

- Part 1 (CHAPTER 4): It delves into investigating the factors that affect the demand side to adopt efficient energy practices within the DR programs and SG technology (CHAPTER 4).
- Part 2 (CHAPTER 5, CHAPTER 6, and CHAPTER 7): The examined factors in Part 1 are considered in the developed innovative strategies in Part 2. Three demand side management strategies are proposed to provide benefits for both energy consumers and the overall energy system and address various aspects, including energy costs, environmental impact, the lifecycle of RESs and ESSs, and the stability of the energy system (CHAPTER 5, CHAPTER 6, and CHAPTER 7).
- Part 3 (CHAPTER 8, CHAPTER 9, and CHAPTER 10): Part three revolves around knowledge and skills for the advancement of the energy sector and industry within smart technologies. It involves three case studies, one focusing on raising awareness of energy transition and sustainability utilizing video game technology (CHAPTER 8) and

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others on enhancing education to well-prepare future engineers (CHAPTER 9 and CHAPTER 10).

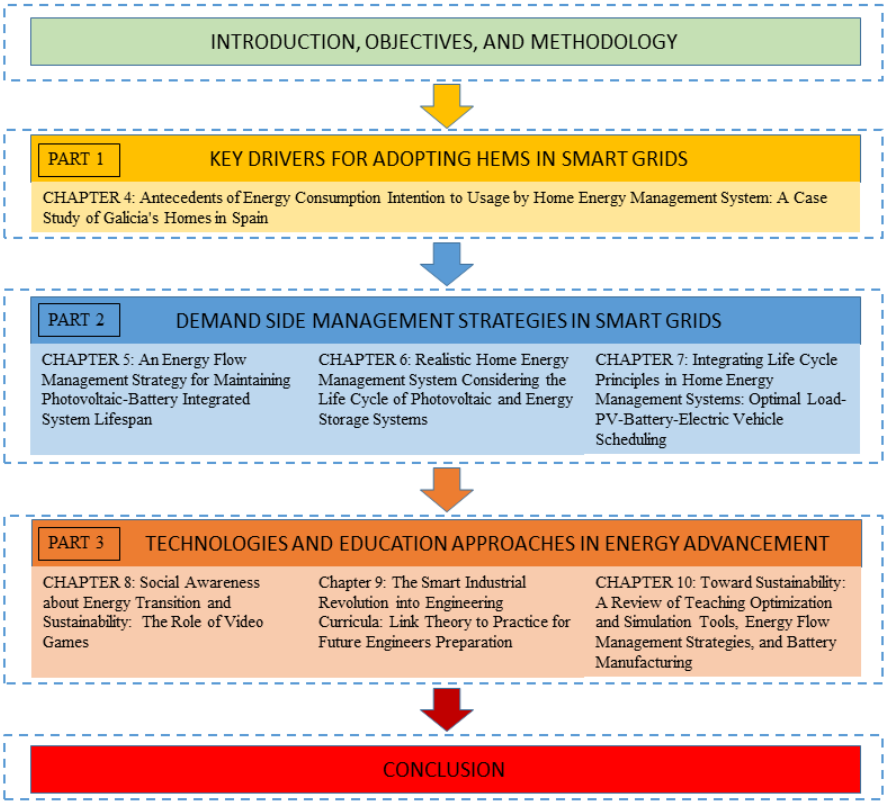

Figure 3.1: Outline of the processes employed in the development

CHAPTER 4 serves as the foundation for Part 2. It carries out a comprehensive investigation to understand household perspectives and intentions about adopting HEMS after the new DR program in Spain. It investigates various dimensions, such as usefulness, effort needed to efficient energy practices, environmental concerns, and financial benefits. The Technology Acceptance Model (TAM) is used and extended by two additional factors, where homeowners in Galicia, Northwest Spain are taken as a sample. Consequently, it highlights the drivers behind the HEMS adoption, assisting policymakers in formulating effective policies and incentives, while also guiding scholars to integrate influential factors into their research strategies.

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The outcomes of CHAPTER 4 are considered in PART 2 and serve as a stepping stone for CHAPTER 5, CHAPTER 6, and CHAPTER 7.

To obtain realistic results, a real case study of a home, weather data, households' preferences, the installation cost of RES and ESSs, and energy usage tariff in Spain are taken in the developed demand side management strategies presented in CHAPTER 5, CHAPTER 6, and CHAPTER 7. Matlab with optimization techniques is used to model and develop the presented strategies in these chapters.

Based on the key drivers' investigation to adopt HEMSs carried out in the fourth chapter, CHAPTER 5 delves into the practical strategy of HEMS using local RESs, ESSs, and the main grid to meet the energy demand. It addresses the challenges of power balance and energy demand variation. It introduces an innovative approach to energy flow management in the residential sector, considering the lifecycle of the local RES and ESSs. This chapter seeks to obtain maximum energy cost reduction, achieve optimal RESs and ESSs performance throughout their operational life, and reduce the environmental impact of using energy. By doing so, it highlights the actual benefits of adopting HEMS and encourages energy consumers to take part in energy transition.

CHAPTER 6 delves more into demand side management, emphasizing flexible energy consumption based on grid conditions, RESs output power, and energy storage levels. It introduces an innovative strategy to optimize energy flow and schedule household appliances to reduce energy costs, ensure optimal performance of RESs and ESSs alongside extending ESSs lifetime, and reduce emissions. The installation cost and life cycle of RESs and ESS are considered in conjunction with energy usage costs from RESs and ESSs. CHAPTER 6 underscores the economic and environmental benefits of appliance scheduling and RESs and ESSs utilization, encouraging consumers to contribute to the energy transition.

CHAPTER 7 takes an innovative strategy by exploring the potential of incorporating EVs into the energy system of the residential sector. By integrating the EVs with the PV, battery, load, and grid, CHAPTER 7 aims to enhance the flexibility of the energy management process. It introduces a multi-faced strategy that addresses optimal parameters of the ESSs, optimal power flow, optimal household

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appliance scheduling, and seasonal conditions. This approach demonstrates how the role of energy consumers and utilization of PV, battery, and EVs can advance energy transition while providing cost savings for consumers.

CHAPTER 8 adopts a pioneering method by delving into the potential of utilizing video games to raise awareness about the role of energy consumers in energy transition and sustainability using smart grid technologies. It aims to harness video games as a tool to aware individuals of the complexities of the current energy landscape and environmental challenges, by engaging them in the concepts of RESs development and energy demand growth. Furthermore, this chapter describes how technologies can be effectively utilized to change behavior toward embracing sustainable energy practices.

Continuing with harnessing technologies and approaches for education and raising awareness, CHAPTER 9 takes university curricula as an approach to educating and skilled future engineers. By incorporating theoretical knowledge and practical experiences into the curriculum, CHAPTER 9 aims to empower students to understand real-world applications, while equipping a mindset to tackle the real-world challenges within manufacturing processes. CHAPTER 9 demonstrates how modernizing the curricula equipped future engineers, positioning them as adept professionals equipped to drive innovation and sustainability within the realm of manufacturing processes.

CHAPTER 10 carries out a literature review focusing on sustainability-related studies. The research method involved a systematic selection process using the Web of Science database with refining criteria. The review comprises three main sections: teaching optimization and simulation tools, demand side management strategies, and battery manufacturing. It aims to consolidate research contributing to the discourse on sustainability in education, energy management, and battery manufacturing while promoting initiatives for a more sustainable future. CHAPTER 10 highlights the utilization of simulation software, optimization tools, and sustainability principles in equipping future engineers and theoretical and practical research in energy management and battery manufacturing. In addition, demonstrates engineers' role in advancing sustainability and the

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importance of equipping future engineers with skills such as optimization techniques for real-world applications.

Ultimately, CHAPTER 11 concludes the thesis by summarizing the key findings and main conclusions drawn from this thesis.

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CHAPTER 4. ANTECEDENTS OF ENERGY CONSUMPTION INTENTION TO USAGE BY HOME ENERGY MANAGEMENT SYSTEM: A CASE STUDY OF GALICIA'S HOMES IN SPAIN

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

- Title: Antecedents Of Energy Consumption Intention To Usage By Home Energy Management System: A Case Study Of Galicia's Homes In Spain
- Authors: Al Muala, Z. A.; Bany Issa, M. A.; Fernández Rodríguez, J. J.; Bello Bugallo, P.M.
- Publisher: EDP Sciences
- Journal: Renewable Energy and Environmental Sustainability.
- eISSN: 2493-9439
- Impact Factor: 2.5 in 2021(Database: Exaly)
- Category: Renewable energy (Database: Exaly)
- Relative position: Q1 (5/31) in 2021(Database: Exaly)
- DOI: https://doi.org/10.1051/rees/2024004
- Year of publication: 2024
- Article views: 730
- Contribution of the doctoral student: contribution to conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing— review and editing, visualization, and project administration.
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SUMMARY

A new electricity tariff has been applied in Spain to make energy consumers manage their energy consumption based on the variation of electricity price during the day, which contributes to energy security, increases the penetration of RESs into the grid, maintains grid stability, and reduces CO_2 emissions. To ensure the successful implementation of the new DR program, it is necessary to investigate the factors that might affect HECs to use HEMSs. This work aims to examine the factors that affect the Spanish HECs' acceptance to participate in DR. In addition, highlights the role of economic benefits and environmental awareness factors in the acceptance of participating in DR using HEMS. TAM is used in this work with four independent factors, one mediating factor, and one dependent variable, then hypotheses were set for each. A diagnostic survey through a standardized questionnaire was done, and Galicia, Northwest Spain was taken as a case study. The results show that the family's economic benefits and environmental awareness significantly shape attitudes toward using HEMS. This attitude, in turn, has a significant impact on the intention to use HEMS. Contrarily, the perceived usefulness and ease of using HEMS do not impact consumer attitudes. Notably, the usefulness has a direct impact on the intention to use HEMS, where the attitude does not affect the relation between them. The results help the Spanish policymakers to draw up policies to effectively disseminate strategies to encourage home consumers to contribute to energy security and assist energy management researchers in incorporating key factors that impact energy consumers into their proposed models. By doing so, these models can clarify the financial and environmental advantages of effective energy consumption management, thereby encouraging energy consumers to adopt more sustainable practices.

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4.1. INTRODUCTION

Consuming energy is a vital part of our modern daily life. The world's population increased by 51.33% between 1990 and 2023 [Worldometer, 2023]. The population growth concurrent with rapid technological advancement drove up energy demand; energy consumption per capita increased in the world by about 64%, while 73% in Spain in the residential sector gradually from 1985 to 2020 [Our World in Data, 2023]. This increase in energy consumption has negative effects on energy security and the environment [Proskuryakova, 2018].

Recently, the risk of energy security which is related to the blackout of the main grid increased due to the high energy demand, especially in peak periods. Many recent power outages have occurred in different parts of the world. The California power crisis in 2020 raised interest in the risk of the shortage of local energy resources to cover the energy demand and power outages during peak periods [California Independent Systems Operator et al., 2020]. In the last cold winter season in China, the power plants could not meet the energy demand, not even keeping lights on during peak periods [Malik et al., 2021]. The biggest blackouts in India were on the 30 and 31 of July 2012, affecting about 670 million people due to high energy demand [Tang et al., 2012]. The power blackout has impacts in many aspects, 1) direct economic impact 2) indirect economic impact 3) social impact [Amadi et al., 2015]. Obviously, it’s a global problem and has a strong relationship to energy consumption behavior.

Nowadays, Spain has grown in sharing RESs in electricity generation. The percentage of sharing RESs in 2016 was 38.6%, and in 2022 it became about 42% [REE, 2022b, 2023]. Though the world is moving to renewable energy, the electrical grid's stability continues to face challenges arising from the fluctuations of renewable power generation caused by changing weather conditions and the varying energy demand throughout the day. Also, a reliable supplier that covers the growth of energy demand in the future is necessary, as integrating more RESs into the grid is difficult without energy consumers’ response to the grid status and adjusting their energy consumption [Aziz et al., 2017; Notton et al., 2018].

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In this context, it's worth noting that the residential sector plays a key role in the energy market, where it consumes 19% of the total energy consumption in Spain [Eurostat, 2023b]. Therefore, making HECs part of the energy system, raising awareness about their roles, and the need to be responsible consumers regarding saving energy could be a part of the solution to the above-mentioned problems, which help in enhancing energy security and improving the RES sector development.

On the other hand, even though the electricity generation mix is relatively diversified, Spain is not endowed with significant fossil fuel reserves; it's the fourth-largest European country in energy consumption, with no local production of oil and natural gas [Eurostat, 2023b]. For example, in 2022 Spain imported natural gas by about 446 terawatt-hours from different countries [Telecinco, 2022]. Therefore, it is necessary to plan for the future energy security.

SG technology allows the end-user to participate in the decision-making of the electricity system based on the information exchange between the consumers and the main grid, which helps in the security and reliability of the grid and efficient energy usage. HEMSs can contribute to energy security by reducing energy consumption in peak periods, using local RESs such as PV, and shifting the operation time of household appliances to the high PV-power generation and grid's low price periods [Mitova et al., 2022; Al Muala, et al., 2023]. Therefore, HEMS helps in reducing the use of auxiliary generators to meet the energy demand, enhancing the grid's stability, reducing the amount of fuel imported from outside, and reducing CO_2 emissions.

Spain put in place a plan to install smart meters for energy consumers and according to the energy policy review report of Spain done by the IEA, 99.64% of the traditional meters were replaced by smart meters by late 2019 [IEA, 2021b]. Many DR programs based on SG have been applied in Europe lately, to make customers use energy efficiently based on the grid generation and demand status [IRENA, 2019]. In Spain, the current electricity tariff which has been applied in 2021 contains three periods (low, medium, and high), whereas the electricity price changes hourly [REE, 2022a]. However, participation in DR in Spain is still low [Larrosa-López et al., 2020]. The main

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barriers affecting using HEMSs are the consumer's dissatisfaction with participating in DR programs or being unaware of DR benefits, in addition to the absence of policy frameworks in support of participation in DR [ACER et al., 2016]. Therefore, policymakers must consider consumer satisfaction and raise awareness of the importance of sharing in HEMS based on DR programs, even for consumers who have not yet engaged.

TAM is one of the most influential theories of technology acceptance that models the causal relationships of internal belief-attitude-intention-actual behavior by two main factors, Perceived Usefulness (PU), and Ease of Use (PE) [Davis, 1989]. PU and PE factors play a fundamental role in shaping the user's Attitude towards (ATT) adopting technology, which, in turn, influences their Intention to Use (INT) [Davis, 1989]. Recently, TAM has been used to study consumers' acceptance of new energy technologies [Chen et al., 2017; Park et al., 2017; Shuhaiber et al., 2019; Khalid, et al., 2021; Billanes et al., 2022; Yang et al., 2021; Zeru et al., 2021; Karunarathna et al., 2023]. However, few studies have examined the relationship between economic benefits, environmental awareness, ease of use, usefulness, and attitude in consumers' acceptance model of adopting SG and HEMSs. Moreover, no research on Spanish consumers' acceptance of participation in DR and adopting HEMS has yet been carried out after the new electricity tariff in Spain, to understand the factors that might affect their acceptance.

The objectives of this work are to investigate the factors influencing the intention of Spanish HECs, to participate in DR after the new electricity prices by managing their home energy consumption efficiently. In addition, helping the policymakers to establish successful policies that enhance the adoption of HEMS and participation in DR by identifying the acceptance factors of HEMS. To accomplish that, we proposed an extended TAM by adding consumers' environmental Perceived Awareness (PW), and Family's Economic Benefits (FEB) factors to TAM, and measuring the mediating effect of attitude between usefulness and intention to adopt HEMS.

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4.2. MATERIALS AND METHODS

To achieve the objectives of this work, some factors that might affect consumers to participate in DR were selected based on a systematic review. After that, TAM theory was used to implement the research model. Then, several hypotheses were proposed, based on a systematic review, to gain a deep understanding of Spanish HECs' attitudes about the possibility of participating in DR programs after the new electricity tariff. A sample case study was selected to carry out the research and extract results, where AMOS 20.0 was used for analyzing the collected data.

4.2.1. Conceptual model

The present study uses TAM to investigate the factors that might affect consumers' acceptance of participating in DR after the new electricity tariff. Two factors were added to the TAM-based model as shown in Figure 4.1. The developed TAM research model consists of four exogenous variables (Consumers' Environmental Awareness, Family's Economic Benefits, Ease of Use, and Usefulness), a mediating effect (Attitude toward Use), and one endogenous variable (Intention to Use).

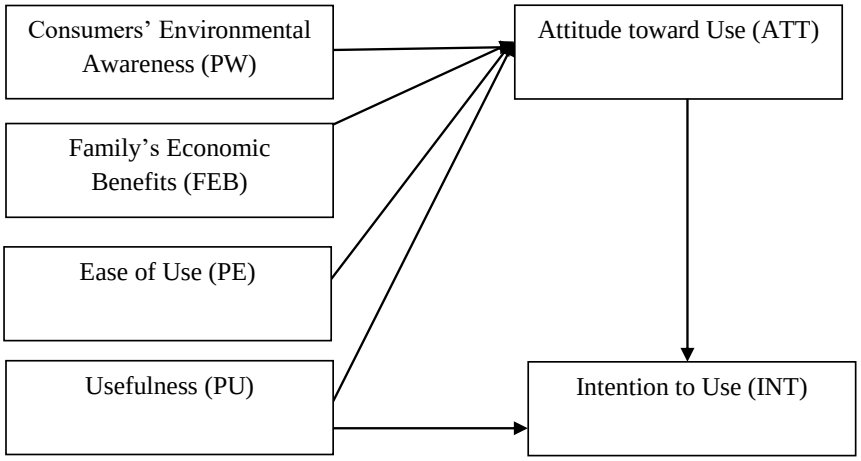

Figure 4.1: The conceptual model

4.2.2. Hypothesis development

In the proposed model, perceived usefulness is expressed that managing energy consumption by engaging in a DR strategy is beneficial.

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According to David [Davis, 1989], the relationship between intention to use and perceived usefulness is direct. Many studies showed that perceived usefulness has a positive effect on the intention to use [Ianole-Călin et al., 2022; Im et al., 2004; Szymanski et al., 2007; Karunarathna et al., 2023].

Attitude toward use is defined as the degree of how the user feels about using HEMS after applying the new electricity tariff, whether positive or negative feelings. According to TAM theory [Davis, 1989], the author contended that the user's intention to use new technology is affected by his attitude toward using it, which was also confirmed by several studies [Chou et al., 2015; Akroush et al., 2019; Billanes et al., 2022; Karunarathna et al., 2023].

The perceived ease of use is a metric of satisfaction in adopting HEMS by easily participating in DR, monitoring smart meters, and turning on/off home appliances free of physical and mental effort. Many studies found that the higher ease of use and usefulness of use HEMS have a positive effect on attitudes toward using HEMS [Tsuei et al., 2019; Hua et al., 2019; Karunarathna et al., 2023]. Moreover, if the direct effect of a variable on another variable is more than the indirect effect through a mediator, this indicates that the mediator has no influence [Baron et al., 1986; Byrne et al., 2001; Karunarathna et al., 2023].

The perceived consumers' environmental awareness variable is the perceived awareness that participation in the DR strategy helps preserve the environment. Environmental awareness has become an important factor in human behavior; it refers to the knowledge and concern about the impact of human behavior on the climate and environment [Schuitema et al., 2013]. Preserving the environment is one of the main goals of DR by decreasing the use of fossil fuels and increasing the integration of RESs. A previous study demonstrated that a high level of environmental awareness helps to make conscious choices for acting in an environmentally friendly way [Partanen-Hertell et al., 1999]. A survey done in the UK indicated that the majority of respondents were accustomed to decreasing the use of electricity and gas due to their effect on the environment, and climate change [Thornton, 2009]. A study was performed on the factors that affect consumers' purchasing

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intention to buy energy-efficient products, the results showed that the energy and environmental awareness of the consumers' have a significant impact on consumers' attitudes toward purchasing energy-efficient products [Akroush et al., 2019]. Factors that affect purchasing energy-saving appliances were studied, and it was found that environmental awareness has a positive effect on attitude [Zhang et al., 2020a]. A case study done on Japanese home consumers indicated that environmental awareness positively influences the adoption of DR [Iliopoulos et al., 2021]. According to Alkawsi and Baashar (2020), it found that environmental awareness of using smart meters positively influences consumers' attitudes toward using smart meters [Alkawsi et al., 2020]. A survey carried out in Poland highlights the importance of energy consumers place on using RESs and saving energy as a means of preserving the environment [Sobocińska, 2022].

The family's perceived economic benefits are about understanding and implementing the basic concept of economics and how families behave and make economic decisions, where economic benefits play a role as a behavior essential to achieving individual well-being [Rustantono et al., 2020]. The perceived family's economic benefits variable is the perception of economic benefit to be gained by participation in the DR strategy. For the attitude toward adopting technologies, the economic incentives and benefits are strong motives for accepting new technologies [Wang et al., 2010; Pei et al., 2015]. HEMSs based on the DR programs can help to decrease the electricity cost by 23% [Beaudin et al., 2015]. Moreover, it is found that consumers' attitudes in managing their energy consumption and saving energy contribute to the country's economic growth, which will reflect positively on them [Rausser et al., 2023]. A study evidenced that reducing the electricity bill affect strongly consumers' attitudes toward saving energy at home [Hoffmann-Burdzińska et al., 2022]. Another study undertaken in Finland aimed to examine the consumers' energy consumption behavior and their intention to adopt HEMSs. The results revealed that consumers are willing to adjust their consumption in return for financial and environmental benefits [Immonen et al., 2022]. It was found that environmental awareness and economic indicators are important to consider for the sustainability measurement of the

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renewable energy sector [Abdolmaleki et al., 2021]. Regarding that, the following hypotheses were set:

H1: Attitude has a positive impact on the intention to use

H2: Perceived usefulness has a positive impact on the intention to use

H3: Perceived consumers' environmental awareness has a positive impact on attitude

H4: Perceived family economic benefit has a positive impact on attitude

H5: Perceived ease of use has a positive impact on attitude

H6: Perceived usefulness has a positive impact on attitude

H7: Attitude toward mediates the relationship between perceived usefulness and intention to use

4.2.3. Data collection and analysis

The study focused on HECs sampling in Galicia, Northwest Spain; 150 questionnaires were distributed by hand and online to consumers. Twenty questionnaires were not received, and ten questionnaires were incomplete (missing) answers.

The survey was done on homeowners in Galicia provinces, Northwest Spain; with seven-point Likert scales for measuring all variables. However, the data set of 120 samples was encrypted and saved in SPSS version 19.0 and analyzed using AMOS 20.0. Hence, 120 answers were used in the post-analysis, where the response rate was 80%.

4.3. RESULTS

4.3.1. Profile of the respondents

The study encompassed a total of 120 participants, comprising 61 men and 59 women, all of whom were over 18 years old. The demographic variables in the study's sample consisted of the following elements: (1) Gender, (2) Age, (3) Marital status, (4) Type of residence, (5) Type of home, (6) Year home built, (7) Members of the family, (8) Province of the residence, (9) Number of inhabitants of the locality, (10) Education level, (11) Salary. Table 4.1 shows the demographic characteristics of the collected data.

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Table 4.1: Demographic characteristics of respondents

Demographic Characteristics		Frequency	Percentage (%)
Gender	Male	61	50.8
	Female	59	49.2
Age	18-30	44	36.7
	30-42	24	20
	42-54	33	27.5
	54-66	17	14.2
	More than 66	2	1.7
Marital status	Single	70	58.3
	Married	41	34.2
	Divorced	6	5
	Widowed	3	2.5
Type of residence	Owner	66	55
	Renter	54	45
Type of home	Independent Single-family home	33	27.5
		10	8.3
	Semi-detached house	75	62.5
	Apartment building	2	1.7
	Other		
Year home built	Before 1991	47	39.2
	1991-2001	35	29.2
	2002-2012	34	28.3
	After 2012	4	3.3
Members of the family	1-2	42	35
	3-4	65	54.2
	5-6	11	9.2
	More than 6	2	1.7
Province of the residence	A Coruña	79	65.8
	Lugo	8	6.7
	Ourense	9	7.5
	Pontevedra	19	15.8
	Outside of Galicia	5	4.2
Number of inhabitants of the locality	More than 50,000	59	47.5
	10,000 - 50,000	35	29.3
	Less than 10,000	28	23.3
Education level	Primary studies / no studies	3	2.5
	Secondary studies	28	23.3

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Demographic Characteristics		Frequency	Percentage (%)
	(baccalaureate / FP)	55	45.8
	Higher studies (University / Higher FP)		
	Doctorate	34	28.3
Salary (per month)	Less than EUR 1000	29	24.2
	EUR 1000 – 2000	43	35.8
	EUR 2000-3000	19	15.8
	More than EUR 3000	21	17.5
	Noun	8	6.7

The data clearly indicates that a significant portion of the surveyed individuals fell within the age range of 19-30 years, accounting for 36.7% of the sample. In terms of marital status, an overwhelming majority, specifically 58.3% of respondents, reported being single. When examining the housing situation, 55% of respondents identified as homeowners, while the remaining 45% were renters. Furthermore, the predominant type of residence was apartment buildings, making up 62.5% of the housing choices among respondents. Additionally, it's worth noting that nearly 39.22% of the homes surveyed were constructed before the year 1990.

Among the surveyed family members, a significant portion, comprising 54.2%, consisted of households with 3-4 individuals. Notably, the majority of respondents hailed from A Coruña, making up 65.8% of the total sample. In terms of the population size of their respective localities, nearly half of the respondents, specifically 47.5%, resided in areas with a population exceeding 50,000 inhabitants. Regarding educational attainment, a substantial 45.8% of respondents had pursued higher studies. Lastly, when it came to the income levels of the participants, a notable 35.8% reported earning a monthly salary falling within the EUR 1000-2000 range.

4.3.2. Descriptive statistics of variables

As depicted in Table 4.2, the average score for consumers' perceived environmental awareness is quite high, standing at 5.3. On the other hand, the ease of use, with an average score of 3.66, appears relatively lower. This suggests that when considering the intention to use, there is

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a clear need to place more emphasis on enhancing the ease of use aspect for consumers.

Table 4.2: Descriptive statistics of constructs

Construct	Original Items	Total Mean	Items after CFA	Composite Reliability
PW	5	5.3	2	0.87
FEB	5	4.31	3	0.80
PE	5	3.66	2	0.74
PU	5	4.34	2	0.88
ATT	5	4.51	2	0.78
INT	4	4.57	2	0.83

4.3.3. Reliability test

Composite reliability (CR) is used to test reliability in Structural Equation Modeling (SEM) analysis [Werts et al., 1974; Hair et al., 2010]. According to many studies, the CR scale should be greater than 0.60, or greater than 0.70 [Bagozzi et al., 1989; Holmes-Smith et al., 2001]. In addition, CR exceeding 0.70 has been said to reveal a satisfactory internal consistency [Hair et al., 1998; Hair et al., 2010]. In this study, the CR test, as illustrated in Table 4.2, was done. The results revealed that all variables within the final structure of the study attained CR values exceeding 0.70. This observation underscores the fact that all constructs demonstrate a commendable level of internal consistency, aligning with established criteria [Bagozzi et al., 1989; Hair et al., 1998; Hair et al., 2010; Al Muala, 2020].

4.3.4. Confirmatory factor analysis

SEM is used to test the study's research model and hypotheses, while Confirmatory Factor Analysis (CFA) is used to verify the factor structure of a set of observed variables [Byrne et al., 2001; Hair et al., 2006].

In this work, the chosen criteria for testing the suitability of fit for the generation model are the chi-square (X^2), P-value, degrees of freedom (DF), Goodness of-fit-Index (GFI), Adjusted GFI (AGFI),

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Incremental Fit Index (IFI), Normed Fit Index (NFI), Comparative Fit Index (CFI), and Root Mean Square Error of Approximation (RMSEA).

Figure 4.2 shows the results of the structural equation model, it is found that X2 has a value of 81.004 with a DF of 53. Where the GFI is 0.974, AGFI is 0.955, IFI is 0.990, NFI is 0.970, CFI 0.989, RMSEA is 0.034, and X^2 / DF of 1.528<3. The results underscore the appropriateness and acceptability of the model generation, as they align with the recommended threshold values [Hair et al., 2006]. Therefore, it can be concluded that all factors are validated and acceptable.

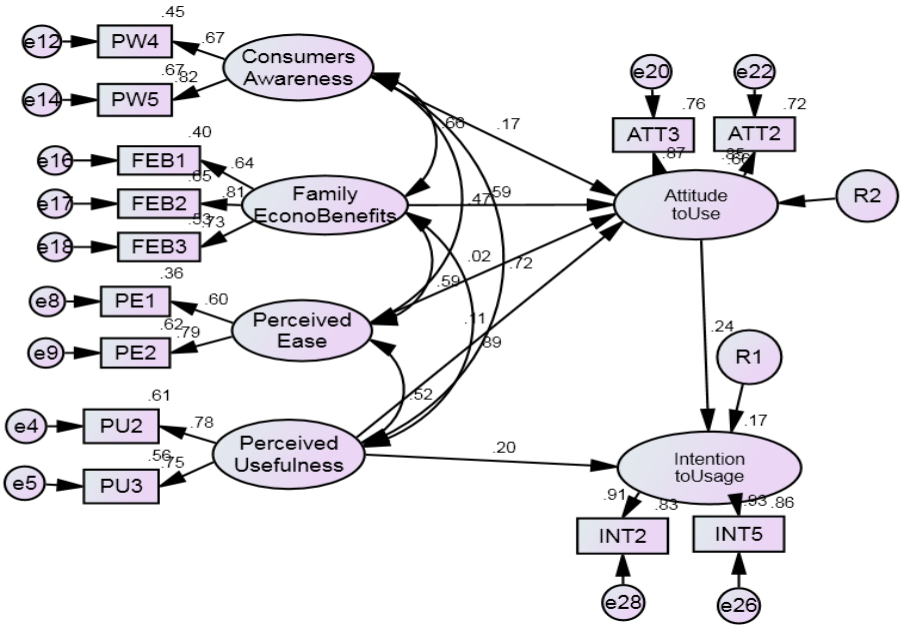

Figure 4.2: Results of the Structural Equation Model

4.3.5. Hypothesis test

The hypotheses were tested using a Path Analysis, with acceptance or rejection decisions made using the P-value based on the Critical Ratio (C.R.) [Anderson et al., 1988]. The direct relationship represents a direct effect through the independent (external) construct on the dependent (internal) construct. Table 4.3 presents the results of the

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estimation of the weight of the regression, the standard error (SE) of the weight of the regression, and the C.R of the weight of the regression.

The results indicated the acceptance of hypotheses H1, H2, H3, and H4, while hypotheses H5 and H6 were found to be rejected. Additionally, an examination was conducted to assess the role of the mediator, specifically the influence of attitude toward use, in mediating the relationship between perceived usefulness and intention to use. Many studies indicated if the direct effect is greater than the indirect effect, this confirms that the mediator has no influence [Baron et al., 1986; Byrne et al., 2001]. Thus, attitude toward use does not affect the relationship between perceived usefulness and intention to use, where the direct influence was 0.197, and the indirect effect was 0.025.

Table 4.3: Results of the hypotheses

H.	From	To	Estimate	SE	C.R.	P-Value	Acceptance
H1	ATT	INT	0.321	0.134	2.393	0.001	YES
H2	PU	INT	0.259	0.131	1.971	0.049	YES
H3	PW	ATT	0.174	0.085	2.047	0.041	YES
H4	FEB	ATT	0.562	0.175	3.215	0.001	YES
H5	PE	ATT	0.016	0.066	0.243	0.808	NO
H6	PU	ATT	0.104	0.188	0.557	0.577	NO

4.4. DISCUSSION

The main objective of this study is to identify factors affecting consumers' participation in DR; by managing their energy consumption in response to the electricity price after the new tariff in Spain. The findings show that PU has a significant effect on the intention to adopt HEMSs after the new electricity tariff. This means that the favorable or unfavorable intention to adopt HEMSs is to the degree to which the person believes HEMS would improve the quality of life and makes consumers take part in contributing to energy security. The results are consistent with prior studies that underscored the positive impact of

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usefulness on the intention to use new technology [Chou et al., 2015; Park et al., 2017; Shuhaiber et al., 2019; Karunarathna et al., 2023]. However, when it comes to PU and PE, this research found that they have no influence on the consumers' attitudes toward adopting HEMSs. This indicates that the perceived ease of turning on/off the appliances and the usefulness of managing energy consumption in response to electricity prices are not directly affecting consumers' attitudes. This finding aligns with prior studies on the acceptance of new technology [Shanmugam et al., 2014; Chin et al., 2016; Koksalmis et al., 2021].

The results show a positive effect of consumers' environmental awareness and family's economic benefits on attitude. This indicates that the higher awareness and family's economic benefits, the more participation in HEMSs and the more contribution to energy security. The results are supported by previous research findings [Kim et al., 2014; Fergen et al., 2016; Olson-Hazboun et al., 2016; Park et al., 2017; Oluoch et al., 2020]. Accordingly, the effect of perceived environmental awareness and economic benefits on consumers' attitudes are important factors to take into consideration, when suggesting energy policies for adopting HEMSs in line with the development of the energy sector; where consumers' attitudes will influence their intention to use HMESs as a means to manage energy consumption. The mediation results reveal that attitude does not mediate the effect between perceived usefulness and intention to use HEMSs. This can be attributed to the fact that the consumers consider the perceived usefulness of using HEMSs relatively important. Based on the results, the attitude has a significant influence on the intention to use HEMSs, which is supported by previous studies [Stragier et al., 2010; Hua et al., 2019; Shuhaiber et al., 2019; Karunarathna et al., 2023]. It can be argued that Spanish consumers' attitude towards using HEMSs is positive owing to the environmental awareness and perceived family's economic benefits of participating in DR and managing energy consumption at home. Thus, policymakers ought to place a focus on these factors by offering financial incentives, encouraging the installation of local RESs at home, and reducing taxes on saving-energy appliances. And clarify the benefits of managing energy consumption according to the new electricity prices on the

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future economic and environmental trajectory of Spain. Furthermore, efforts should be directed towards enhancing consumer awareness regarding the risks associated with fossil fuel usage, the advantages of using RESs, and the importance of using HEMS to preserve the environment and enhance energy security. These endeavors can be facilitated through various channels such as social media, informative articles, the inclusion of relevant content in university curricula, and the organization of scientific symposiums and seminars.

4.5. CONCLUSIONS

An extended model of TAM was proposed to investigate the factors that might affect the intention to use HEMSs and participate in DR after the new electricity tariff in Spain. Based on the literature review, the perceived customer's environmental awareness and family's economic benefits were added to the TAM model. The study was done in Galicia, Northwest Spain. After gathering the data, it underwent analysis using Amos 20. The data analysis results fulfilled the research objectives, providing valuable insights into the influence of each factor on the intention to use HEMSs.

The study elucidated the impact that various factors exert on shaping the attitude toward and intention to use HEMSs. The results show a positive impact of the consumers' environmental awareness and family's economic benefits on the attitude toward using HEMSs. In addition, the results show a direct positive effect of usefulness and attitude toward use on the intention to use HEMSs. It is worth noting that the higher the economic benefits and environmental awareness, the more attitude to use HEMSs, which in turn leads to formulating positive intention to use HEMSs. The perceived family's economic benefit (C.R.= 3.215) stands out as the most important factor in improving consumer acceptance, which is consistent with the function of HEMSs; saving energy and consuming energy in the low-price periods reduces the bill. Likewise, the influence of environmental awareness (C.R. = 2.047) on the attitude towards using HEMSs holds notable significance. In other words, energy consumers are willing to manage their energy consumption to preserve the environment. This willingness is contingent upon them gaining adequate awareness of climate change

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issues and realizing their essential role in participating in DR aimed at environmental enhancement. Besides, the results reveal that usefulness has a positive and direct impact on intention to use, and the attitude does not mediate the relation between usefulness and intention to use. Hence, the higher the usefulness of using HEMSs in enhancing life quality, the more intention to use HEMSs. While the perceived ease of use and usefulness have insignificant effects on the attitude toward use. In light of the findings, policymakers should take measures that accentuate the economic benefits for energy consumers and the positive impact on the environment of adopting HEMSs and draw up policies that support these factors.

The researchers can use the above-mentioned findings as a foundation to further develop the proposed model and explore additional factors that could potentially impact consumer acceptance in Spain. By doing so, researchers can offer policymakers a richer understanding of the factors at play, thereby assisting in the formulation of more effective strategies aimed at enhancing consumer acceptance of the new electricity tariff. To gain a more comprehensive understanding of the subject in Spain, it is highly advised to broaden the scope of the research by increasing the sample size and carrying out a larger-scale survey encompassing various cities across the country. Such an approach would yield more comprehensive and robust results, contributing to a more thorough comprehension of consumer behavior and preferences related to the new tariff.

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CHAPTER 5. AN ENERGY FLOW MANAGEMENT STRATEGY FOR MAINTAINING PHOTOVOLTAIC-BATTERY INTEGRATED SYSTEM LIFESPAN

SUMMARY

The world is moving towards using RESs. However, there are some concerns related to power balance due to the weather conditions fluctuations and the energy demand variation. As the residential sector consumes a high amount of energy, managing energy consumption at homes became necessary to contribute to energy security. Various studies were conducted on energy management strategies focused on cost reduction of using grid energy. This work proposes an efficient strategy that manages the energy flow, aiming to reduce an actual energy cost considering the RESs and ESSs lifecycle. An energy usage cost model is proposed considering the installation cost of the integrated system and introduced into an energy flow management strategy. A real case study data is gathered from a home in Vigo, Spain. A one-minute time slot model is designed in Matlab to obtain accurate results. The results demonstrate that the proposed work effectively maintains the integrated system while simultaneously achieving an actual reduction in energy costs through optimized energy distribution. In addition, it indicates that this approach fosters consumer engagement and participation, thereby contributing to the enhancement of the overall energy system.

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5.1. INTRODUCTION

Over the past few decades, the world has witnessed exponential population growth and economic expansion, driving an unprecedented demand for energy resources [Tanaka, 2010]. Consequently, CO_2 emissions from fossil fuels have surged by approximately 90% since 1970 [Boden et al., 2009]. This escalation has intensified concerns about ensuring energy security and the environmental repercussions of consuming energy, alongside meeting growth in energy demand [Khan et al., 2016; Narula, 2019]. Dealing with this issue, a global shift towards cleaner and more dependable energy systems is in progress. In Europe, the proportion of RESs in the EU's gross energy consumption surged from 14.2% in 2012 to 21.8% in 2021 [Statista, 2022].

However, this rapid integration of RESs into the main grid has posed challenges due to the intricate balance required between demand and generation, influenced by unpredictable weather conditions and variations in energy demands. The fluctuation of RESs generation has exacerbated grid stability issues, leading to electricity outages, particularly during peak periods, resulting in electricity price spark, jeopardizing the stability of the overall electricity system, exacerbating CO_2 emissions by operating auxiliary fossil fuel generators [Haas et al., 2015; Zedalis, 2017].

In response, policymakers have turned to DR programs leveraging SG technology to manage energy demand effectively and optimize energy system utilization in real time. DR programs dynamically adjust electricity prices throughout the day based on prevailing generation and demand conditions, prompting consumers to modify their energy consumption behaviors in alignment with grid dynamics. Consequently, demand-side management based on DR contributes to enhancing the future of energy supply security [Darby et al., 2012; Islam et al., 2014].

The integration of ESSs with PV is a widely adopted approach in the residential sector. This integration offers numerous advantages, including reduced electricity costs for consumers and suppliers, environmental benefits through the reduction of CO_2 emissions, and enhanced grid stability. ESSs ensure a more efficient and reliable energy supply, contributing to a sustainable energy future, by storing

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excess energy generated by PV systems. Moreover, the integration of RES necessitates innovative approaches to energy management to mitigate grid instability and optimize resource utilization. Advanced strategies leveraging technologies such as HEMSs have emerged. These systems enable households to actively monitor and manage their energy consumption in real-time, optimizing energy usage in alignment with grid conditions and individual preferences.

While RESs and ESSs offer significant benefits, their widespread adoption faces challenges, primarily due to the high initial capital costs associated with their installation. Despite their effectiveness in addressing the intermittent nature of renewable energy, especially with batteries being recognized as a key solution [Stephan et al., 2016], these costs can deter many potential users. Moreover, the operational lifespan of batteries and the optimization of their usage present additional concerns. Maximizing the efficiency and longevity of batteries should be considered for ensuring the economic viability and sustainability of energy storage solutions. Therefore, there is a pressing need to develop optimal energy flow strategies that can effectively manage the operation of RESs and ESSs within residential energy systems. Addressing these challenges requires innovative approaches and advancements in technology. Overcoming these barriers, the residential sector can unlock the full potential of RESs integration and ESS, paving the way for a more sustainable and resilient energy future.

Various studies have endeavored to address the challenge of optimizing energy flow within integrated systems. However, many of these studies have primarily focused on energy cost reduction from the grid, neglecting factors such as installation costs and system life cycle [Elkazaz et al., 2019; Mbungu et al., 2019; Zhang, 2020b; Bhattacharjee et al., 2021; Dinh et al., 2021; Waseem et al., 2021]. While these technical strategies are undoubtedly valuable in enhancing the efficiency and performance of integrated energy systems, neglecting the installation costs and life cycle principles considerations could make outcomes that deviate from real-world feasibility. Additionally, the absence of accurate pricing mechanisms for energy sold back to the grid, as assumed in several studies [Dinh et al., 2021; Waseem et al.,

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2021], results in inefficient utilization of PV and ESS systems, leading to imprecise estimations of electricity cost reductions.

The inefficiencies in PV and battery utilization can have detrimental effects, such as shortened lifespans and increased energy losses. Moreover, the purported cost reductions may be misleading, as they often neglect the expenses linked to system installation. To confront these challenges head-on, our study concentrates on devising an energy flow management strategy that not only factors in the installation costs of PV and ESSs but also incorporates real grid prices for both purchasing and selling energy. By integrating these critical components into the proposed strategy, we aim to provide a more accurate representation of the actual costs and benefits associated with the deployment of RESs. Through this approach, we seek to optimize the operation of PV and ESSs while simultaneously ensuring cost-effectiveness and sustainability in energy management strategies.

5.2. MATHEMATICAL MODEL

5.2.1. System architecture

As illustrated in Figure 5.1, the proposed model architecture comprises PV, battery, and load connected to the main grid. This configuration facilitates the flow of data throughout the system, enabling the efficient management and allocation of energy resources. With PV generation, storage capabilities, and grid connectivity seamlessly integrated, the model enables dynamic energy flow management, ensuring optimal utilization and distribution across the system.

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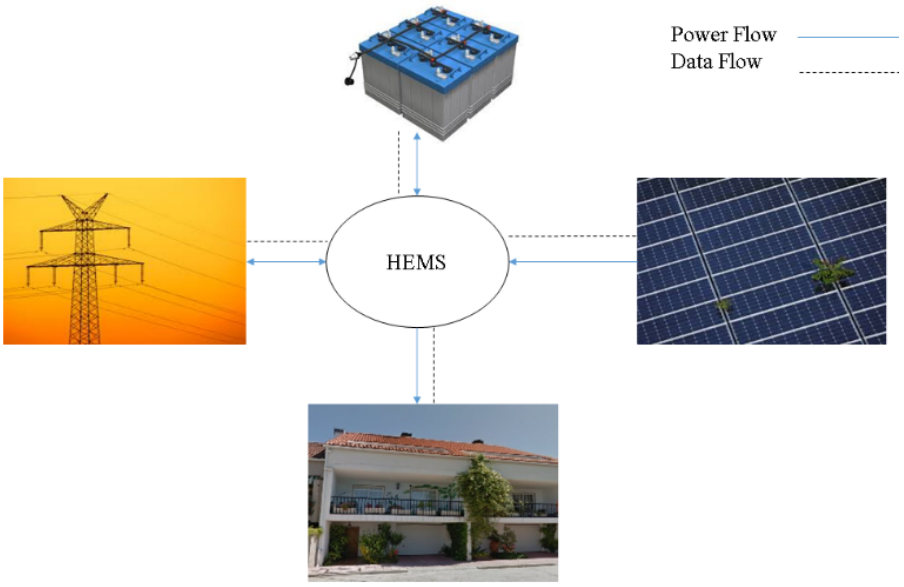

Figure 5.1: System architecture

5.2.2. System model

5.2.2.1. Solar panel

The output power of the PV generator $P_{PV}(t)$ at each time slot *t* for each solar panel is modeled in [Eq. 5.1].

$$P_{PV}(t) = A * \gamma * Ir(t) * \mu_{conv} \quad \text{[Eq.5.1]}$$

Where A (m^2) is the area of the solar panel and the efficiency of the PV system is γ (%), Ir denotes the solar irradiance (W/m^2), μ_{conv} is the efficiency of the (DC/AC) inverter which is assumed to be 97%.

5.2.2.2. Battery storage

The model of the battery behavior is presented in [Eq. 5.2], considering the converter losses during the charging and discharging processes.

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$$E_B(t+1) = E_B(t) + P_B^{ch}(t) * \eta * \Delta t - \frac{P_B^{dis}(t)}{\eta} * \Delta t \quad \text{[Eq.5.2]}$$

Where $E_B(t)$ represents the amount of current energy in the battery at each time slot *t*. $P_B^{ch}(t)$ denotes the total stored power in the battery at each time slot t, whereas$P_B^{dis}(t)$ is the total supplied power from the battery. η is the converter efficiency of charging and discharging which is assumed to be 0.95 and Δt is the simulation time which is equal to 1 divided by 60. The battery energy losses due to converter losses are calculated using [Eq. 5.3].

$$B_{losses}(t) = P_B^{ch}(t) * \frac{1-\eta}{\eta} + P_B^{dis}(t) * (1-\eta) * \Delta t \quad \text{[Eq.5.3]}$$

Moreover, ESSs must adhere to specific limitations to prevent excessive charging and discharging of the battery, as well as restrictions on the amount of charging/discharging that can occur during each time slot *t*. To ensure meeting these limitations, [Eq. 5.4-5.6] were set.

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad \text{[Eq.5.4]}$$

$$0 \leq P_B^{ch}(t) * \Delta t \leq CH_{rate} \quad \text{[Eq.5.5]}$$

$$0 \leq P_B^{dis}(t) * \Delta t \leq Dis_{rate} \quad \text{[Eq.5.6]}$$

Where the State of Charge (SOC) is the ratio of the total amount of energy stored in the battery relative to its overall energy capacity, CH_{rate}, Dis_{rate} are the maximum charge/discharge rate of the battery at each time slot *t*.

5.2.2.3. Energy consumption

The total energy demand $E_{home}^{min}(t)$ at each time step *t* calculated using [Eq. 5.7].

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$$E_{home}^{min}(t) = \sum_{P=1}^{m} P_a * OP\left(a_P(t)\right) * \Delta t \qquad \text{[Eq.5.7]}$$

Where P= (b_1,b_2,b_3,…, b_m) is the set of the home appliances for t=(1,2,3,…,1440). P_a is the rating power of the home appliances respectively. $OP\left(a_P(t)\right)$ denotes the status of the appliances at each time slot *t*.

5.3. THE PROPOSED ENERGY FLOW MANAGEMENT STRATEGY

Figure 5.2 illustrates the proposed energy flow management strategy (PEFMS), which diverges from previous approaches by incorporating the installation cost and system lifecycle, as described in Figure 5.2. The methodology involves accurate planning and optimization to ensure efficient energy utilization and cost-effectiveness throughout the system's operational lifespan. This comprehensive approach enhances the accuracy and practicality of energy management strategies in real-world applications.

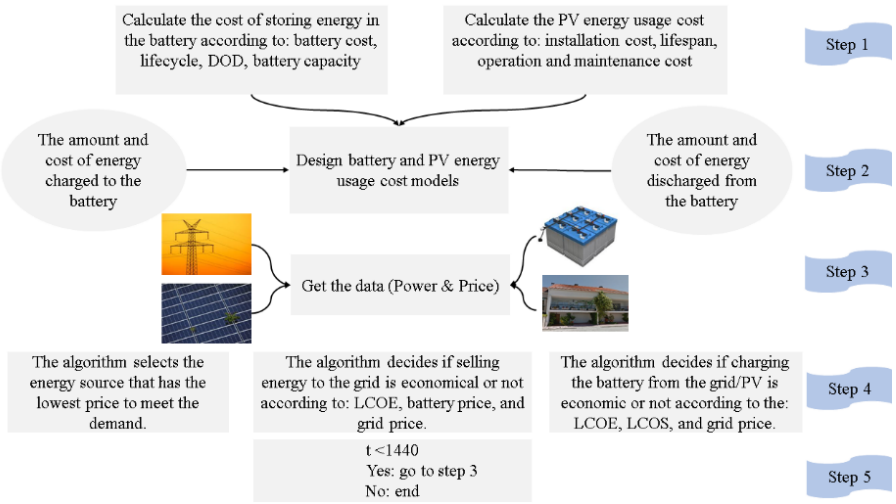

Figure 5.2: The proposed home energy management strategy

The approach is delineated as follows, encompassing a series of systematic steps to ensure comprehensive energy flow management:

Step 1: Determining the Levelized Cost of Storage (LCOS) for battery storage involves calculating the cost per kilowatt-hour (EUR/kWh) over its lifespan, as described in [Eq. 5.8]. This entails considering factors such as the initial installation cost, battery capacity, and the expected number of lifecycle cycles at a specified Depth of Discharge (DOD), as prescribed by the manufacturer. Similarly, the Levelized Cost of Energy (LCOE) for the PV system in the residential sector in Spain is determined, considering relevant parameters to express the cost per kilowatt-hour (EUR/kWh) of energy generated over its operational lifetime.

$$B_{LCOS} = \frac{C_B}{E_{batt} * N_{cycle} * DOD} \quad \text{[Eq.5.8]}$$

Where B_{LCOS} expresses the cost of using the battery throughout its lifespan (kWh), C_B is the battery capital cost (EUR), N_{cycle} is the number of battery cycles, DOD is the battery depth of discharge (%), and E_{batt} is the nominal energy of the battery system (kWh).

Step 2: A comprehensive cost model is devised to evaluate the energy consumption from the integrated system and grid, incorporating factors such as the LCOS, LCOE, and battery status. Additionally, the model incorporates the quantity of charged energy and its associated cost, which dynamically influences the battery price with each operational cycle. This dynamic adjustment ensures that the battery price accurately reflects its current state and usage patterns. By considering the installation cost of the integrated systems and their respective lifecycles, the cost model provides a holistic framework for efficient utilization. This approach ensures that the integrated system operates optimally, maximizing cost-effectiveness while meeting energy demands reliably. Through continuous monitoring and adjustment based on real-time data, the cost model enables stakeholders to make informed decisions regarding energy usage and system optimization, ultimately driving efficiency and sustainability in energy

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consumption and the integrated energy system. The battery energy usage cost at each time slot *t* is calculated using [Eq. 5.9] and [Eq. 5.10].

$$B_{price}(t+1) = \frac{[E_B(t) * B_{price}(t)] + [EB_{ch}(t) * C_{ch}(t)]}{E_B(t) + EB_{ch}(t)} \quad \text{[Eq.5.9]}$$

$$C_C(t) = P_{gth}(t) * Grid^{buy}_{price}(t) + P_{bth}(t) * B_{price}(t) + P_{pvth}(t) * LCOE_{pv} * \Delta t \quad \text{[Eq.5.10]}$$

Where $Grid^{buy}_{price}(t)$ is the grid electricity tariff (EUR/kWh) at each time slot *t*, $EB_{ch}(t)$ denotes the total charged energy (kWh) at each time slot *t*, $C_{ch}(t)$ is the price of the total charged energy (EUR/kWh), $B_{price}(t)$ is the price of battery energy (EUR/kWh) at each time slot *t*, $LCOE_{pv}$ is the LCOE of the PV (EUR/kWh) at each time slot *t*, and $C_C(t)$ is the energy consumption cost from the grid, battery, and PV (EUR) at each time slot *t*. $P_{gth}(t)$, $P_{bth}(t)$, $P_{pvth}(t)$ are the amount of power consumed at home (kW) from the grid, battery, and PV at each time slot *t*, respectively.

Step 3: At each time slot *t*, essential data including grid prices, PV power, LCOE of PV, battery price, battery net power, and load, is transmitted to the energy flow management system. Table 5.1 and Figure 5.3 illustrate the dataset gathered for a typical home located in Spain and introduce it to the energy flow management strategy to facilitate the implementation of the energy flow management strategy.

Table 5.1: System parameters

Parameter	Value
PV Size (kWp)	1.045
Battery Capacity (kWh)	2.4
SOCmin-max (%)	10-90
Battery lifecycle	6000
LCOE (EUR/kWh)	0.092
LCOS (EUR/kWh)	0.072

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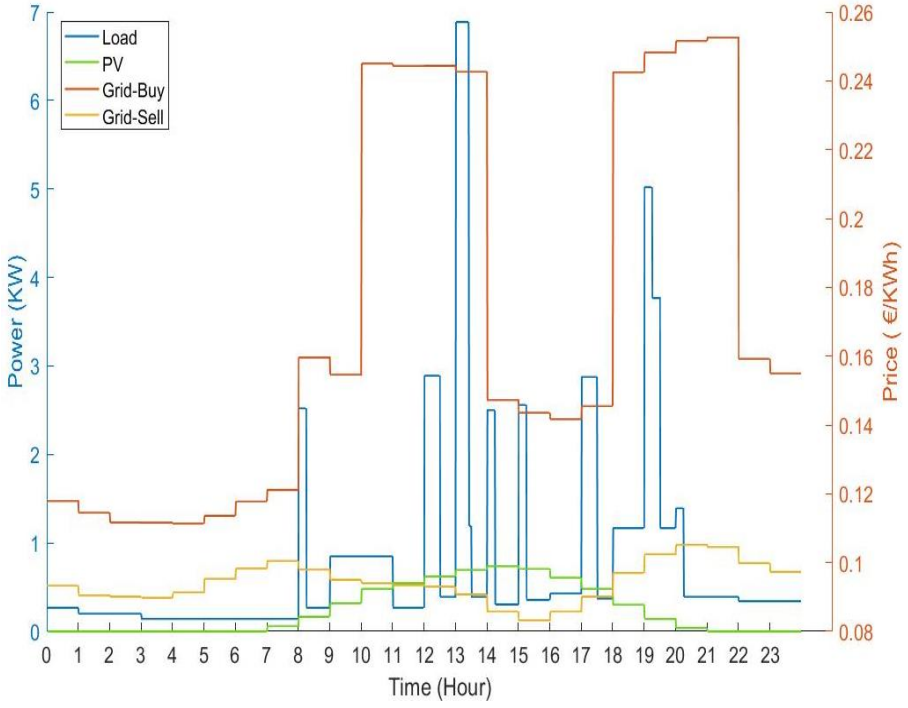

Figure 5.3: Case study data

Step 4: PEFMS manages energy distribution by analyzing various parameters PV price, battery price, and grid price. It aims to optimize energy utilization by minimizing costs associated with meeting the load demand. In instances of surplus PV energy, PEFMS evaluates factors such as LCOE, battery price, and grid price to determine whether storing excess energy in the battery is more cost-effective than selling it to the grid. Furthermore, PEFMS continuously evaluates the economic viability of charging the battery from the grid or PV at each time slot *t*. By dynamically adjusting energy storage and distribution strategies based on real-time pricing and demand data, PEFMS optimizes energy management processes to achieve cost-efficiency and reliability in energy supply.

Step 5: The PEFMS operates continuously until it reaches the end of the time horizon, which spans 1440 minutes corresponding to a full 24-hour period. [Eq. 5.11] depicts the power balance equation at each

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time slot *t*, ensuring that energy generation and consumption are appropriately aligned throughout the entire duration of the simulation.

$$(P_l(t) - P_{pvth}(t) + P_{gth}(t) + P_{bth}(t)) * \Delta t = 0 \quad \text{[Eq.5.11]}$$

Where $P_l(t)$ is the power consumption (kW) at each time slot *t*.

5.4. RESULTS

The research centers around a residential sector in Spain, a home in Vigo, Northwest Spain is taken as a case study. The total daily demand is 18.464 kWh and the total daily electricity cost is EUR 3.7584. The Solar radiation data and grid prices were sourced from the PVGIS 5.2 database and Red Eléctrica de España, respectively [European Commission, 2022e; REE, 2022a, 2022c). LCOE for PV systems in Spain's residential sector was determined based on the International Renewable Energy Agency report (IRENA) [IRENA, 2021], while battery data was obtained from Wccsolar [Wccsolar, 2022].

The presence of PV systems significantly reduces the reliance on energy procured from the primary grid. It contributes to reducing electricity bills and facilitates the utilization of surplus energy, either in batteries or through selling surplus energy back to the grid. ESSs further contribute to cost reduction by charging during periods of low grid prices and surplus PV energy generation and discharging in periods of high grid prices and shortage of PV generation. The simulation results of applying the proposed approach are delineated in this section. MATLAB R2021a is used as a simulation tool employed in this study, providing the computational framework necessary for analysis and extracting results. Figure 5.4 shows the energy balance of the system and Figure 5.5 shows the energy usage cost of PV, battery, and grid.

In the pursuit of optimizing energy distribution, the proposed methodology stands out for its comprehensive consideration of various factors. An illustration of its efficacy lies in the periods from 08:01 to 10:00 and 17:01 to 17:30. During these intervals, the analysis reveals a preference for importing energy from the grid as opposed to utilizing stored battery energy. The rationale behind this preference is rooted in

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the observation that the cost associated with utilizing battery energy exceeds that of grid energy. Consequently, it becomes evident that relying on battery reserves during these timeframes is economically disadvantageous.

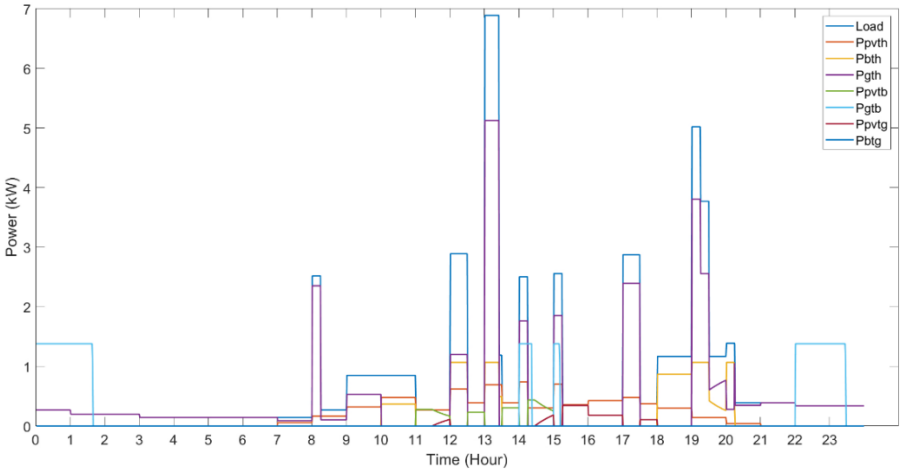

Figure 5.4: The power balance

Besides, the analysis reveals a different scenario during the periods from 10:01 to 11:00 and 18:01 to 19:00. Here, the analysis indicates a preference for utilizing battery energy over grid energy. This preference stems from the lower cost associated with using battery energy compared to the grid prices, considering both the cost of storing energy and the cost of energy charged. Thus, it is recommended to leverage battery reserves during these intervals to optimize energy utilization and minimize costs.

Figure 5.4 provides a visual representation of the power balance within the system and the corresponding energy prices described in Figure 5.5. Notably, the simulation showcases that the battery did not engage in selling energy to the grid. This strategic decision aligns with the overarching objective of preserving the battery life cycle and minimizing electricity costs, where the grid sell price is less than the price of energy stored in the battery. Furthermore, the analysis underscores the financial inefficiency of selling PV energy to the grid, as the cost of producing PV power outweighs its selling price. Consequently, the utilization of PV power within the home or storing it

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in a battery emerges as the preferred course of action, mitigating the inappropriate decisions associated with grid selling.

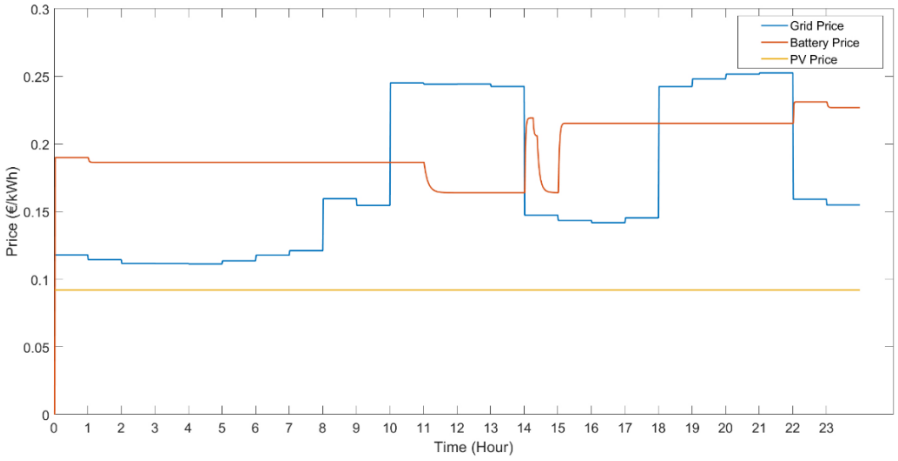

Figure 5.5: The energy usage prices

The outcomes of the simulation analysis reveal compelling insights into the benefits derived from the proposed energy management strategy. Through meticulous assessment encompassing PV, battery, and grid energy utilization costs, our findings reveal a notable reduction in overall cost. Specifically, the actual energy cost is EUR 3.163, incorporating PV, battery, and grid energy utilization expenses. This represents a reduction of 15.841% compared to the baseline scenario. Furthermore, the bill cost, factoring in grid energy usage, is EUR 2.782, reflecting a 25.979% reduction. These findings underscore the economic benefits of efficient energy utilization and management practices.

For the battery performance, the analysis reveals valuable insights into energy storage dynamics and associated losses. The total charged and discharged battery energy is 9.047 kWh, with battery losses amounting to 0.46771 kWh. Correspondingly, the associated battery loss cost is computed at EUR 0.071. Moreover, a comprehensive analysis incorporating various parameters is undertaken to calculate the expected battery lifespan. Factors such as the amount of charged and discharged energy, battery lifecycle, and the duration of the year are considered. It is found that the estimated battery lifespan stands at 4.36

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years. This insight into battery longevity is a foundational element in informing future decision-making processes related to energy storage infrastructure investments and operational strategies.

Based on the findings, the proposed work empowers stakeholders to make informed choices that optimize energy utilization and promote sustainability. Moreover, the framework's adaptability and scalability make it well-suited for application across diverse residential energy systems. Whether in Spain or elsewhere, the principles underlying the framework are widely applicable.

5.5. CONCLUSION

An energy flow management strategy is proposed in this work. An energy usage cost model of PV and battery is modeled considering their installation cost. It expresses the cost of storing energy, operation and maintenance costs, and the cost of the purchased energy. The simulation analysis shows the efficient energy distribution, focusing on achieving actual cost reduction and optimal operation of the battery. During periods of PV power shortfall, the proposed strategy strategically conserves battery reserves, prioritizing discharging operations when grid price outweighs battery price. Additionally, findings underscore the economic inefficacy of selling surplus energy to the grid, a practice often yielding lower returns than home consumption. The proposed work shows an actual energy cost reduction associated with the PV and battery installation costs, encouraging consumers to install local energy systems and manage their energy consumption. Consequently, these findings underscore the role of decentralized energy solutions in enhancing energy security and sustainability.

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CHAPTER 6. REALISTIC HOME ENERGY MANAGEMENT SYSTEM CONSIDERING THE LIFE CYCLE OF PHOTOVOLTAIC AND ENERGY STORAGE SYSTEMS

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

- Title: Realistic Home Energy Management System Considering The Life Cycle Of Photovoltaic And Energy Storage Systems
- Authors: Al Muala, Z. A.; Bany Issa, M. A.; Sansó-Rubert Pascual, D.; Bello Bugallo, P.M.
- Publisher: MDPI
- Journal: Sustainability
- eISSN: 2071-1050
- Impact Factor: 3.3 in 2023 (Database: Web of Science)
- Category: Environmental sciences (Database: Web of Science)
- Relative position: Q2 (159/358) in 2023 (Database: Web of Science)
- DOI: https://doi.org/10.3390/su151411205
- Year of publication: 2023
- Citations: 5 in Google Scholar, 3 in MDPI, 1 in Web of Science
- Article views: 1662
- Contribution of the doctoral student: contribution to conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing— review and editing, visualization, and project administration.
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SUMMARY

HEMSs have become necessary due to energy security and climate change concerns. Scheduling the operating time of household appliances is one of the most effective strategies used by HEMSs to reduce electricity costs, with several studies proposing optimization strategies for this purpose, emphasizing the reduction of grid energy usage costs. This study extends this paradigm by incorporating energy costs derived from RESs and ESSs into the appliance-scheduling strategy and energy flow management. The objectives are reducing real electricity costs, extending battery lifespan, minimizing charging/discharging losses, and optimizing the utilization of PV power. To achieve these objectives, we developed PV and battery energy usage pricing models. These models were introduced into the optimization problem solved using the Augmented Grey Wolf Optimization (AGWO) and Particle Swarm Optimization (PSO) algorithms in MATLAB. We developed an efficient energy flow management algorithm, collected real data from a home in Vigo, Spain, and simulated four scenarios. The results underscore the efficacy of the proposed system, implemented through AGWO and PSO, in substantially reducing real energy costs. Comparative analyses against an existing energy-usage-pricing model reveal noteworthy reductions in energy losses and an extended battery lifespan. Additionally, the proposed system achieves breakeven sooner than existing models, indicating its enhanced efficiency. These findings contribute valuable insights for advancing HEMS optimization strategies and promoting sustainable energy practices.

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6.1. INTRODUCTION

The increasing energy consumption in the world is directly connected to population growth and technological development. Energy consumption in the residential sector is still rising drastically; it has risen by 31% in Europe compared with the 1980s [Ritchie et al., 2023]. The population and energy use growth led to a rise in CO_2 emissions; a 1% increase in population is associated with a 1.28% increase in CO_2 emissions [Shi, 2001]. Additionally, the concerns regarding supply disruptions, long-term availability of energy supply to meet the growth in demand, widely fluctuating energy prices, and climate change have heightened anxieties about energy security [Ang et al., 2015; Azzuni et al., 2018].

Research and projects have been beginning to work on the ground by moving toward renewable energy sources to address the aforementioned issues by establishing a reliable power system that meets the increasing energy demand and considering environmental and economic concerns. Europe has witnessed progress in establishing renewable power plants in line with the current world direction, as the participation of renewable energy in final consumption in 2022 increased by 56% compared with that in 2004 [Eurostat, 2022].

There are still problems related to electrical grid stability due to the fluctuations in generation by renewable power plants owing to changes in weather conditions and the variations in energy demand during the day [Khoussi et al., 2017]. To address this issue, policymakers have created electricity-pricing programs called DR, where electricity prices vary at different times during the day. DR programs aim to involve the consumer in contributing to energy security by managing their energy consumption according to prices [Qdr, 2006].

HEMS is a DR tool that enables HECs to manage their energy consumption by exchanging information with the electrical grid through smart meters [Beaudin et al., 2015], where the significance of the change in electricity prices is to express the state of the electrical grid in terms of energy generated and energy demand.

Scheduling the operating time of household appliances is one of the most effective strategies of HEMSs, helping householders to reduce electricity bills and contributing to the electrical grid stability, where

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researchers have directed their focus. Installing a PV system in a house also plays an important role, as it is possible to shift the operation time of appliances to periods of high PV generation. ESSs can be used for charging during low-price periods and excess PV-power periods, discharging in periods of high-price, and PV power shortages, and reducing electricity bills; this contributes to enhancing the power system's flexibility and reduces electricity bills [Aghdam et al., 2020; Chua et al., 2020].

Although PV and ESSs contribute to reducing costs, CO_2 emissions, and making the system flexible, some studies utilized grid power to meet the energy demand in HEMSs [Awais et al., 2018; Hussain et al., 2018; Ruzbahani et al., 2019; Alfaverh et al., 2020]. Using PV and ESSs incurs a financial cost to install, in addition to the fact that these systems have a lifespan. Therefore, this requires using them effectively, considering their lifecycle and the installation cost.

However, most studies focused on reducing the grid energy usage cost in the optimization strategies [Ahmad et al., 2017; Dinh et al., 2020; Imran et al., 2020; Iqbal et al., 2020; Lee et al., 2020; Liu et al., 2020; Dinh et al., 2021; Rehman et al., 2021; Waseem et al., 2021; El Sayed et al., 2022]. As for energy management flow, the priority of using a power source to meet the energy demand and charging/discharging the battery was based on the grid price [Ahmad et al., 2017; Imran et al., 2020; Iqbal et al., 2020; Rehman et al., 2021; Waseem et al., 2021; Dorahaki et al., 2022]. This can be improved by involving the energy usage cost of the PV battery system in the optimization strategy and energy flow management model, considering the PV battery installation cost and lifecycle to minimize the actual electricity cost and maintain the lifecycle of the PV battery system.

Bouakkaz et al. (2021) proposed a battery energy-usage price model based on the SOC; the price increases when the SOC is low and decreases when the SOC is high [Bouakkaz et al., 2021]. Many papers assumed energy-selling prices to the grid and introduced them in the optimization strategy [Iqbal et al., 2020; Dinh et al., 2021; Waseem et al., 2021]. Assuming random energy-selling prices lead to increasing ESS energy losses and wasteful use of PV power, where the real energy-selling price is usually low.

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Previous studies focused on optimizing the operation time of home appliances based on minimizing the cost of energy used from the grid. This work focuses on managing home energy consumption using PV and ESS by scheduling the operation time of home appliances considering the installation cost and lifecycle of the PV-ESS.

The objective of this work is to achieve realistic cost reduction of using energy, energy savings through efficient energy utilization, and maintaining the integrated system lifespan.

The main contributions of this work are the development of battery and PV energy usage cost models; the implementation of a model of selling energy to the grid, and the introduction of the previous steps to an optimization problem. Additionally, creating an efficient energy-flow-management algorithm and a model of a one-minute time slot is considered for the optimization problem, which makes the results more accurate. These contributions consider the installation cost and the lifecycle of the integrated system, which will help with efficient energy utilization and reduce energy losses and wasted energy. Moreover, a real case study was used to obtain realistic results to encourage HECs to manage their energy consumption.

6.2. METHODOLOGY

To accomplish the objectives of this work, the methodology undertaken is as follows:

1. Mathematical model formulation of PV, ESSs, and home energy demand.
2. Mathematical model formulation of the PV and battery energy-usage cost and selling energy to the grid, considering the PV battery installation cost and lifecycle.
3. Algorithm development to obtain an optimal energy flow.
4. Objective function development.
5. Selection and description of the case study (load profile, solar radiation, PV battery systems size, and grid buying/selling price).
6. Optimization algorithms implementation for scheduling home appliances (one-minute operation time interval).

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7. Selection and analysis of sustainability factors, including modeling and running: expected battery lifespan, carbon emission intensity, and the breakeven point of the system.
8. Evaluation of the proposed system's: simulation by previous scenarios definition and final results obtainment.

6.3. DEVELOPMENT

Figure 6.1 shows the architecture of HEMSs, which includes PV, ESS, home appliances, and the main grid. In addition, the data (PV power, PV energy-usage price, battery's capacity, battery energy-usage price, grid price, and load) flows through the system to manage energy consumption and power flow.

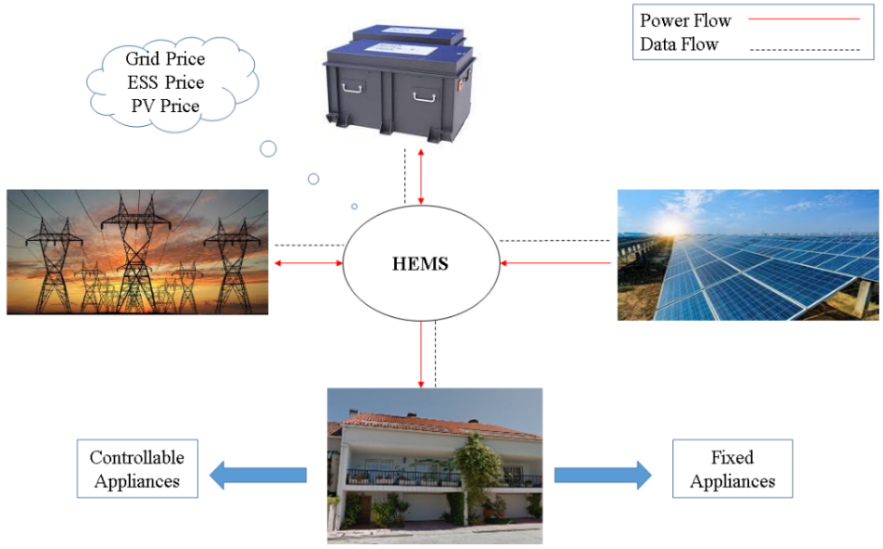

Figure 6.1: System architecture

6.3.1. System model

6.3.1.1. PV generation model

The PV output power is calculated using [Eq.6.1] [Fuselli et al., 2013].

$$P_{PV}(t) = A * \gamma * Ir(t) * \mu_{conv} \quad \text{[Eq.6.1]}$$

Where $P_{PV}(t)$ is the PV output power (kW) at each time slot *t*, A is the area of the solar panel (m^2) and the efficiency of the PV system is γ (%), Ir the solar irradiation (kW/m^2), the efficiency of the (DC/AC) inverter μ_{conv}, which is assumed to be 97%.

6.3.1.2. Battery storage model

The instantaneous energy in the battery is presented in [Eq.6.2], considering the converter losses during the charging and discharging process [Imran et al., 2020].

$$E_B(t+1) = E_B(t) + P_B^{ch}(t) * \eta * \Delta t - \frac{P_B^{dis}(t)}{\eta} * \Delta t \quad \text{[Eq.6.2]}$$

Where $E_B(t)$ represents the amount of current energy in the battery at each time slot *t* (kWh) and $E_B(t+1)$ is the amount of energy of the battery in the next time slot *t* (kWh). $P_B^{ch}(t)$ denotes the total stored power in the battery (kW) at each time slot *t*, whereas $P_B^{dis}(t)$ is the total supplied power from the battery (kW). η is the converter efficiency of charging and discharging which is assumed to be 0.95; Δt is the simulation time which is equal to 1 divided by 60.

[Eq.6.3-6.5] are used to calculate the battery energy losses due to converter losses.

$$ch_{losses}(t) = P_B^{ch}(t) * \frac{1-\eta}{\eta} \quad \text{[Eq.6.3]}$$

$$dis_{losses}(t) = P_B^{dis}(t) * (1-\eta) \quad \text{[Eq.6.4]}$$

$$B_{losses}(t) = ch_{losses}(t) + dis_{losses}(t) \quad \text{[Eq.6.5]}$$

Where $ch_{losses}(t)$ represents the battery charging losses (kW) at each time slot *t*, $dis_{losses}(t)$ represents the battery discharging losses

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(kW) at each time slot *t*, and $B_{losses}(t)$ refers to the overall battery losses (kW) at each time slot *t*. Furthermore, ESSs have certain constraints to avoid deep charging and discharging of the battery and some limits for charging/discharging at each time slot *t*. For this purpose, the constraints in [Eq.6.6–6.8] were set.

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad \text{[Eq.6.6]}$$

$$0 \leq P_B^{ch}(t) * \Delta t \leq CH_{rate} \quad \text{[Eq.6.7]}$$

$$0 \leq P_B^{dis}(t) * \Delta t \leq Dis_{rate} \quad \text{[Eq.6.8]}$$

Where SOC represents the ratio of total energy storage to the total energy capacity of the battery (%) at each time slot *t*, CH_{rate} is the maximum charge rate of the battery (kWh) during the time slot *t*, and Dis_{rate} is the maximum discharge rate of the battery (kWh) during the time slot *t*, which is determined by the battery's characteristics.

6.3.1.3. Energy demand model

In this work, the household appliances are classified into two categories: fixed and controllable appliances. The set of fixed appliances are presented as X = (b_1,b_2,b_3, …,bm) over a scheduling duration of t = (1,2,3,…,1440). [Eq.6.9] is used to calculate the total energy consumption of the fixed appliances, and [Eq.6.10] expresses the operating status of the fixed appliances.

$$E_{fixed}(t) = \sum_{X=1}^{m} P_X * OP\big(b_X(t)\big) * \Delta t \quad \text{[Eq.6.9]}$$

$$OP(b_X(t)) = \begin{pmatrix} 1, if\ the\ fixed\ appliance\ is\ on \\ 0, if\ the\ fixed\ appliance\ is\ off \end{pmatrix} \quad \text{[Eq.6.10]}$$

Where $E_{fixed}(t)$ represents the total energy consumption of the fixed appliances (kWh) at each time slot *t*. P_X is the rated power of the

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fixed appliances (kW), and $OP\left(b_X(t)\right)$ is a variable that indicates the status of the fixed appliance if it is operating or not at each time slot *t*.

Controllable appliances are those whose usage can be shifted to off-peak hours. The set of controllable appliances are presented as Y = (c_1,c_2,c_3, …,c_n) over a scheduling duration of t = (1,2,3,…,1440). [Eq.6.11] is used to calculate the total energy consumption of the controllable appliances; [Eq.6.12] expresses the operating status of the controllable appliances.

$$E_{controllable}(t) = \sum_{y=1}^{n} P_Y * OP\left(C_y(t)\right) * \Delta t \qquad \text{[Eq.6.11]}$$

$$OP(c_y(t)) = \begin{pmatrix} 1, if\ the\ controllable\ appliance\ is\ on \\ 0, if\ the\ controllable\ appliance\ is\ off \end{pmatrix} \qquad \text{[Eq.6.12]}$$

Where $E_{controllable}(t)$ is the total energy consumption of the controllable appliances (kWh) at each time slot *t*. P_Y is the rated power of the controllable appliances (kW), and $OP(C_y(t))$ is a variable that indicates whether the controllable appliances are operating or not at each time slot *t*.

The total energy demand $E_{home}^{hourly}(t)$ (kWh) at each time step *t* is calculated using [Eq.6.13], whereas [Eq.6.14] is used to calculate the total daily demand E_{home}^{total} (kWh).

$$E_{home}^{hourly}(t) = E_{fixed}(t) + E_{controllable}(t) \qquad \text{[Eq.6.13]}$$

$$E_{home}^{total} = \sum_{t=1}^{1440} E_{fixed}(t) + \sum_{t=1}^{1440} E_{controllable}(t) \qquad \text{[Eq.6.14]}$$

6.3.2. Energy usage pricing model

6.3.2.1. Battery energy usage price

Batteries play a key role in power systems' stability, balancing supply and demand, and reducing electricity bills. However, batteries have an installation cost. Thus, the battery energy-usage price is modeled and

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introduced into the optimization problem to use the battery efficiently and enhance its lifespan.

LCOS expresses the cost of storing energy in the battery throughout its lifespan. To calculate LCOS, the investment cost of the battery C_B (EUR), the number of cycles N_{cycle}, the battery's DOD (%), and nominal energy of the battery system E_{batt} (kWh) were considered. LCOS is calculated using [Eq.6.15], where the unit of B_{LCOS} is EUR /kWh.

$$B_{LCOS} = \frac{C_B}{E_{batt} * N_{cycle} * DOD} \quad \text{[Eq.6.15]}$$

The battery energy-usage price is determined based on the LCOS, and the amount of energy purchased from PV/grid and stored in it. The cost of purchased energy from the PV /grid and stored it in the battery are calculated using [Eq.16] and [Eq.6.17], respectively. The total price of purchased and stored energy in the battery Ch_{price} (EUR/kWh) in each time slot *t* is calculated using [Eq.6.18].

$$Pch_{pv}(t) = \left(P_{pvtb}(t) * \left(LCOE_{pv} + B_{LCOS}\right)\right) * \Delta t \quad \text{[Eq.6.16]}$$

$$Pch_{grid}(t) = \left(P_{gtb}(t) * \left(Grid^{buy}_{price}(t) + B_{LCOS}\right)\right) * \Delta t \quad \text{[Eq.6.17]}$$

$$Ch_{price}(t) = \frac{PCh_{pv}(t) + PCh_{grid}(t)}{P_{pvtb(t)} + P_{pgtb(t)}} * \Delta t \quad \text{[Eq.6.18]}$$

Where $Pch_{pv}(t)$ is the cost of the energy purchased from PV and stored in the battery (EUR) at each time slot *t*. $LCOE_{pv}$ denotes the PV energy usage price (EUR/kWh). $Pch_{grid}(t)$ is the cost of energy purchased from the grid and stored in the battery (EUR) at each time slot *t*. $P_{pvtb}(t)$, $P_{gtb}(t)$ are the amount of PV and grid-stored power in the battery (kW) at each time slot *t*, respectively. $Grid^{buy}_{price}(t)$ is the grid price (EUR/kWh) at each time slot *t*.

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The battery energy usage price varies during the day. The overall price of the battery energy usage is calculated using [Eq.6.19], which is based on the previous price of the battery, the previous amount of energy in the battery, in addition to the new price of purchased energy, and the new amount of purchased energy. [Eq.6.20] expresses the cost of battery energy usage in the home $C_{batt}(t)$ (EUR) at each time slot *t*. Where the battery energy losses cost $B_{LC}(t)$ due to the energy losses (EUR) during the process of charging the battery from the grid/PV, and discharging the battery to the home/grid, taking into account the energy prices and amount of charged/discharged energy at each time slot *t* is calculated using [Eq.6.21].

$$B_{price}(t+1) = \frac{(B_{price}(t) * P_b(t)) + (Ch_{price}(t) * (P_{pvtb}(t) + P_{gtb}(t)))}{P_b(t) + P_{pvtb}(t) + P_{gtb}(t)} \quad \text{[Eq.6.19]}$$

$$C_{batt}(t) = B_{price}(t) * P_{bth}(t) * \Delta t \quad \text{[Eq.6.20]}$$

$$B_{LC}(t) = \left\{ \begin{array}{l} \left[P_{gtb}(t) * \frac{1-\eta}{\eta} * Grid^{buy}_{price}(t)\right] + \left[P_{pvtb}(t) * \frac{1-\eta}{\eta} * LCOE_{pv}\right] \\ + \left[P_{bth}(t) * (1-\eta) * B_{price}(t)\right] + \left[P_{btg}(t) * (1-\eta) * B_{price}(t)\right] \end{array} \right\} * \Delta t \quad \text{[Eq.6.21]}$$

Where $B_{price}(t+1)$ expresses the price of battery energy usage (EUR/kWh) for the next time slot (*t*+1) after adding the newly charged energy price $Ch_{price}(t)$, where $B_{price}(t)$ is the price of the battery energy usage (EUR /kWh) in the time slot *t*, and $P_b(t)$ express the battery net power at the time slot *t* (kW). $P_{bth}(t)$, $P_{btg}(t)$ express the amount of power sent from the battery to the home and grid (kW) at each time slot *t*, respectively.

6.3.2.2. PV energy usage price

PV supplies energy to the load and battery and sells to the grid. To ensure that PV is used efficiently throughout its life cycle, the LCOE of PV is expressed as the price of PV energy usage price; this price takes

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the installation cost and overall Operation and Maintenance (O&M) expenses into account. The cost of PV energy consumed in the home $C_{PV}(t)$ (EUR) at each time slot *t* is calculated using [Eq.6.22], where $P_{Pvth}(t)$ is the amount of PV power usage in the home (kW) at each time slot *t*.

$$C_{PV}(t) = LCOE_{pv} * P_{Pvth}(t) * \Delta t \quad \text{[Eq.6.22]}$$

6.3.2.3. Selling energy to the grid

In the process of selling energy to the grid, the profit is expressed based on the PV, battery, and grid energy usage prices to obtain efficient energy management that considers the installation cost and lifespan of systems. [Eq.6.23] calculates the profit of selling energy from PV to the grid, taking into account the grid prices at each time slot *t* and LCOE. The higher the grid-selling price compared to the LCOE, the greater the profit. The same applies to selling energy from the battery to the grid; [Eq.6.24] calculated the profit. The higher the grid-selling price compared to the battery price, the greater the profit. These equations express the real profit of selling energy; thus, they are introduced into the optimization problem. The overall profit of selling energy to the grid $Profit_{sell}(t)$ (EUR) at each time slot *t* is calculated using [Eq.6.25].

$$Profit_{pvtg}(t) = ((P_{pvtg}(t) * (Grid_{sell}(t) - LCOE_{pv})) * \Delta t \quad \text{[Eq.6.23]}$$

$$Profit_{btg}(t) = \left(P_{btg}(t) * \left(Grid_{sell}(t) - (B_{price}(t)\right)\right) * \Delta t \quad \text{[Eq.6.24]}$$

$$Profit_{sell}(t) = Profit_{pvtg}(t) + Profit_{btg}(t) \quad \text{[Eq.6.25]}$$

Where $Profit_{pvtg}(t), Profit_{btg}(t)$ represents the economic benefit of selling energy from PV and battery to the grid (EUR) at each time slot *t*, respectively. P_{pvtg} represents the amount of PV power sent to the grid (kW) at each time slot *t*, and $Grid_{sell}$ is the energy selling price to the grid (EUR /kWh) at each time slot *t*.

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6.3.3. Energy flow management algorithm development

Figure 6.2 illustrates the Proposed Energy Flow Management Algorithm (PEFMA). It considers the life cycle of the battery and PV by using them efficiently. At first, PV provides power to the appliances. During the periods of excess PV generation, PEFMA compares the economic benefit of storing the excess energy in the battery to use it during the grid high price periods (grid high price - (LCOS + LCOE)) versus selling the excess energy to the grid (LCOE - grid selling price). If the economic benefit of storing the excess energy in the battery is higher than selling it to the grid, PEFMA will store the excess energy in the battery. Otherwise, PEFMA will sell the excess energy to the grid.

In the event that the PV generation is insufficient to meet the load, PEFMA compares the battery energy usage price against the grid price to determine the best alternative. If the battery price is lower than the grid price, PEFMA will give priority to the battery to cover the load, then to the grid. Otherwise, PEFMA will cover the load from the grid only.

Battery charging/discharging from/to the grid takes into account the battery life cycle as well as the economic gain. For each possible period of charging the battery from the grid, PEFMA checks if the cost of storing energy (LCOS+ grid price) is lower than the grid high price; if it is, PEFMA will charge the battery from the grid. Otherwise, the battery will not be charged because it will not be beneficial for future use. For each possible period of discharging the battery to the grid, PEFMA checks if the economic benefit of selling battery energy to the grid (grid selling price–battery price) is higher than discharging it to cover the load in the grid high price period (grid high price–battery price); if it is, PEFMA will sell the battery energy to the grid. Otherwise, the battery will not be discharged.

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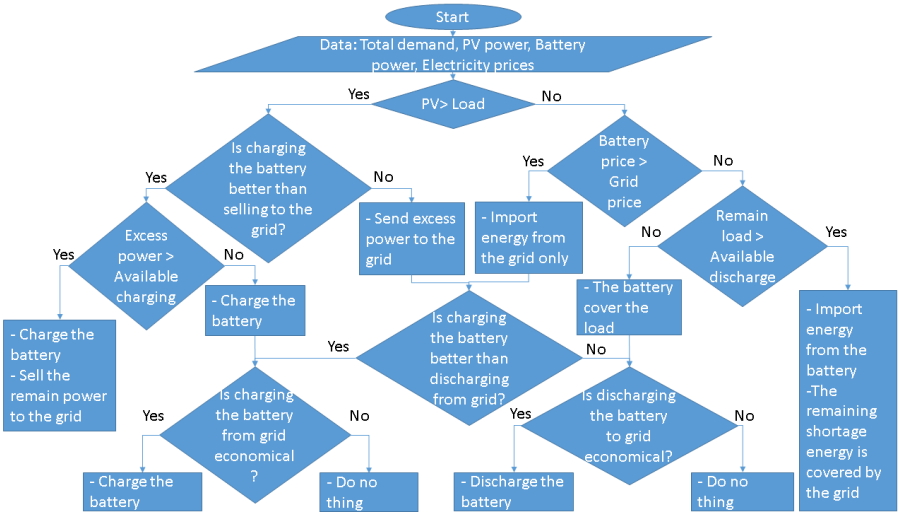

Figure 6.2: The proposed energy flow management algorithm

6.3.4. Objective function

The main aim of this work is to schedule the home appliances and manage the energy flow considering the installation cost and life cycle of PV and battery. The energy usage cost of using PV and battery is modeled and considered in the objective function. Moreover, the profit from selling energy to the grid is considered in the objective function. [Eq.6.26] represents the objective function of the optimization strategy; it aims to minimize the real energy cost by scheduling the home appliances and using the battery, PV energy, and grid utilization optimally. $C_{Grid}(t)$ expresses the cost of power imported from the grid to home (EUR) at each time slot *t*.

$$Minimize\ (Real\ Cost) = Min \sum_{1}^{1440} C_{Grid}(t) + C_{PV}(t) + C_{batt}(t) - Profit_{sell}(t) \quad \text{[Eq.6.26]}$$

The objective function is subjected to the constraints of user preferences based on the minimum/maximum starting time of each controllable appliance, as shown in Table 6.1. The usual operation time

of each appliance, the Starting Time (ST) and Ending Time (ET), is described in Table 6.1.

Table 6.1: Home electrical appliances description

Appliance	Rated Power (kW)	Category	Priority	ST	ET	Min. Start time	Max. Start time
Xbox	0.072	controllable	Low	22	00	19	23
TV (Living room)	0.069	controllable	Low	14	18	15	18:00
Electric fryer	2.2	controllable	High	14&15	14:15&15:15	11:30&14:30	14&16
Oven	2.5	controllable	High	12&17	12:30&17:30	10:30&16:00	12&18
Dishwasher	0.9	controllable	Low	18	20	18	22
Washing Machine	0.579	controllable	Low	09	11	08	22
Iron	2.6	controllable	Low	19	19:30	08	22
Vacuum cleaner	0.8	controllable	Low	13	13:30	08	22
Ceramic cooktop	5.7	controllable	High	13	13:25	-	-
TV (Bedroom)	0.12	Fixed	-	20	22	-	-
TV (Kitchen)	0.12	Fixed	-	12	14	-	-
Coffee machine	1.25	Fixed	-	08&19	8:15&19:15	-	-
Microwave	1	Fixed	-	08&20	8:15&20:15	-	-
Fridge	0.1	Fixed	-	00	23	-	-
Laptop Lenovo	0.035	Fixed	-	14	18	-	-
Laptop HP	0.045	Fixed	-	00	00	-	-
Mobile chargers	0.054	Fixed	-	01&15	03&17	-	-
Light bulbs	0.124	Fixed	-	00&08	01&00	-	-

The priority of each controllable appliance to be shifted is classified into low and high. The low-priority appliances have the possibility to schedule the starting operation time within a period that is longer than the high-priority appliances' period. The user sets the controllable appliances, their minimum/maximum starting time, and the priority of each appliance.

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6.3.5. Case study

The load data of a home in Vigo (Spain) are used as a case study, where the user determined the category and operating time constraints of the home appliances as shown in Table 6.1. The PV system of 1.035 kWp size is used, where the solar radiation data was collected from the PVGIS 5.2 database of Vigo [European Commission, 2022e]. Figure 6.3 shows the power demand, PV power generation throughout the day, and the grid prices [REDE, 2022a; REDE, 2022c]. The average data for two months in the summer (June and July) of solar radiation and grid prices are taken.

The battery system with a capacity of 2.4 kWh is employed, starting with a 0% initial state of charge. The LCOS is calculated using Equation (11), where the battery cycles are 6000 with 80% DOD [Wccsolar, 2022]. It is found that LCOS is equal to 0.072 EUR/kWh. According to the IREA, the LCOE of PV is 0.092 EUR/kWh for the Spanish residential sector in 2020 [IRENA, 2021].

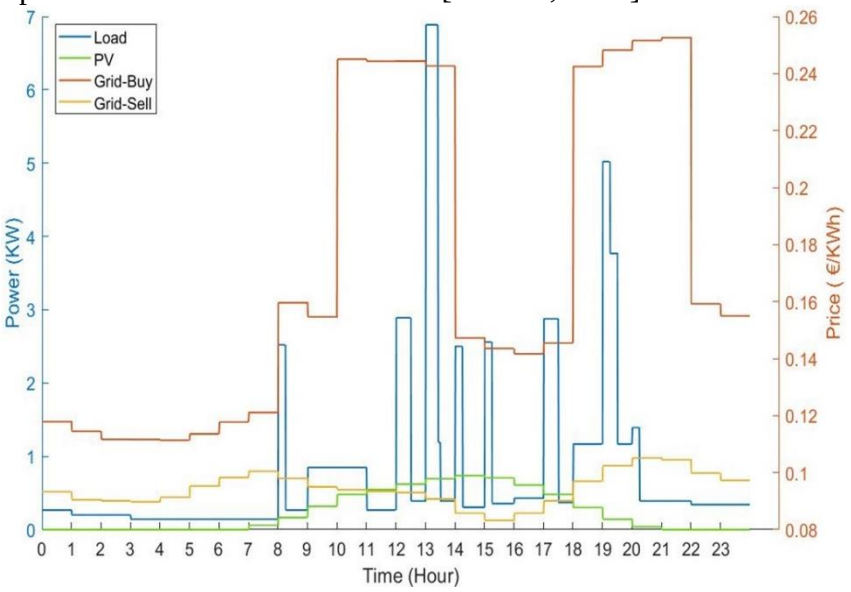

Figure 6.3: Case study data

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6.3.6. Optimization algorithms

6.3.6.1. Augmented gray wolf optimization algorithm

The Grey Wolf Optimizer (GWO) is a meta-heuristic algorithm inspired by the pack of wolf's community, which is based on hunting behavior and their social leadership [Mirjalili et al., 2014]. There are four-level of wolf packs, and the leader of the whole pack alpha wolf (α) supervises several tasks such as hunting, searching for a sleeping place, and determining the time to wake. The second level is beta wolves (β), which possess the traits of a leader in the case of the alpha wolf becoming old or passing away, as well as acting as an advisor to the alpha and giving commands to the lower levels of the wolves' pack. The third level is delta wolves (δ) which ensures the safety and well-being of the pack, supervised by alpha wolves and beta wolves, and participating in hunting and decision-making tasks. Finally, the lowest level of the grey wolf pack is omega wolves (ω), which act as scapegoats, i.e., all the other wolves in the pack rule them. However, the GWO was developed into an AGWO [Qais et al., 2018]. Unlike GWO exploration and exploitation α based, where this parameter changes linearly from 0-2, AGWO α based changes nonlinearly and randomly within the range 1-2. Furthermore, in AGWO, hunting and decision-making are solely based on the updating of α and β, unlike GWO, which is dependent on α β, and δ. These improvements give to AGWO possess greater exploration capabilities in comparison with GWO.

6.3.6.2. Particle swarm optimization algorithm

PSO is a metaheuristic optimization algorithm inspired by the social behavior of bird flocking or fish schooling developed in 1995 by Eberhart and Kennedy [Kennedy et al., 1995]. PSO involves a population of particles moving through a search space to find the optimal solution to an optimization problem. Each particle represents a potential solution and adjusts its position and velocity based on its own experience and the collective knowledge of the swarm. By continuously updating their positions and velocities, particles explore and exploit the search space, converging towards the global optimum. Its effectiveness lies in the cooperation and information sharing among particles,

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allowing them to collectively search the solution space and converge towards the global optimum. Besides, PSO is known for its simplicity and effectiveness in solving various optimization problems.

6.3.7. Analysis of sustainability factors

6.3.7.1. Battery lifespan

One of the aims of this study is to sustain the battery's lifespan, which is influenced by a number of charge-discharge cycles [Tankari et al., 2012]. Each battery has a number of cycles throughout its lifespan, a single cycle means that the battery is being charged to full capacity and then drained to empty either in a single sitting or at irregular intervals. Therefore, the number of charging/discharging cycles throughout the day $B_{daycycles}$ is calculated using [Eq.6.27], and the expected lifespan of the battery B_{life} (in years) which is based on the number of battery cycles specified by the manufacturer over its lifespan N_{cycle}, calculated using [Eq.6.28] where d_y represents the number of days in one year.

$$B_{daycycles} = \frac{\sum_1^{1440} P_B^{ch}(t) * \Delta t + \sum_1^{1440} P_B^{dis}(t) * \Delta t}{E_{batt}} \quad \text{[Eq.6.27]}$$

$$B_{life} = \frac{N_{cycle}}{B_{daycycles} * d_y} \quad \text{[Eq.6.28]}$$

6.3.7.2. Carbon emission intensity

The fossil fuel power plants have negative environmental and human health effects, the residential sector can help with reducing CO_2 emissions by adopting local RESs and scheduling home energy consumption. The amount of CO_2 emissions is calculated using [Eq.6.29]. $P_{gth}(t)$ is the amount of grid power sent to the home at each time step *t* (kW), I_{CO_2} express the carbon emission intensity of electricity generation. In the case of Spain, I_{CO_2} is equal to 0.177 (kgCO_2/kWh) in 2020 [EEA, 2023a].

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$$CO_2 = I_{CO_2} * \sum_{t=1}^{1440} (P_{gth}(t) + P_{gtb}(t) \quad \text{[Eq.6.29]}$$

6.3.7.3. Breakeven point of the integrated system

The breakeven point of the PV battery system refers to the point at which the installation cost equals the financial benefits it gained over its lifetime. In other words, it is the point at which the savings from electricity generation offset the system's initial investment and ongoing expenses. The following model calculates the expected breakeven point of the proposed system. [Eq.6.30] shows the daily saved cost d_{saving} calculation during the battery lifespan and after the battery lifespan that only PV supports the load. Where [Eq.6.31] is used to calculate the overall saved cost PVB_{saving} during the battery lifespan integrating with PV (EUR). The PV daily cost saving PV_{saving} after the battery stops working (EUR/day) is calculated using [Eq.6.32]. [Eq.6.33] is used to calculate the expected breakeven point of the PV battery system Y_{BP} (in years).

$$d_{saving} = \begin{pmatrix} PVB_{saving}, & during\ the\ battery\ lifespan \\ PV_{saving}, & after\ the\ battery\ stops\ working \end{pmatrix} \quad \text{[Eq.6.30]}$$

$$PVB_{saving} = \sum_{1}^{B_{life}} (B_{cost} - Sch_{cost}) \quad \text{[Eq.6.31]}$$

$$PV_{saving} = \sum_{t=1}^{1440} \left(P_{pvth}(t) * G_{Buy_{price}}(t)\right) + \left(P_{pvtg}(t) * Grid_{sell}(t)\right) * \Delta t \quad \text{[Eq.6.32]}$$

$$Y_{BP} = \left(B_{life} + \frac{Inv_{sys} - PVB_{saving}}{PV_{saving}}\right)/365 \quad \text{[Eq.6.32]}$$

Where B_{cost} denotes the electricity cost without using the PV battery system, Sch_{cost} express the scheduling strategy electricity cost

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(EUR). Inv_{sys} express the investment cost of the installed PV battery system (EUR), and B_{life} unit is days.

6.4. RESULTS

AGWO and PSO algorithms are used for solving the optimization problem with 100 populations, and 200 iterations. For simulations, we used MATLAB installed on Intel(R) Core(TM) i7-3520M CPU @ 2.90GHz and 8 GB RAM with Windows 10 Pro. Each simulation run needed seven hours to finish the 200 iterations and obtain the best solutions. Four scenarios were simulated to evaluate the effectiveness of the proposed optimization strategy and the PEFMA.

6.4.1. The base scenario (the first scenario)

In this scenario, the home energy demand is covered by the main grid. The total daily demand is 18.464 kWh, with 3.268 $kgCO_2$, and the total daily electricity cost is EUR 3.7584. The results of the base scenario are used to compare them to the proposed system and other scenarios.

6.4.2. The proposed energy flow management algorithm (the second scenario)

The PEFMA manages the distribution of energy in an effective manner taking into account the grid prices, LCOE, and LCOS. As shown in Figure 6.4, during the periods 08:01-10:00 and 17:01-17:30, importing energy from the grid is preferable to importing energy from the battery. However, during the periods 10:01-11:00 and 18:01-19:00, using battery energy is preferable to importing energy from the grid.

Figure 6.5 shows the energy balance of the system: the battery sold no energy to the grid, where the cost of the battery's energy usage is higher than the grid-selling price. The same behavior is observed for PV owing to the low selling price, often less than LCOE: it is preferable to supply the PV power to the home or store it in a battery rather than sell it to the grid. The results show that the real cost is EUR 3.163. The total charged and discharged battery energy is 9.047 kWh, the battery losses amount to 0.46771 kWh, and the battery losses cost is EUR 0.071, where the estimated battery lifespan is 4.36 years. The amount of CO_2 emissions is 2.79 $kgCO_2$.

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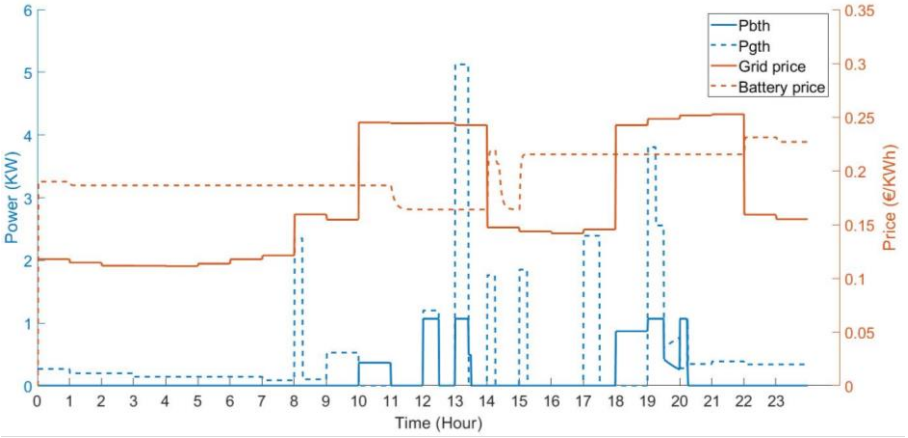

Figure 6.4: Grid and battery energy flow

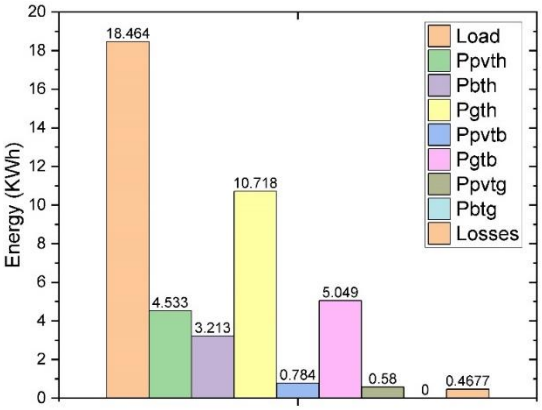

Figure 6.5: The energy balance

6.4.3. The proposed optimization strategy (the third scenario)

In this scenario, the objective function includes the cost of battery energy usage, the cost/profit of imported/sold energy from/to the grid, and the PV energy usage cost.

The simulation results of AGWO show that the real cost is EUR 2.786. The total charged and discharged battery energy is 8.447 kWh, the battery losses amount to 0.436 kWh, and the battery losses cost is

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EUR 0.06424, where the estimated battery lifespan is 4.67 years. In addition, the amount of CO_2 emissions is 2.773 $kgCO_2$.

In the case of PSO, the real cost is EUR 2.782. The total charged and discharged battery energy is 7.6687 kWh, the battery losses amount to 0.397 kWh, and the battery losses cost is EUR 0.059, where the estimated battery lifespan is 5.14 years. In addition, the amount of CO_2 emissions is 2.755 $kgCO_2$. Figures 6.6 and 6.7 show the convergence of the AGWO and PSO algorithms. Figures 6.8 and 6.9 show the energy balance of the system.

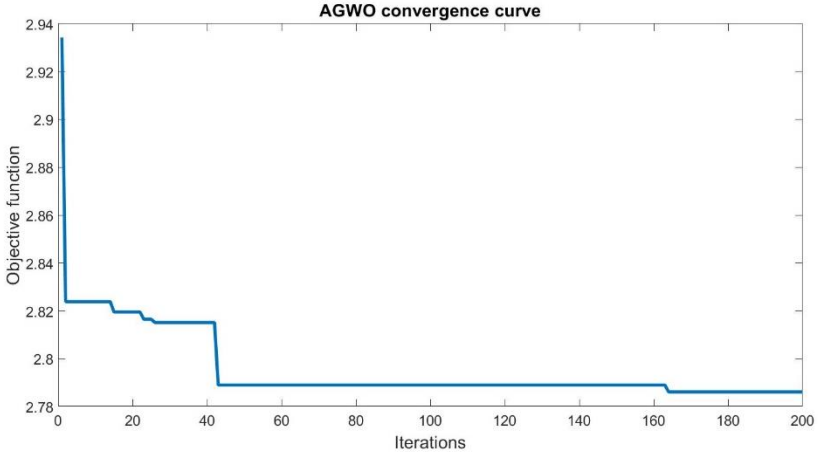

Figure 6.6: The convergence of the AGWO

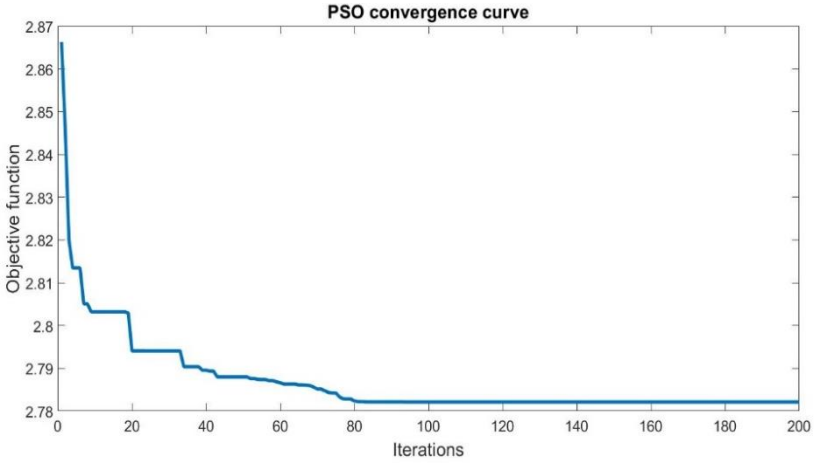

Figure 6.7: The convergence of the PSO

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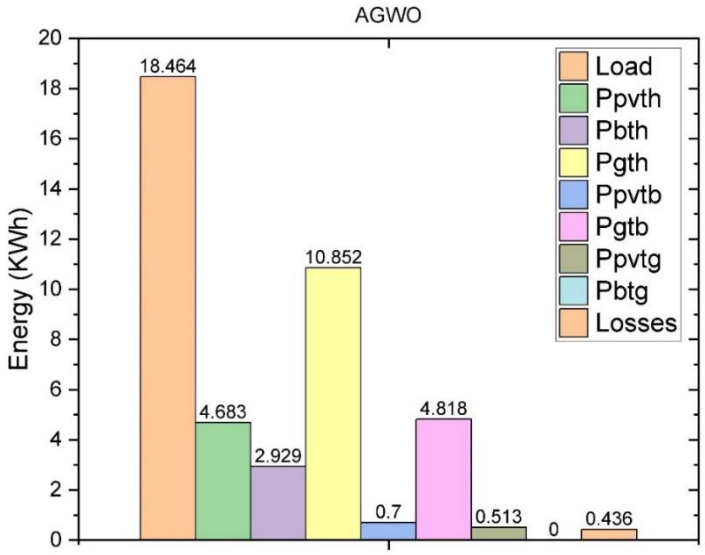

Figure 6.8: The energy balance of the AGWO algorithm for the third scenario

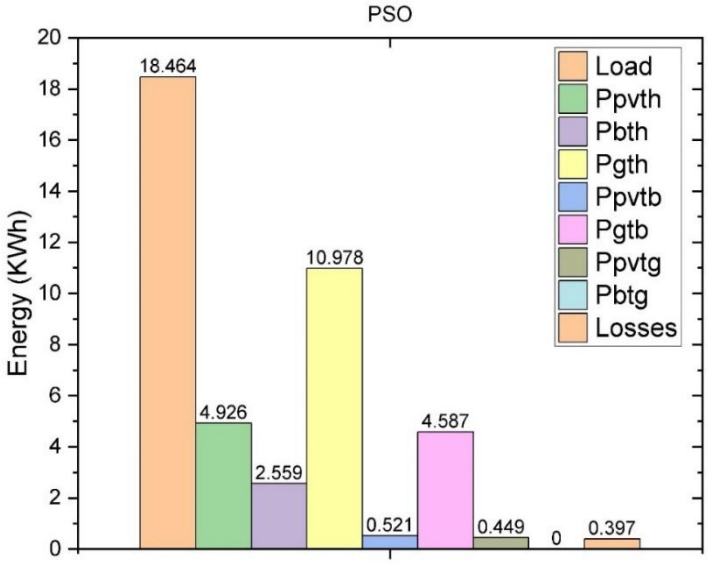

Figure 6.9: The energy balance of the PSO algorithm for the third scenario

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6.4.4. A previous study scheduling strategy (the fourth scenario)

To evaluate the proposed system, a previous study on appliance scheduling strategy is modeled and compared to it. Bouakkaz et al. (2021) modeled a battery energy usage price based on the SOC of the battery and included it in the optimization problem for scheduling the household appliances, where the battery energy price increases when the SOC is low and decreases when the SOC is high [Bouakkaz et al., 2021]. They attempted to use the battery more efficiently with fewer energy losses. We applied Bouakkaz et al. (2021) scheduling strategy to the same data in this scenario, using the same objective function based on their energy usage-pricing model [Bouakkaz et al., 2021].

After getting the optimal appliances' operation time, we calculated the real electricity cost. The results of AGWO show that the real cost is EUR 3.029. The total charged and discharged battery energy is 14.2159 kWh, the battery losses amount to 0.7319 kWh, and the battery losses cost is EUR 0.092, with an estimated battery lifespan of 2.775 years. In addition, the CO_2 emissions are 2.553 kgCO_2. In the case of PSO, the real cost is EUR 3.025, the total charged and discharged battery energy is 14.165 kWh, the battery losses amount to 0.729 kWh, and the battery losses cost is EUR 0.0945, with an estimated battery lifespan of 2.785 years. In addition, the CO_2 emissions are 2.576 kgCO_2. Figures 6.10 and 6.11 show the convergence of the AGWO and PSO algorithms. It is observed that the minimum electricity cost is lower than the real electricity cost; this is because the Bouakkaz et al. (2021) model did not consider the battery's LCOS and PV's LCOE. This led to inefficient utilization of energy. Figures 6.12 and 6.13 show the energy balance of the system.

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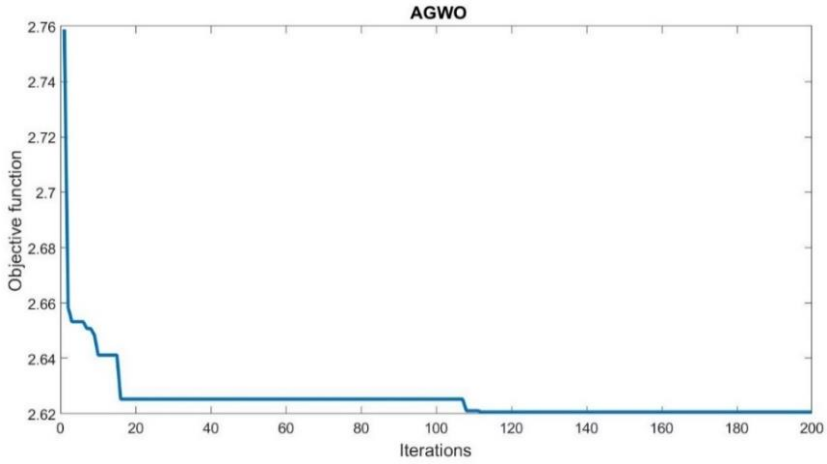

Figure 6.10: The convergence of the AGWO

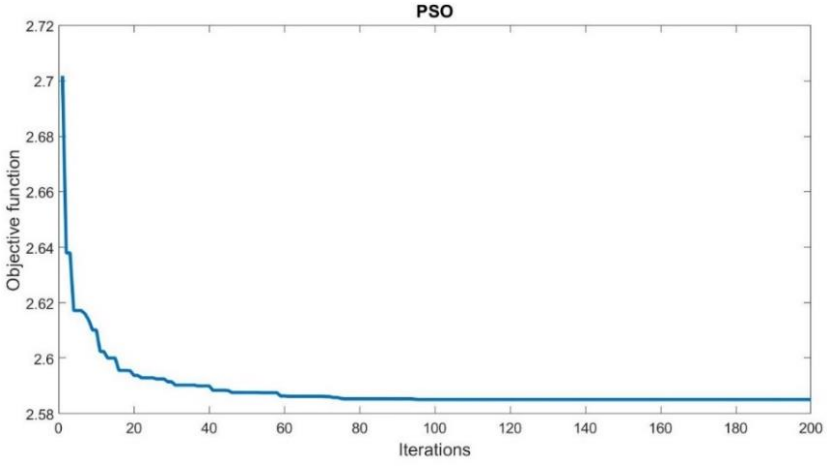

Figure 6.11: The convergence of the PSO

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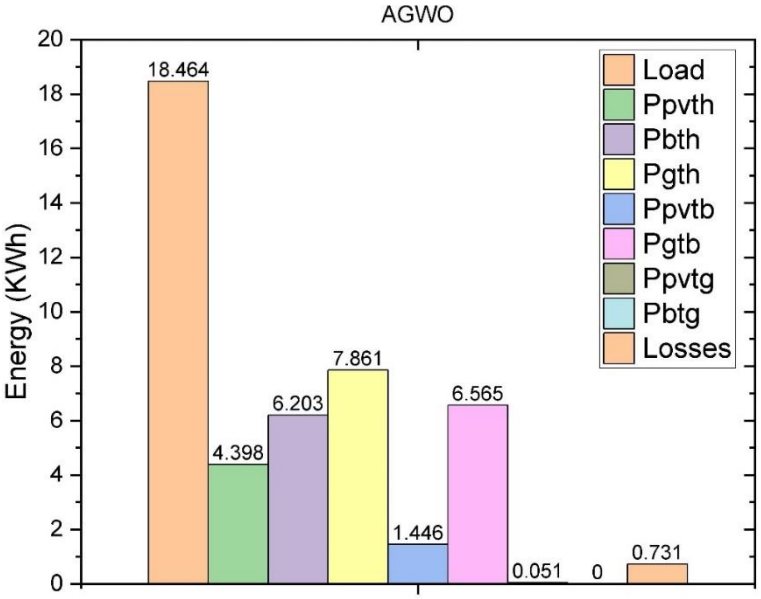

Figure 6.12: The energy balance of the AGWO algorithm of the fourth scenario

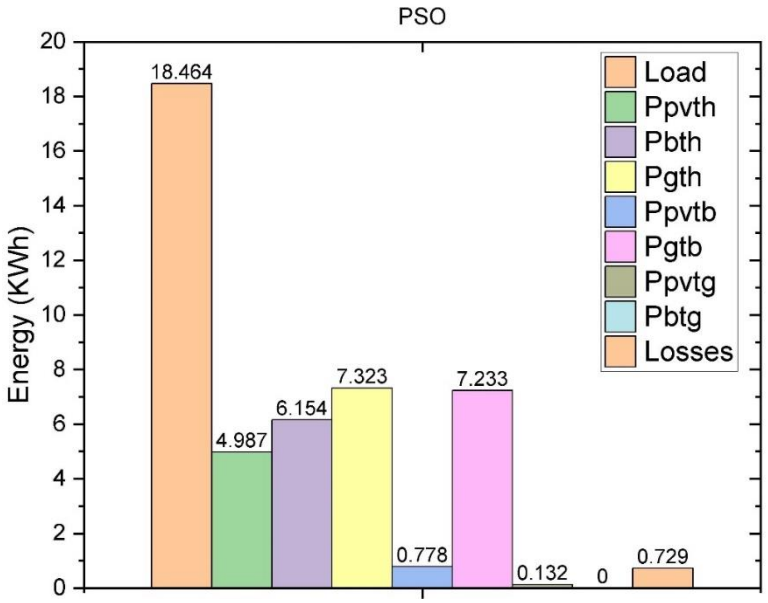

Figure 6.13: The energy balance of the PSO algorithm of the fourth scenario

6.5. DISCUSSION

Four scenarios were done to show the effectiveness of the proposed system in reducing cost by scheduling the appliances with efficient usage of the battery and PV, maintaining the system's lifespan. This section discusses the obtained behavior in terms of the real electricity cost, battery lifespan, energy losses, energy usage cost pricing, and breakeven point. In addition, we compared our proposed system to a previous work on energy usage cost using AGWO and PSO.

6.5.1. Cost

Figures 6.14 and 6.15 describe the comparison simulation results of the real electricity cost and cost reduction compared to the base scenario using AGWO and PSO. In both cases of AGWO and PSO, the proposed system (third scenario) has achieved the best cost reduction, being 28.87% using AGWO and 25.98% for PSO. The fourth scenario reduces the cost by 19.4% for AGWO and 19.51% for PSO.

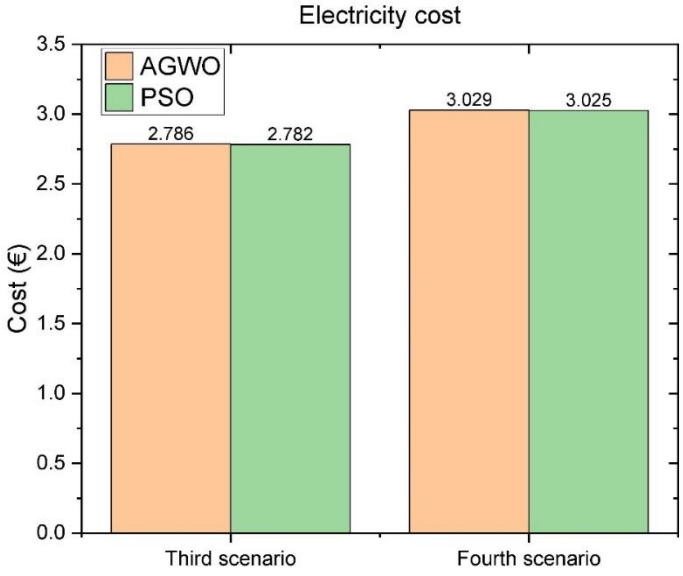

Figure 6.14: Electricity cost simulation results

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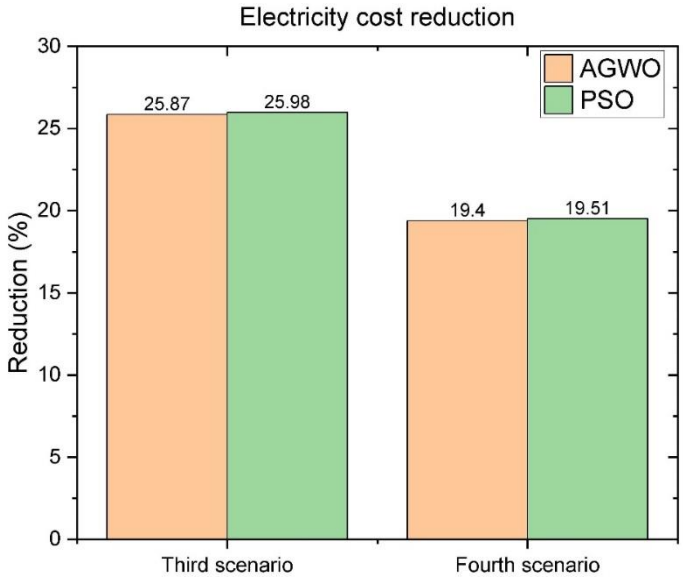

Figure 6.15: Electricity cost reduction simulation results

6.5.2. Battery lifespan and energy losses

Figures 6.16 and 6.17 illustrate the comparison of battery lifespan and energy loss results of the third and fourth scenarios using AGWO and PSO. The results show that the proposed system accomplished the most extended battery lifespan of 4.67 years and 5.14 years using the AGWO, and PSO, respectively. While the AGWO and PSO results of the fourth scenario show that, the battery lifespan is 2.775 years, 2.785 years, respectively. Compared to Bouakkaz et al. (2021) strategy in the fourth scenario [Bouakkaz et al., 2021], the proposed system extends the battery lifespan by 68.282 % and 84.56% in the case of AGWO and PSO, respectively. Moreover, the proposed system achieves the fewest energy losses compared to the fourth scenario. In the case of AGWO, the energy losses of the third and fourth scenarios are 0.436 kWh and 0.7319 kWh, respectively. The proposed system reduces energy losses by 40.429%. Similarly, the energy losses using PSO in the third and fourth scenarios are 0.397 kWh and 0.729 kWh, respectively. The PSO reduces energy losses by 45.540%. This indicates the effectiveness of our proposed system in saving energy and maintaining the battery lifespan.

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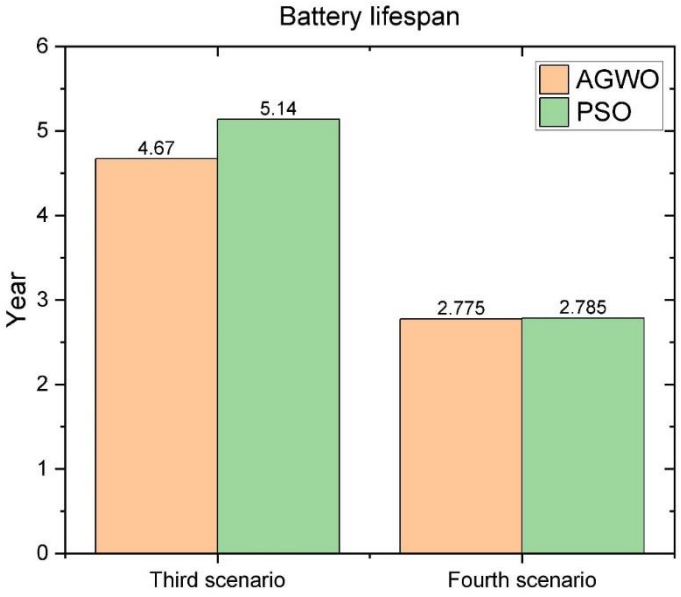

Figure 6.16: Battery lifespan simulation results

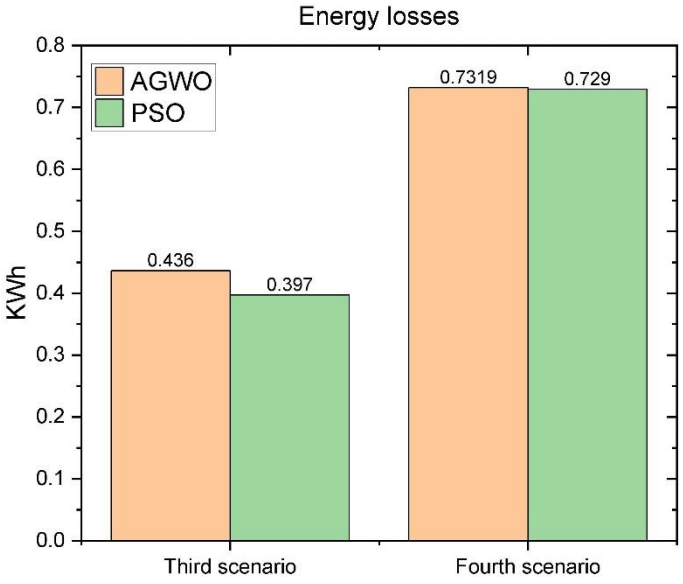

Figure 6.17: Energy loss simulation results

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6.5.3. Energy usage prices

Figure 6.18 shows the energy usage price of the third and fourth scenarios. The battery energy price of Bouakkaz et al. (2021) in the fourth scenario is far from the real price [Bouakkaz et al., 2021]. Several times, the battery price is lower than the grid price, which leads to using the battery energy longer and scheduling the appliances more in the battery's low-price periods. In the case of the battery's high-price periods with a low amount of energy, the battery does not contribute to covering the load demand even if the grid price is high in reality.

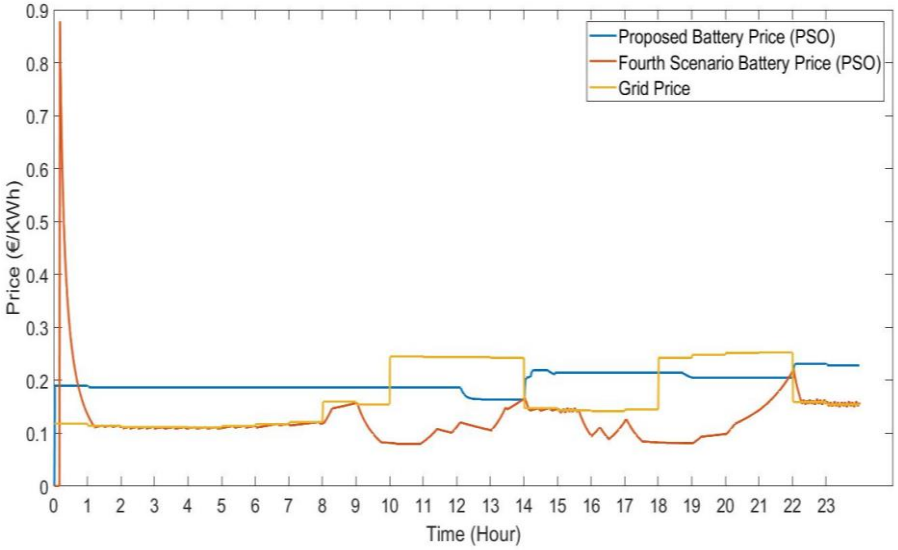

Figure 6.18: Energy usage price

For example, at 8 a.m. the grid price is 0.121 EUR/kWh, and the proposed battery energy price is 0.192 EUR/kWh, whereas the battery energy price of the fourth scenario is 0.118 EUR/kWh at SOC 60.8%. This leads to inefficient use of the battery, where the actual price of the battery is based on LCOS and the cost of the energy stored in it, which is equal to 0.192 EUR/kWh. In addition, the grid energy price is actually lower than the real battery price. Thus, the proposed system operates the battery in an efficient manner in terms of the battery energy losses and maintaining its lifespan and cost reduction compared to the fourth scenario. The findings demonstrate that the proposed system successfully addresses these issues and presents an optimization

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strategy that yields superior results, as detailed in the results and discussion sections.

6.5.4. Breakeven point

The cost of installing a PV battery system depends on the system size and component type of the system. In this study, the investment cost of the PV battery system is assumed to be EUR 2000 according to the market prices [Autosolar, 2023]. Using the mathematical model in section 6.3.7.3, we calculated the expected breakeven point of the PV battery system. As shown in Figure 6.19, the results demonstrate that the proposed system reached the breakeven point in a shorter time compared to the fourth scenario. In the case of AGWO, the breakeven point of the proposed system and fourth scenario are 4.26 years and 4.32 years, respectively. Similarly, the results of PSO illustrated that the proposed system reached the breakeven point in 4.09 years, while the fourth scenario needs 4.25 years.

The results of the AGWO and PSO show that the proposed system reached the breakeven point in a short time compared to the fourth scenario. Moreover, the results show that the proposed system reached the breakeven point before the battery stopped working; the AGWO extended the battery lifespan of 4.67 years with a 4.26 years breakeven point, and the PSO extended the battery lifespan of 5.14 years with a 4.09 years break-even point. This indicates that the proposed system is economical and sustains the battery lifespan, where the battery remains functional even after the system reaches the breakeven point, in contrast to the fourth scenario, where the battery ceases to operate before the breakeven point is reached around 1.5 years.

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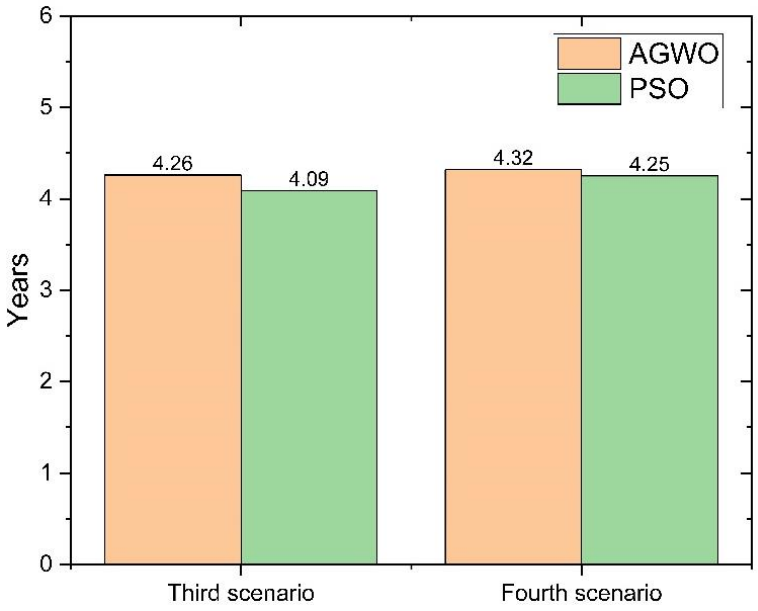

Figure 6.19: The breakeven point of the system

6.6. CONCLUSIONS AND FUTURE WORK

This paper proposes an efficient optimization method of scheduling appliances in conjunction with an efficient energy flow management system that considers PV and battery life cycles, as well as installation costs. Battery and PV energy usage pricing models are proposed and considered in the optimization strategy and energy flow management system. For optimization, we used AGWO and PSO algorithms in MATLAB. Real data was used for a house in Vigo, Spain in order to provide realistic results that encourage Spanish customers to manage their energy consumption after the new electricity tariff in Spain. To show the effectiveness of the proposed system, a comparison is applied with a previous model of pricing energy usage. The proposed system accomplishes a better reduction in cost and energy losses, a longer extension to the lifespan of the battery, and reaches the breakeven point in a short time. In addition, it encourages energy consumers to contribute to grid stability and energy security by highlighting the economic and environmental benefits of scheduling appliances in

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conjunction with using PV and batteries during their lifespan compared to their installation costs. In the future, the authors propose the possibility of studying the energy consumption reduction cost with the integration of electric vehicles. Furthermore, it is recommended to expand the scope of the study by incorporating multiple homes to study the mechanism of energy exchange between them, considering the preferences of each user. Additionally, suggesting integrating thermostatically controlled loads into the energy demand model.

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CHAPTER 7. INTEGRATING LIFE CYCLE PRINCIPLES IN HOME ENERGY MANAGEMENT SYSTEMS: OPTIMAL LOAD PV-BATTERY-ELECTRIC VEHICLE SCHEDULING

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

- Title: Integrating Life Cycle Principles in Home Energy Management Systems: Optimal Load PV-Battery-Electric Vehicle Scheduling
- Authors: Al Muala, Z. A.; Bany Issa, M. A.; Bello Bugallo, P.M
- Publisher: MDPI
- Journal: Batteries
- eISSN: 2313-0105
- Impact Factor: 4.6 in 2023 (Database: Web of Science)
- Category: Electrochemistry (Database: Web of Science)
- Relative position: Q2 (16/45) in 2023 (Database: Web of Science)
- DOI: https://doi.org/10.3390/batteries10040138
- Year of publication: 2024
- Article views: 1102
- Contribution of the doctoral student: contribution to conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing— review and editing, visualization, and project administration.
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SUMMARY

Energy management in the residential sector contributes to energy system dispatching and security with optimal use of RESs and ESSs and utilizing the main grid based on its state. This work focuses on optimal energy flow, ESSs parameters, and energy consumption scheduling based on DR programs. The primary goals of the work consist of minimizing electricity costs while simultaneously extending the ESSs' lifetime in conjunction with extracting maximum benefits throughout their operational lifespan and reducing CO_2 emissions. An effective ESSs and PV energy usage prices are modeled and an efficient energy flow management algorithm is presented, which considers the lifecycle of the ESSs including battery and EVs, efficient use of the PV system while reducing the cost of energy consumption. In addition, an optimization technique is employed to obtain the optimal ESSs parameters including the size and DOD, considering the installation cost, LCOS, winter and summer conditions, energy consumption profile, and energy prices. Finally, an optimization technique is applied to obtain the optimal energy consumption scheduling. The proposed system provides all the possibilities of exchanging energy between EV, battery, PV, grid, and home. The optimization problem is solved using the PSO in Matlab with an interval time of one minute. The results show the effectiveness of the proposed system in reducing costs, energy losses, and CO_2 emissions. Moreover, it extends the lifetime of ESSs while maximizing financial contributions. The system demonstrates its capability in achieving optimal energy utilization, energy consumption, ESSs parameters, and dynamic responsiveness to seasonal and contextual factors.

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7.1. INTRODUCTION

Over the last decade, there has been a rise in energy demand, which is directly tied to population growth around the world [Ritchie et al., 2023]. As countries heavily depend on energy for their development, reducing energy consumption poses significant challenges. Globally, concerns over the environmental impact of fossil fuels and issues related to the geopolitics of global energy security have emerged as crucial topics demanding attention and resolution [Proskuryakova, 2018]. Accordingly, due to environmental and energy security issues, harnessing RESs to be an alternative to fossil fuel sources to generate energy has become of utmost importance [Gökgöz et al., 2018]. However, intermittent and erratic RESs generation is un-avoidable and it does not provide consistent performance in fulfilling continuous energy demand, significantly affecting grid stability [Aziz et al., 2017; Notton et al., 2018]. Therefore, continuously meeting energy demand is the main challenge of any power generation system. Hence, in the sustainability realm, the role of ESSs is to improve the reliability of the energy system by storing surplus energy from RESs and redistributing it during the RESs energy shortage and grid peak periods. This dynamic functionality ensures a more resilient and efficient energy system, marking a significant stride toward a sustainable and reliable energy future [Mahesh et al., 2020; Al-Saadi et al., 2023].

For example, the residential sector represented 27% of the final energy consumption, emphasizing its notable contribution to overall energy usage, optimizing consumption through energy-efficient practices, and contributing to energy sustainability [Eurostat, 2023a]. Integrating ESSs such as batteries and EVs with a local PV system in the residential sector proves to be an efficient strategy. This strategy addresses the fluctuations of PV generation by storing excess energy during periods of abundance and discharging it when faced with insufficient PV generation and periods of high grid energy price [Mohandes et al., 2020; Gong et al., 2021]. Furthermore, RESs and ESSs compose a large portion of the distributed generators in the residential sector [Mahesh et al., 2020], especially with the continuous drop in their installation costs [IRENA, 2021]. In addition, utilizing RESs and ESSs has economic benefits in the residential sector by

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reducing energy costs [Rana et al., 2022]. The implementation of SG technology and innovative electricity tariffs, such as Real-time Pricing (RTP) and Time-of-Use (TOU), play a pivotal role in sustainable energy management [Meliani et al., 2021]. Accordingly, HECs receive real-time information about the grid's electricity prices by employing smart meters that facilitate seamless data exchange.

While harnessing the potential of PV systems involves an initial investment, mitigating this challenge requires a strategic approach that entails optimizing the utilization of PV systems by synchronizing their operation with the fluctuating energy demand and energy prices throughout the day. In addition, making informed decisions on whether to store excess energy in ESSs or capitalize on selling it to the grid. Failure to effectively align the use of PV systems with demand patterns and market conditions can directly impact the owner's income, particularly concerning the initial investment and operational costs. Hence, prudent management of energy resources and market dynamics is essential for maximizing returns on PV system investments [SA Power Networks, 2020]. Similarly, ESSs have an investment cost, requiring an efficient operational approach. Accordingly, considering the fluctuating charging prices from the grid throughout the day, it becomes imperative to manage the charging/discharging operations time [Dong et al., 2020]. This consideration not only optimizes the lifecycle of ESSs but also yields real economic benefits for HECs. The DOD holds significant importance in the operations of ESSs and profoundly influences their lifecycle [Omar et al., 2014]. Moreover, when evaluating the LCOS, the DOD exhibits an inverse relationship with the LCOS, while directly correlating with the allowable charge/discharge to/from the ESSs. Therefore, establishing an optimal DOD for ESSs ensures both cost-effectiveness and efficient charge/discharge operations. Thus, energy management through finding the optimal energy distribution and scheduling energy consumption has benefits for consumers and operators in ensuring system reliability [Haddadian et al., 2017] and achieving various goals such as reducing electricity bills [Mbungu et al., 2018], reducing CO_2 emissions [Tabar et al., 2018], effective use of PV power [Kusakana, 2020], and preserving the life cycle of ESSs [Al Muala et al., 2023].

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As the HEMSs field continues to evolve, significant strides have been made in understanding and enhancing strategies such as optimal power flow and scheduling the operating time of household appliances. The literature abounds with noteworthy advances, with various research studies proposing innovative approaches to optimize further and refine these crucial aspects of HEMSs functionality. In the system presented By Bouakkaz et al. [Bouakkaz et al., 2019], the prioritization involves utilizing RESs power as the primary source, followed by the battery, and ultimately the DG power to meet the load. The optimization of energy consumption scheduling revolves around minimizing the number of battery cycles. Bhattacharjee et al. [Bhattacharjee et al., 2021] proposed an energy flow strategy focused on scheduling power generation from the PV system, biogas engine generator, energy stored in the battery, and grid. The prioritizes in the event of a shortage of RESs based on the available discharge energy in the biogas engine generator, followed by the battery, and ultimately the grid price. The optimization cost is based on minimizing the operation and maintenance expenses of the energy sources, and battery, along with the imported/exported energy cost from/to the grid. In the work published by Mbungu et al. [Mbungu et al., 2019], a flexible communication control strategy was created to manage the energy flow for the residential sector, aiming to maximize the energy usage from RESs and ESSs and thereby reduce the purchased energy from the grid. The system algorithm is designed based on the FMINCON optimal structure, in which the grid and RESs energy usage prices are constant. In the work performed by Mbungu et al. [Mbungu et al., 2022], a closed-loop optimization was applied to manage the energy flow of an EV connected to a home and grid. The EV functions as an energy supplier to the home and can also be charged from the grid, where the objective function is minimizing the cost of energy imported from the grid. The Genetic Algorithm (GA) was employed to schedule the energy flow in a residential power system [Zhang et al., 2019]. The dispatching ratio of energy sold to the grid was considered an optimization variable. The objective function is to minimize the energy cost by maximizing the benefit of energy sold to the grid and minimizing the cost of energy imported from the grid. To meet the

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energy demand, the order of priority was assigned to RESs, followed by the battery, and, as a final source, the grid. Li et al. [Li et al., 2022] developed a dynamic programming algorithm based on the Bellman equation to solve an energy flow optimization problem considering battery-cycling aging. Azaroual et al. [Azaroual et al., 2021] proposed an energy management strategy based on the GA, Pattern Search Optimization Solver (PSOA), Fmincon Optimization Solver, and hybrid GA-Fmincon algorithms to maximize self-consumption utilizing a combination of PV, wind turbine, and battery resources. The optimization problem incorporated factors such as energy cost imported from the grid, daily battery operation, battery degradation, and profit from selling excess energy to the grid. Another study proposed a HEMS optimization strategy using GWO to minimize the electricity cost and Peak-to-Average Ratio (PAR), in which the ESS charging/discharging management strategy was formulated based on the average of RTP over the day and the SOC [Mohammad et al., 2022]. The PSO and Jaya algorithms were employed by Wang et al. [Wang et al., 2022a] to achieve optimal energy scheduling. The proposed system offers the capability to fulfill the energy demand through EVs. The daily costs associated with RESs and ESSs were incorporated into the optimization problem to be constant according to their installation costs and lifecycles. A Mixed Integer Linear Programming (MILP) optimization algorithm was implemented by Munankarmi et al. [Munankarmi et al., 2022] to address a multi-objective HEMS model. This model problem revolves around optimizing energy cost, ensuring thermal comfort, and considering PAR. A model for optimal energy flow considering the battery life cycle was introduced by Lee et al. [Lee et al., 2022] to minimize grid and battery energy usage costs. The optimization problem incorporated the battery degradation cost, with its determination based on the SOC. An energy management system was designed by Seal et al. [Seal et al., 2020] to minimize grid energy purchases, optimize selling energy to the grid for profit, and ensure thermal comfort. The optimization problem was solved using the MATLAB function FMINCON. Bouakkaz et al. proposed a model for battery energy-usage pricing based on the battery capital cost and lifecycle, incorporating the SOC as a determining factor, the price

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increases with low SOC and decreases with high SOC [Bouakkaz et al., 2021]. A multi-objective HEMS model was introduced by Huy et al. [Huy et al., 2023] to achieve optimal energy scheduling. The optimization problem was addressed through the augmented ε-constraint method and lexicographic optimization. The optimization considerations relate to economic, technical, and end-user comfort factors.

The innovation of the present work lies in its comprehensive approach to energy management in the residential sector by integrating an effective energy management system including optimal power flow, optimal ESSs parameters, and optimal energy consumption scheduling. The proposed system aims to reduce electricity costs while extending the ESSs lifetime, reducing energy losses, reducing CO_2 emissions, and maximizing the benefits of PV-battery-EV energy systems throughout their lifetime. The main contributions of the proposed system involve:

1. The possibilities of energy exchange are as follows: EV to grid (EV2G), EV to battery (EV2B), EV to home (EV2H), battery to grid (B2G), battery to EV (B2EV), battery to home (B2H), PV to home (PV2H), PV to battery (PV2B), PV to EV (PV2EV), PV to grid (PV2G), grid to home (G2H), grid to battery (G2B), and grid to EV (G2EV).
2. Developing PV, battery, and EV energy usage prices.
3. Creating an effective energy flow management algorithm.
4. Optimizing the size and DOD parameters for the battery and EV's battery.
5. Optimizing the operation time of home appliances.
6. Considering seasonal conditions (winter and summer) in the optimization processes.
7. Applying the PSO algorithm for solving the previous optimization problems with an interval time of one minute to obtain an accurate solution.
8. A real case study is considered.

7.2. METHODOLOGY

The methodology section provides insight into the approach taken to accomplish the objectives of this work, and it is outlined as follows:

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1. Describing the system configuration and the dynamic process of energy exchange.
2. Mathematical model formulation of PV, battery, and EV systems.
3. Mathematical model formulation of the selling energy to the grid, DOD and lifecycle relationship, PV/battery/EVs energy-usage costs, objective function, and problem constraints.
4. Developing an algorithm for achieving optimal energy flow.
5. Developing an optimization strategy for obtaining optimal ESSs parameters and scheduling home appliances focusing on one-minute operation intervals.
6. Selecting and outlining the case study (load profile, solar radiation, temperature, PV-battery-EV integrated system, and grid's buying/selling price).
7. Selection and assessment of sustainability factors, including modeling and running: estimated battery and EV lifespan, CO_2 emission intensity, and the integrated energy system's contribution throughout their lifecycles.

7.3. DEVELOPMENT

7.3.1. System architecture

The configuration of the typical grid-connected residential power system is shown in Figure 7.1. It includes the grid, PV system, battery storage system, EVs, and load profile. The Energy Flow Management System (EFMS) assumes responsibility for the optimal scheduling of power systems operation and energy exchange between the system's components and grid. The energy management process requires control inputs such as the grid electricity price (buy/sell), PV power generation, EV parameters, battery parameters, and energy demand at each time step.

Moreover, the work proposes and introduces the energy usage cost of PV, battery, and EV systems as control inputs. This approach helps to utilize these systems efficiently considering their lifecycle, and installation costs, thus reducing actual costs, minimizing energy losses, and prolonging the system lifespan. Figure 7.2 illustrates the energy exchange process among the system's agents.

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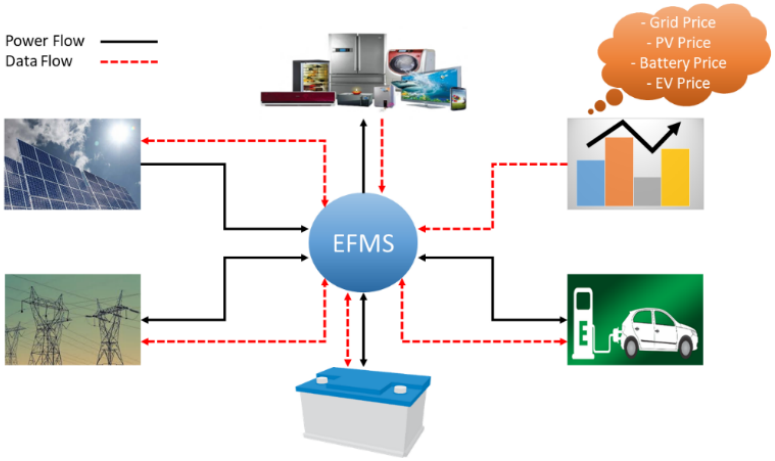

Figure 7.1: System configuration

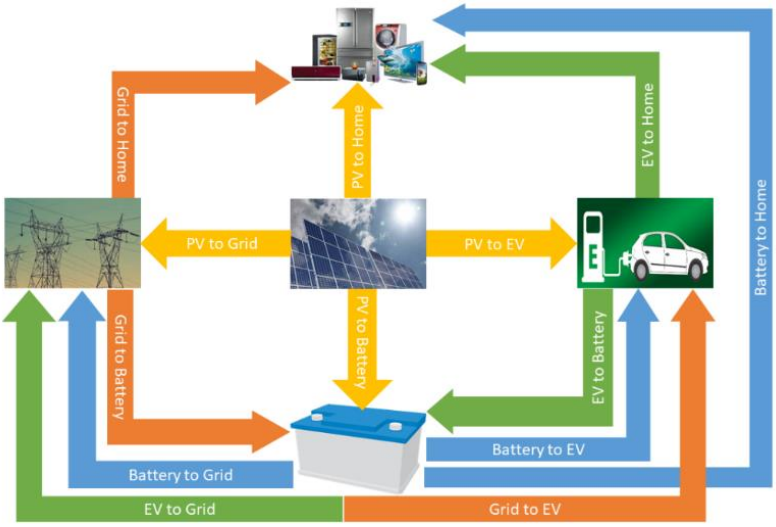

Figure 7.2: Energy exchange process

7.3.2. System modeling

7.3.2.1. PV model

The generated power of PV depends on the number and area of solar panels, PV system efficiency, ambient temperature, and solar irradiance. The PV output power is calculated using [Eq.7.1] [Mohamed et al., 2007].

$$P_{PV}(t) = P_{STC} * \frac{I_r(t)}{I_r, STC} * (1 + \gamma_T * (T_o(t) - T_{STC})) \quad \text{[Eq.7.1]}$$

Where $P_{PV}(t)$ represents the PV output power (kW) at each time slot *t*. P_{STC} is the maximum power of the PV (kW) module at standard test condition (STC), $I_r(t)$ is the solar irradiance (kW/m^2) at each time slot *t*, and I_r, STC is the solar irradiance at STC (kW/ m^2). γ_T denotes the temperature coefficient which is equal to 0.005, respectively. $T_o(t)$ is the ambient temperature (C^o) at each time slot *t* and T_{STC} represents the reference temperature at STC (25 C^o).

7.3.2.2. Battery model

The battery's energy varies at each time slot *t*, determined by its charging or discharging status. The charging process includes charging the battery from the PV, EV, and grid. The discharging process includes discharging the battery to the home, EV, and grid. The instantaneous energy in the battery is calculated as follows:

$$E_B(t+1) = E_B(t) + P_B^{ch}(t) * \mu * \Delta t - \frac{P_B^{dis}(t)}{\mu} * \Delta t \quad \text{[Eq.7.2]}$$

$$P_B^{ch}(t) = P_{pvtb}(t) + P_{evtb}(t) + P_{gtb}(t) \quad \text{[Eq.7.3]}$$

$$P_B^{dis}(t) = P_{bth}(t) + P_{btev}(t) + P_{btg}(t) \quad \text{[Eq.7.4]}$$

Where $E_B(t+1)$ expresses the energy stored in the battery (kWh) at *t*+1, $E_B(t)$ represents the energy stored in the battery (kWh) at *t*. $P_B^{ch}(t)$, $P_B^{dis}(t)$ define the amount of charging/discharging power

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to/from the battery (kW) at each time slot *t*, respectively. μ is the converter charging/discharging efficiency assumed to be 0.95, and Δt is the simulation time (equal to 1 divided by 60). $P_{pvtb}(t)$ and $P_{evtb}(t)$ represent the amount of power sent from the PV and EV to the battery (kW) at each time slot *t*, respectively, and $P_{gtb}(t)$ is the amount of power imported from the grid for charging the battery (kW) at each time slot *t*. $P_{bth}(t)$, $P_{btev}(t)$ express the power discharged from the battery to the home and EV (kW) at each time slot *t*, respectively. $P_{btg}(t)$ is the amount of power exported from the battery to the grid (kW) at each time slot *t*.

7.3.2.3. EV model

The EV's battery can be used as a storage energy system to store and provide electrical energy, where many EV key features can be employed in an SG environment. Similar to the battery storage system, the EV battery energy varies according to the charging/discharging processes. In particular, the charging process involves charging the EV from the PV, battery, and grid, while the discharging process involves discharging the EV to the home, battery, grid, and energy consumed during the EV trip distance. The instantaneous energy in the EV battery is calculated using [Eq.7.5], and the charged/discharged power are calculated using [Eq.7.6] and [Eq.7.7], respectively. The required energy EV_{trip} for the EV trip (kWh) is calculated using [Eq.7.8] [Abdalla et al., 2020].

$$E_{EV}(t+1) = E_{EV}(t) + P_{EV}^{ch}(t) * \mu * \Delta t - \frac{P_{EV}^{dis}(t)}{\mu} * \Delta t - EV_{trip} \quad \text{[Eq.7.5]}$$

$$P_{EV}^{ch}(t) = P_{pvtev}(t) + P_{btev}(t) + P_{gtev}(t) \quad \text{[Eq.7.6]}$$

$$P_{EV}^{dis}(t) = P_{evth}(t) + P_{evtb}(t) + P_{evg}(t) \quad \text{[Eq.7.7]}$$

$$EV_{trip} = \mu_{driving} * D \quad \text{[Eq.7.8]}$$

Where $E_{EV}(t+1)$ expresses the energy stored in the EV's battery (kWh) at *t*+1, $E_{EV}(t)$ is the energy stored in the EV's battery (kWh) at

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t. $P_{EV}^{ch}(t)$, $P_{EV}^{dis}(t)$ define the charging/discharging power to/from the EV battery (kW) at each time slot *t*, respectively. $P_{pvtev}(t)$ and $P_{btev}(t)$ are the amount of power sent from the PV and battery to the EV battery (kW) at each time slot *t*, respectively, and $P_{gtev}(t)$ is the power imported from the grid for charging the EV battery (kW) at each time slot *t*. $P_{evth}(t)$, $P_{evtb}(t)$ expresses the power discharged from the EV battery to the home and battery (kW) at each time slot *t*, respectively. $P_{evg}(t)$ is the power exported from the EV battery to the grid (kW) at each time slot *t*. $\mu_{driving}$ is the vehicle efficiency (kWh/km), and D represents the vehicle travel distance (km).

7.3.3. Problem formulation

7.3.3.1. PV energy usage price

The LCOE is the cost of generating energy from an energy system over its lifespan, considering the planning, initial investment, operation, maintenance costs, construction, and cost of capital [Branker et al., 2011; Lai et al., 2017]. LCOE expresses the price of generated energy, and the U.S. Department of Energy (DOE) selected it as a primary metric for assessing the PV system [Shen et al., 2020]. The LCOE of PV systems in the Spanish residential sector was found to be equal to 0.092 EUR/kWh [IRENA, 2021]. In this work, the LCOE expressed the cost of using PV energy in the residential sector, while [Eq.7.9] calculates the cost of using the PV energy (EUR/kWh) at each time slot *t*. The LCOE of PV is introduced into the optimization problem to utilize the PV power generated efficiently.

$$C_{PV}(t) = LCOE_{pv} * P_{pvth}(t) * \Delta t \qquad \text{[Eq.7.9]}$$

Where $C_{PV}(t)$ is the cost of using PV energy to cover the load at each time slot *t*, $LCOE_{pv}$ expresses the PV energy usage price (EUR/kWh) at each time slot *t*, and $P_{pvth}(t)$ represents the power (kW) sent from the PV system to the load at each time slot *t*.

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7.3.3.2. Battery energy usage price

Batteries play a crucial role in system balance and reducing electricity costs by storing energy in the cases of RES excess energy and during the low-price periods of the grid to fulfill the energy demand in the cases of shortage of RES energy and high-price periods. Moreover, batteries can be used to charge EVs. However, batteries have installation costs, such as battery, infrastructure, and power of balance costs [Zakeri et al., 2015; Aghdam et al., 2018]. The capital cost of the battery can be calculated using [Eq.7.10] [Zakeri et al., 2015; Li et al., 2022].

$$B_{capital} = C_{Unit} * E_b + C_{BOP} * E_{batt} + C_{PCS} * P_B \quad \text{[Eq.7.10]}$$

Where $B_{capital}$ is the capital cost of the battery system (EUR), C_{Unit} is the cost of the battery per unit (EUR/kWh). C_{BOP} expresses the infrastructure cost of the battery system (EUR/kWh), and C_{PCS} expresses the power conversion system cost (EUR/kW). The C_{BOP} and C_{PCS} were assumed to be 33.868/ kWh and 24.695 /kWh, respectively [Schoenung, 2011; Zakeri et al., 2015]. E_{batt} represents the battery capacity (kWh).

Manufacturers provide a data sheet for each product showing the specifications and the operation conditions. For batteries, manufacturers provide information such as the expected number of battery lifecycle n at a specific DOD. These two parameters are more relevant to consider to operate the battery effectively. The LCOS is the investment cost divided by the amount of energy stored in the storage system during its life cycle. The present study uses the LCOS to calculate and express the cost of storing and discharging energy during the battery lifespan. Regarding that, the cost of storing and discharging energy during the battery lifespan in the unit (EUR/kWh) can be calculated based on the capital cost, E_{batt}, n, and DOD. The expected amount of charged/discharged energy to/from the battery $B_E^{lifespan}$ (kWh) during its lifespan can be calculated using [Eq.7.11]. The cost of using the battery throughout its lifespan, which is presented as B_{LCOS} (EUR/kWh) can be calculated using [Eq.7.12].

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$$B_E^{lifespan} = E_{batt} * n * DOD \quad \text{[Eq.7.11]}$$

$$B_{LCOS} = \frac{B_{capital}}{B_E^{lifespan}} \quad \text{[Eq.7.12]}$$

The term "battery energy usage price" refers to the price associated with using the energy stored in a battery. This cost can vary depending on various factors and contexts, such as the battery specifications, the battery capital cost, the cost of energy purchased from the grid and RES, the cost of charging the battery from the EVs, LCOS, and the charging/discharging process (time & amount). Regarding that, we designed a price model for battery energy usage that expresses the battery price for each time slot t. Hence, the battery can be used efficiently. [Eq.7.13-7.15] are used to calculate the cost of purchased energy from the PV, grid, and EV, respectively, including the storing cost of the purchased energy in a battery.

$$C_{pvtb}(t) = [(P_{pvtb}(t) * LCOE_{pv}) + ((P_{pvtb}(t) * B_{LCOS})] * \Delta t \quad \text{[Eq.7.13]}$$

$$C_{gtb}(t) = [\left(P_{gtb}(t) * Grid_{price}^{buy}(t)\right) + \left(P_{gtb}(t) * B_{LCOS}\right)] * \Delta t \quad \text{[Eq.7.14]}$$

$$C_{evtb}(t) = [\left(P_{evtb}(t) * EV_{price}(t)\right) + (P_{evtb}(t) * B_{LCOS})] * \Delta t \quad \text{[Eq.7.15]}$$

Where $C_{pvtb}(t)$, $C_{gtb}(t)$, and $C_{evtb}(t)$ are the cost of purchased energy from the PV, grid, and EV and stored in the battery (EUR), respectively, at each time slot *t*. $Grid_{price}^{buy}(t)$ expresses the grid price (EUR/kWh) at each time slot *t*. $EV_{price}(t)$ represents the EV energy usage price (EUR/kWh) at each time slot *t*, which is calculated in the next section.

Then, the price of the total purchased energy $B_{price}^{ch.}(t)$ from the PV, grid, and EV, which is stored in the battery (EUR/kWh) at each time slot *t* can be expressed in the unit (EUR/kWh) using [Eq.7.18]; this is achieved by dividing the total cost of the purchased energy by the

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total purchased energy. [Eq.7.16] calculates the total cost, while [Eq.7.17] calculates the total purchased energy at each time slot *t*.

$$T_b^{cost}(t) = C_{pvtb}(t) + C_{gtb}(t) + C_{evtb}(t) \quad \text{[Eq.7.16]}$$

$$T_b^{energy}(t) = [P_{pvtb}(t) + P_{gtb}(t) + P_{evtb}(t)] * \Delta t \quad \text{[Eq.7.17]}$$

$$B_{price}^{ch.}(t) = \frac{T_b^{cost}(t)}{T_b^{energy}(t)} \quad \text{[Eq.7.18]}$$

Where $T_b^{cost}(t)$ is the total cost of the purchased energy stored in the battery (EUR) at each time slot *t*, and $T_b^{energy}(t)$ represents the total purchased energy stored in the battery (kWh) at each time slot *t*.

The newly purchased energy that charged the battery will be added to the previous battery's net energy. The newly purchased energy price will be factored into the overall battery energy usage price. Consequently, a fresh battery energy usage price for the next time slot *t*+1 will be established, considering the updated quantity and price of the purchased energy in addition to the previous battery's net power and its associated price. [Eq.7.19] is used to calculate the battery energy usage price, while [Eq.7.20] expresses the cost of battery energy usage in the home $C_{batt}(t)$ (EUR) at each time slot *t*.

$$B_{price}^{overall}(t+1) = \frac{\left(B_{price}^{overall}(t) * E_B\right) + \left(B_{price}^{ch.}(t) * T_b^{energy}(t)\right)}{E_B + T_b^{energy}(t)} \quad \text{[Eq.7.19]}$$

$$C_{batt}(t) = B_{price}^{overall}(t) * P_{bth}(t) * \Delta t \quad \text{[Eq.7.20]}$$

Where $B_{price}^{overall}(t+1)$ is the battery energy usage price (EUR/kWh) for the time slot *t*+1. $B_{price}^{overall}(t)$ is the battery energy usage price (EUR/kWh) in the time slot *t*.

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7.3.3.3. EV's battery energy usage price

Electric vehicles are crucial in reducing CO_2 emissions, saving energy, and grid stability. Having an EV at home offers homeowners financial savings, convenience, environmental benefits, and the potential for energy management and backup power. However, the replacement of EV's battery cost and its lifecycle should be considered to ensure efficient EV's battery operation. The cost of using the EV's battery during its lifespan is calculated using [Eq.7.21].

$$EV_{LCOS} = \frac{EV_{capital}}{NE_{ev} * n_{ev} * DOD_{ev}} \quad \text{[Eq.7.21]}$$

Where $EV_{capital}$ represents the replacement cost of the EV's battery, EV_{LCOS} signifies the cost of using the EV's battery throughout its lifespan (EUR/kWh), and NE_{ev} quantifies the nominal energy of the EV's battery (kWh). n_{ev} corresponds to the number of charging/discharging cycles of the EV's battery at a specific DOD denoted as DOD_{ev}.

In the proposed model, the EV can exchange energy with the load, battery, and grid. Thus, it's necessary to manage the operation time of the EV efficiently. Firstly, the cost of purchasing energy from PV, battery, and the grid is calculated using [Eq.7.22-7.24]. In contrast, [Eq.7.25-7.27] are used to calculate the price of the total purchased energy stored in the EV's battery.

$$C_{pvtev}(t) = [(P_{pvtev}(t) * LCOE_{pv}) + ((P_{pvev}(t) * EV_{LCOS})] * \Delta t \quad \text{[Eq.7.22]}$$

$$C_{gtev}(t) = [\left(P_{gtev}(t) * Grid_{price}^{buy}(t)\right) + \left(P_{gtev}(t) * EV_{LCOS}\right)] * \Delta t \quad \text{[Eq.7.23]}$$

$$C_{btev}(t) = [\left(P_{btev}(t) * B_{price}^{overall}{}_{price}(t)\right) + (P_{btev}(t) * EV_{LCOS})] * \Delta t \quad \text{[Eq.7.24]}$$

$$T_{ev}^{cost}(t) = C_{pvtev}(t) + C_{gtev}(t) + C_{btev}(t) \quad \text{[Eq.7.25]}$$

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$$T_{ev}^{energy}(t) = [P_{pvtev}(t) + P_{gtev}(t) + P_{evtb}(t)] * \Delta t \quad \text{[Eq.7.26]}$$

$$EV_{price}^{ch.}(t) = \frac{T_{ev}^{cost}(t)}{T_{ev}^{energy}(t)} \quad \text{[Eq.7.27]}$$

Where $C_{pvtev}(t)$, $C_{gtev}(t)$, and $C_{btev}(t)$ are the cost of purchased energy from the PV, grid, and battery and stored in the EV's battery (EUR), respectively, at each time slot *t*. $EV_{price}^{ch.}(t)$ is the price of the total purchased energy from the PV, grid, and battery, which is stored in the EV's battery (EUR/kWh) at each time slot *t* can be expressed in the unit (EUR/kWh), $T_{ev}^{cost}(t)$ is the total cost of the purchased energy and stored in the EV's battery (EUR) at each time slot *t*, and $T_{ev}^{energy}(t)$ is the total purchased energy and stored in the EV's battery (kWh) at each time slot *t*.

Then, the purchased energy for recharging the EV's battery is integrated with the existing net energy of the EV's battery. The cost of the newly charged energy is then factored into the comprehensive calculation of the price of the EV's battery energy usage. As a result, the energy usage price for the EV's battery for the next time slot *t*+1 is determined, considering the updated quantity and cost of the purchased energy, along with the net power of the previous EV's battery and its associated price. [Eq.7.28] is the designated formula for calculating the price of the EV's battery energy usage. [Eq.7.29] expresses the cost of EV's battery energy usage in the home $C_{EV}(t)$ (EUR) at each time slot *t*.

$$EV_{price}^{overall}(t+1) = \frac{\left(EV_{price}^{overall}(t) * EV_B(t)\right) + (EV_{price}^{ch.}(t) * T_{ev}^{energy}(t))}{EV_B(t) + T_{ev}^{energy}(t)} \quad \text{[Eq.7.28]}$$

$$C_{EV}(t) = EV_{price}^{overall}(t) * P_{evth}(t) * \Delta t \quad \text{[Eq.7.29]}$$

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Where $EV_{price}^{overall}(t+1)$ is the EV's battery energy usage price (EUR/kWh) for the time slot t+*1*. $EV_{price}^{overall}(t)$ is the EV's battery energy usage price (EUR/kWh) in the time slot *t*.

7.3.3.4. Selling energy to the grid

The profitability model hinges on a comprehensive analysis of PV, battery, EV, and grid energy usage prices to optimize energy selling to the grid. This holistic approach ensures efficient energy management while factoring in installation costs and system lifecycle. [Eq.7.30-32] calculate the net profit of selling energy from the PV, battery, and EV systems to the grid considering the integrated system installation cost and lifespan. [Eq.7.33] calculates the total net profit of selling energy $Profit_{Sell}(t)$ from the integrated system to the grid (EUR).

$$Profit_{pvtg}(t) = ((P_{pvtg}(t) * (Grid_{sell}(t) - LCOE_{pv})) * \Delta t \quad \text{[Eq.7.30]}$$

$$Profit_{btg}(t) = (P_{btg}(t) * (Grid_{sell}(t) - B_{price}^{overall}(t))) * \Delta t \quad \text{[Eq.7.31]}$$

$$Profit_{evtg}(t) = (P_{evtg}(t) * (Grid_{sell}(t) - EV_{price}^{overall}(t)) * \Delta t \quad \text{[Eq.7.32]}$$

$$Profit_{Sell}(t) = Profit_{pvtg}(t) + Profit_{btg}(t) + Profit_{evtg}(t) \quad \text{[Eq.7.33]}$$

Where $Profit_{pvtg}(t)$, $Profit_{btg}(t)$ represents the economic benefit of selling energy from PV and battery to the grid (EUR) at each time slot *t*, respectively. $Profit_{evtg}(t)$ (t) is the economic benefit of selling energy from EV to the grid (EUR) at each time slot *t*, $P_{pvtg}(t)$ represents the amount of PV power sent to the grid (kW) at each time slot *t*, and $Grid_{sell}(t)$ is the energy selling price to the grid (EUR/kWh) at each time slot *t*.

7.3.3.5. Depth of discharge and life cycle relationship

DOD determines the extent to which the stored energy in the ESS is utilized, directly affecting the system's performance and life cycle

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[Omar et al., 2014]. The DOD has an inverse relationship with the life cycle for ESSs, the more DOD increases, the more life cycle decreases [Kintner-Meyer et al., 2010]. Consequently, this study aims to optimize the DOD for the ESS to obtain the optimal ESS life cycle to gain maximum financial benefit compared to the investment costs through their life cycle. [Eq.7.34] expresses the relationship between the DOD and the life cycle for Lithium-ion batteries [Dallinger et al., 2014].

$$N_{cycle,ESS} = a * DOD^{b} \quad \text{[Eq.7.34]}$$

Where $N_{cycle,ESS}$ means the ESS lifecycle at a specific DOD, while the parameters a and b were simulated as 4000 and -1.632, respectively [Dallinger et al., 2014].

7.3.3.6. Objective function

The main objective function of this study is to achieve an optimal HEMS that minimizes the total cost of electricity while reducing energy losses and ensuring an extended lifespan for the integrated system. [Eq.7.35] shows the objective function comprising five parts. The first part is the cost of power purchased from the grid for home use, as determined by [Eq.7.36]. The second and third parts are the daily PV and battery energy usage costs for home consumption, respectively. The fourth part is the cost of using the EV's battery energy in the home to meet home energy demand. The fifth part is the cost of using the EV's battery energy for traveling as formulated in [Eq.7.37]. The sixth part calculates the total daily profit from selling excess power back to the grid from the integrated system.

$$Minimize\ (Cost) = Min \sum_{1}^{1440} C_{Grid}(t) + C_{PV}(t) + C_{Batt}(t) + C_{EV}(t) + C_{Trip}(t) - Profit_{Sell}(t) \quad \text{[Eq.7.35]}$$

$$C_{Grid}(t) = P_{gth}(t) * Grid_{price}^{buy}(t) * \Delta t \quad \text{[Eq.7.36]}$$

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$$C_{Trip}(t) = EV_{trip}(t) * EV_{price}^{overall}(t) * \Delta t \quad \text{[Eq.7.37]}$$

Where $C_{Grid}(t)$ means the cost of grid energy usage for the vehicle trip (EUR) at each time slot *t*, $P_{gth}(t)$ represents the power sent from the grid to home (kW) at each time slot *t*, and $C_{Trip}(t)$ represents the cost of EV energy usage cost for the vehicle trip (EUR) at each time slot *t*.

7.3.3.7. Constraints

In the modeling process, constraints serve as essential parameters that define the boundaries and limitations within which the system operates. These restrictions are pivotal in shaping the behavior and outcomes of the model, ensuring that it aligns with real-world systems. For the PV system, the sum of PV power supplied for home use, charging the battery and EV, and exporting to the grid should equal the total PV power generated. Therefore, [Eq.7.38] is modeled for this purpose.

$$P_{pvth}(t) + P_{pvtb}(t) + P_{pvtev}(t) + P_{pvtg}(t) = P_{PV}(t) \quad \text{[Eq.7.38]}$$

For the battery system, the SoC is a percentage value representing how much electrical energy a battery currently holds, expressed as a percentage of its total capacity, as described in [Eq.7.39]. To avoid deep charging/discharging and ensure that the battery operates within the minimum and maximum allowable capacity, [Eq.7.40] was introduced as a constraint. Furthermore, the battery has other constraints regarding the maximum battery charging/discharging powers during each period; consequently, [Eq.7.41] and [Eq.7.42] are established to address these constraints.

$$SoC\ (t)_B = \frac{E_b(t)}{E_{batt}} \quad \text{[Eq.7.39]}$$

$$SoC_{min} \leq SoC\ (t)_B \leq SoC_{min} \quad \text{[Eq.7.40]}$$

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$$0 \leq P_B^{ch}(t) * \Delta t \leq Ch_B^{max} \quad \text{[Eq.7.41]}$$

$$0 \leq P_B^{dis}(t) * \Delta t \leq Dis_B^{max} \quad \text{[Eq.7.42]}$$

Where Ch_B^{max}, Dis_B^{max} represent the maximum charge and discharge rate of the battery (kWh) during the time slot *t*, respectively, which are determined by the battery's characteristics.

Similar to the battery SoC constraint, the SoC for the EV must maintain its SoC within a specified range defined by the maximum and minimum SoC levels, as detailed in [Eq.7.43] and [Eq.7.44]. Moreover, the EV's battery has specific limitations concerning its maximum charging and discharging powers during each interval. For that, we introduced [Eq.7.45] and [Eq.7.46].

$$SoC\ (t)_{EV} = \frac{E_{EV}(t)}{NE_{ev}} \quad \text{[Eq.7.43]}$$

$$SoC_{min} \leq SoC\ (t)_{EV} \leq SoC_{min} \quad \text{[Eq.7.44]}$$

$$0 \leq P_{EV}^{ch}(t) * \Delta t \leq Ch_{EV}^{max} \quad \text{[Eq.7.45]}$$

$$0 \leq P_{EV}^{dis}(t) * \Delta t \leq Dis_{EV}^{max} \quad \text{[Eq.7.46]}$$

Where Ch_{EV}^{max} represents the maximum charge rate of the EV's battery (kWh) during the time slot *t*, and Dis_{EV}^{max} is the maximum discharge rate of the EV's battery (kWh) during the time slot *t*, which is determined by the characteristics of EV's battery.

For power balance, the total supplied power from the PV, battery, EV, and grid should meet the home load $P_l(t)$ (kW) at each time slot *t*. For this purpose, the following constraint is set.

$$P_{pvth}(t) + P_{bth}(t) + P_{evth}(t) + P_{gth}(t) = P_l(t) \quad \text{[Eq.7.47]}$$

Moreover, to ensure the optimal performance of ESSs during the life cycle, it is necessary to avoid simultaneous charging and

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discharging. This objective is accomplished by incorporating constraints as specified in [Eq.7.48] and [Eq.7.49].

$$P_{pvth}(t) + P_{bth}(t) + P_{evth}(t) + P_{gth}(t) = P_l(t) \quad \text{[Eq.7.48]}$$

$$P_{EV}^{ch}(t) * P_{EV}^{dis}(t) = 0 \quad \text{[Eq.7.49]}$$

7.3.4. Energy flow management algorithm development

In Figure 7.3, the EFMS algorithm (EFMSA) is illustrated. This algorithm is designed for optimal energy utilization, considering the PV, battery, and EV life cycles, and ensuring efficient use. Initially, the PV system powers household appliances. During periods of excess PV generation, EFMSA evaluates the economic benefits of storing PV surplus energy in the battery or EV for utilization during high-priced grid periods versus selling it to the grid. If storing PV surplus energy in the battery or EV proves more economically advantageous, EFMSA determines the optimal choice based on the lowest LCOS of the battery and EV. Otherwise, if selling the PV surplus energy to the grid is more beneficial, EFMSA opts for this alternative.

When PV generation falls short of the load, the EFMSA assesses the PV, battery, and grid energy usage price to determine the best viable option. If the battery price is the lowest, the EFMSA prioritizes the battery to fulfill the remaining consumption. If the battery cannot cover the remaining consumption, the EFMSA selects either the EV or grid based on the lowest energy usage price to assist the PV and battery to meet the energy demand. If the EV energy usage price is the lowest, the EFMSA prioritizes the EV to meet the energy demand. However, if the EV cannot the remaining consumption, the EFMSA chooses between the battery and grid based on the lowest energy usage price to assist the PV and EV in meeting the energy demand. While, in the case that the grid energy usage price is the lowest, the EFMSA gives priority to the grid to meet the energy demand.

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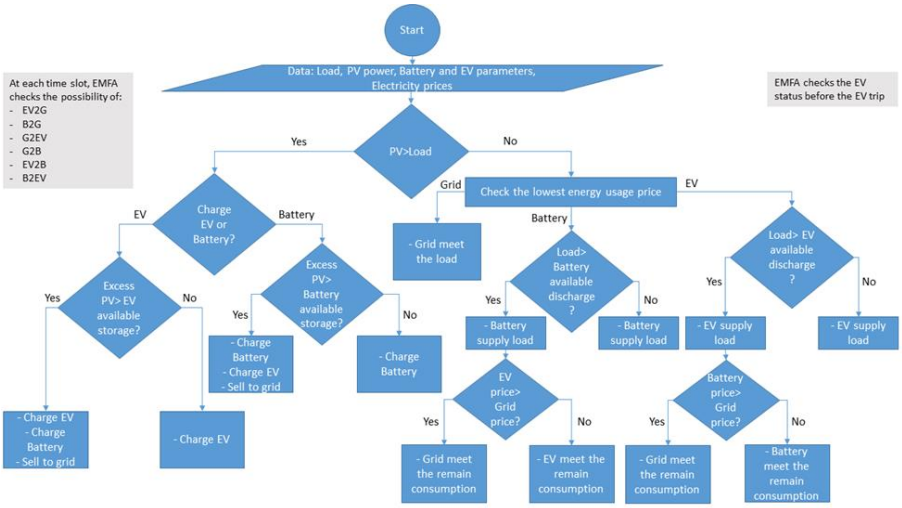

Figure 7.3: The EFMS algorithm

The EFMSA ensures efficient battery and EV charging/discharging from/to the grid, considering the life cycle and economic considerations. During potential charging periods, EFMSA evaluates whether storing energy is cost-effective compared to the grid's high prices; if so, it proceeds with charging the battery/EV. Otherwise, if the economic benefit of selling battery/EV energy to the grid outweighs discharging it to cover the load during high-priced periods, EFMSA opts for selling the energy to the grid. Otherwise, the battery/EV remains uncharged or undischarged. In the context of energy exchange between the battery and EV, the EFMSA ensures an efficient process. During potential charging periods, the EFMSA evaluates whether charging the battery from the EV is cost-effective for discharging this energy from the battery during the grid's high prices and absence of the EV; if so, it proceeds with charging the battery from the EV. Similarly, for charging the EV from the battery, the EFMSA evaluates whether charging the EV from the battery is cost-effective for using this energy in the vehicle trip rather than later in the grid's high price periods and rather than charging the EV from the grid. Moreover, before each trip, the EFMSA ensures that the EV has sufficient energy for the upcoming trip. It's worth noting that, in this work, the energy flow prioritization

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varies from period to period based on grid, battery, PV, and EV energy usage prices.

7.3.5. Optimization strategy

PSO has demonstrated remarkable efficacy in yielding favorable outcomes in various optimization tasks [Jain et al., 2022]. Its inherent capacity to mimic social behavior and swarm intelligence enables it to navigate solution spaces effectively and converge toward optimal results. PSO's ability to balance exploration and exploitation enables the identification of solutions that achieve the optimal objective function while considering diverse constraints. In addition, the iterative nature of PSO ensures continual refinement, allowing it to converge toward solutions that align with the specified optimization goals [Kennedy et al., 1995]. PSO stands out as a robust algorithm in the realm of home energy management, especially household appliance scheduling [Dinh et al., 2020; Menos-Aikateriniadis et al., 2022; Nguyen et al., 2020; Al Muala et al., 2023]. As a result, the optimal ESSs parameters and operation time matrix of each appliance for this study are computed with the PSO, as described in Figure 7.4.

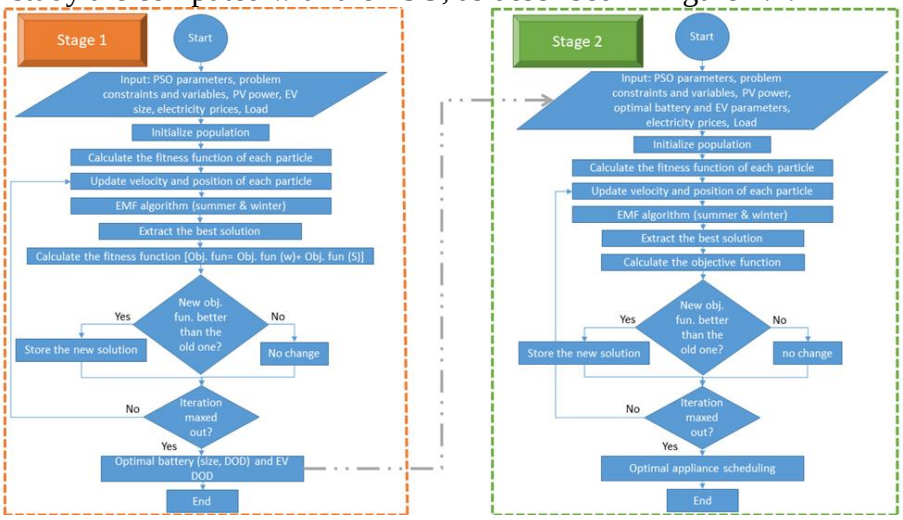

Figure 7.4: The Flow Chart of Optimization Strategy

The optimization process of this study consists of two key stages. The first stage optimizes the battery's size and DOD and EV's battery

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DOD. The goal is to identify optimal parameters that guarantee maximum energy cost reduction and sustainable utilization of the integrated system throughout the life cycle. The optimization strategy considers seasonal factors such as the summer and winter conditions for selecting the optimal parameters. Therefore, one value of each parameter appropriate for both seasons' conditions in terms of the objective function is obtained, which is about getting the minimum summation of the energy cost for winter and summer. Following the determination of optimal parameters for the ESS in the first stage of optimization, the study progresses to the second optimization stage. In this stage, the previously identified optimal parameters serve as inputs for scheduling household appliance operation times. The primary objective of this stage is to achieve the minimum energy cost by strategically managing the timing of household appliances, contributing to the overall efficiency and cost-effectiveness of the integrated system.

7.3.6. Case study

Figure 7.5 illustrates the daily power demand, along with the PV power generation and grid prices on both winter and summer days [REE, 2022a, 2022c]. The home energy consumption and user preference of a home in Spain are used as a case study obtained from a previous work Al Muala et al. [Al Muala et al., 2023].

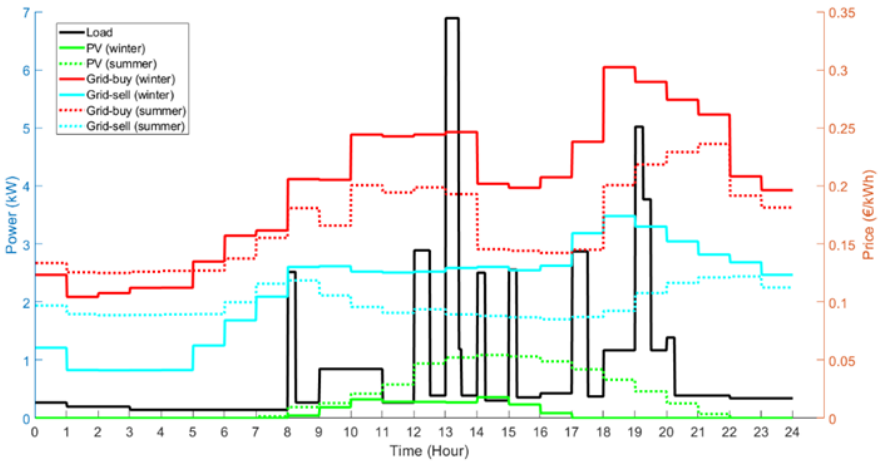

Figure 7.5: Case study data

The PV system of 1.125 kWp size is used [SECONDSOL, 2023], where the solar radiation data and temperature were collected from the database of PVGIS 5.2 and Open-Meteo, respectively [European Commission, 2022e; Open-Meteo, 2023]. For the optimization process of ESSs parameters, it was considered three battery systems with capacities of 2.4 kWh, 3.6 kWh, and 4.8 kWh, along with varying DOD levels (ranging from 50% to 100% in 10% increments). The data and prices for these batteries were sourced from [WccSolar, 2022]. Besides, a Kia e-Niro was selected as an EV with a 64 kWh battery capacity (7.2kW charger) and an efficiency of 171 Wh/km. The data and the battery replacement cost (EUR/kWh) of the EV were obtained from [Office of Energy Efficiency & Renewable Energy, 2023; Electrical Vehicle Database, 2024; Kia, 2024]. The daily EV trip is divided into two intervals: the first, from 8 a.m. to 12 p.m., with a distance of 34 km, and the second trip, from 3 p.m. to 6 p.m., with a distance of 48 km.

7.3.7. Sustainability factors analysis

7.3.7.1. ESSs lifetime

This study significantly emphasizes extending the batteries' lifespan in conjunction with maximum benefits, a goal tied to the count of charge/discharge cycles [Aghdam et al., 2018]. Throughout its operational life, each battery undergoes a series of cycles. A cycle is a process wherein the battery is charged to full capacity and discharged to empty. This process can occur in a single continuous interval or intermittently at irregular intervals. [Eq.7.50] and [Eq.7.51] are used to calculate the expected lifetime of the ESSs (battery and EVs).

$$ESS_{daycycles} = \frac{\sum_1^{1440} P_{ESS}^{ch}(t) * \Delta t + \sum_1^{1440} P_{ESS}^{dis}(t) * \Delta t}{E_{ESS}} \quad \text{[Eq.7.50]}$$

$$ESS_{life} = \frac{N_{cycle,ESS}}{ESS_{daycycles} * d_y} \quad \text{[Eq.7.51]}$$

Where $ESS_{daycycles}$ means the number of charging/discharging cycles throughout the day of ESS, whether for battery or EV. $P_{ESS}^{ch}(t)$, $P_{ESS}^{dis}(t)$ the charged/discharged power to/from the ESS (kWh) at each

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time slot *t*, respectively. E_{ESS} represents the nominal energy of the ESS (kWh), ESS_{life} denotes the expected ESS lifetime (years), $N_{cycle,ESS}$ the number of ESS cycles, which is calculated using Equation (32), and d_y the total days within a year.

7.3.7.2. CO_2 emissions

Moving towards local RES and implementing efficient HEMSs provides a viable strategy for curbing the adverse environmental and health effects linked to fossil fuel power plants, ultimately leading to a reduction in CO_2 emissions. According to the European Environment Agency (EEA), the CO_2 emission intensity I_{CO_2} directly correlates with electricity generation, which in Spain is estimated to be 0.177 ($kgCO_2/kWh$) in 2020 [EEA, 2023a]. Consequently, the CO_2 emissions can be calculated using [Eq.7.52].

$$CO_2 = I_{CO_2} * \sum_{t=1}^{1440} \left(P_{gth}(t) + P_{gtb}(t) + P_{gtev}(t)\right) * \Delta t \quad \text{[Eq.7}$$

Where CO_2 is the amount of CO_2 emission produced from the energy consumed in the home ($kgCO_2$) at each time slot *t*.

7.3.7.3. The integrated energy system contribution

Implementing sustainable practices involves optimizing the management of energy resources by utilizing them efficiently during their lifetime, which is what our proposed system aims to do. On the other hand, HECs express valid economic concerns when considering the installation of solar panels and batteries. However, consumers often weigh these upfront costs against the potential long-term benefits and return on investment. For that, in this study, careful consideration was given to the installation costs associated with the integrated system. We proposed an efficient HEMS to maximize financial benefit throughout its lifecycle relative to installation costs.

[Eq.7.53-55] calculate the daily contribution of each energy system in reducing the energy cost, whereas [Eq.7.56-58] calculate the net contribution during the system's lifetime. This approach would

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exemplify a real cost reduction compared to the installation cost, encouraging HECs to install local energy systems and optimize their energy consumption patterns.

$$PV_{con.} = \sum_{t=1}^{1440} (P_{pvth}(t) * (Grid_{price}^{buy}(t) - LCOE_{pv}) + P_{pvtg}(t) * (Grid_{sell}(t) - LCOE_{pv})) * \Delta t \quad \text{[Eq.7.53]}$$

$$B_{con.} = \sum_{t=1}^{1440} (P_{bth}(t) * \left(Grid_{price}^{buy}(t) - B_{price}^{overall}(t)\right) + P_{btg}(t) * (Grid_{sell}(t) - B_{price}^{overall}(t))) * \Delta t \quad \text{[Eq.7.54]}$$

$$EV_{con.} = \sum_{t=1}^{1440} (P_{evth}(t) * \left(Grid_{price}^{buy}(t) - EV_{price}^{overall}(t)\right) + P_{evtg}(t) * (Grid_{sell}(t) - EV_{price}^{overall}(t))) * \Delta t \quad \text{[Eq.7.55]}$$

$$PV_{con.}^{lifecycle} = PV_{con.} * PV_{life} \quad \text{[Eq.7.56]}$$

$$B_{con.}^{lifecycle} = B_{con.} * B_{life} \quad \text{[Eq.7.57]}$$

$$EV_{con.}^{lifecycle} = EV_{con.} * EV_{life} \quad \text{[Eq.7.58]}$$

Where $PV_{con.}$, $B_{con.}$, and $EV_{con.}$ represent the total daily contribution of the PV, battery, and EV (EUR), respectively. $PV_{con.}^{lifecycle}$, $B_{con.}^{lifecycle}$, and $EV_{con.}^{lifecycle}$ the total contribution of the PV, battery, and EV (EUR), respectively. PV_{life} represents the estimated PV system lifetime, which is 25 years [IRENA et al., 2016]. B_{life}, EV_{life} the estimated battery and EV lifetime, which are calculated using [Eq.7.50] and [Eq.7.51].

7.3.7.4. Energy saving

The dynamics of ESS losses and costs contribute to assessing the overall sustainability of energy systems. Achieving sustainability in this context involves minimizing losses during the charging and discharging

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processes, optimizing the lifetime of batteries, and ensuring a balance between economic benefits and energy saving. This approach ensures that energy systems meet economic objectives and align with sustainable practices. Therefore, [Eq.7.59-61] are formulated to quantify the energy losses and associated costs, providing a comprehensive assessment of the proposed system.

$$ch_{losses}(t) = P_B^{ch}(t) + P_{EV}^{ch}(t) * \frac{1-\mu}{\mu} * \Delta t \quad \text{[Eq.7.59]}$$

$$dis_{losses}(t) = P_B^{dis}(t) + P_{EV}^{dis}(t) * (1-\mu) * \Delta t \quad \text{[Eq.7.60]}$$

$$\begin{aligned} ESS_{LC}(t) = {} & [(P_{pvtb}(t) + P_{pvtev}(t)) * \frac{1-\mu}{\mu} * LCOE_{pv} * \Delta t] \\ & + [(P_{gtb}(t) + P_{gtev}(t)) * \frac{1-\mu}{\mu} * Grid_{price}^{buy}(t) \\ & * \Delta t] + [P_{btev}(t) * \frac{1-\mu}{\mu} * B_{price}^{overall}(t) * \Delta t] \\ & + [P_{evtb}(t) * \frac{1-\mu}{\mu} * EV_{price}^{overall}(t) * \Delta t] \\ & + [(P_{bth}(t) + P_{btg}(t)) * (1-\mu) * B_{price}^{overall}(t) \\ & * \Delta t] + [(P_{evth}(t) + P_{evtg}(t)) * (1-\mu) \\ & * EV_{price}^{overall}(t) * \Delta t] \end{aligned} \quad \text{[Eq.7.61]}$$

Where $ch_{losses}(t)$, $dis_{losses}(t)$ are the ESS energy losses (kWh) due to the converter efficiency during the charging and discharging intervals at each time slot *t*, respectively. $ESS_{LC}(t)$ represents the cost of energy losses (EUR) associated with the ESSs charging and discharging process at each time slot *t*.

7.4. RESULTS

The optimization problem is solved using the PSO algorithm with a population size of 100 and 200 iterations. Simulations are implemented using MathWorks MATLAB R2021a installed on Intel(R) Core(TM) i7-3520M CPU @ 2.90GHz and 8 GB RAM with Windows 10 Pro. Four scenarios for summer and winter conditions, detailed in Table 7.1,

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are simulated to evaluate the performance of the EFMSA and the proposed optimization strategy.

Table 7.1: Simulation Scenarios

Scenario	PV	Battery	EV	Grid	EFMSA	Optimizing ESS Parameters	Household Appliance Scheduling
1	×	×	✓	✓	×	×	×
2	✓	✓	✓	✓	✓	×	×
3	✓	✓	✓	✓	✓	✓	×
4	✓	✓	✓	✓	✓	✓	✓

7.4.1. First scenario

In this scenario, the main grid fulfills the home energy consumption, with a total daily demand of 18.464 kWh. Additionally, the main grid charges the EV's battery assuming the EV's DOD is 90%, using Equations (21) and (32), the LCOS of the EV's battery is equal to 0.033 EUR/kWh with 4,750 cycles. Table 7.2 describes the results of the first scenario.

Table 7.2: The simulation results of the first scenario

	Winter	Summer
Cost (EUR)	6.620	5.723
Grid Imported Energy (kWh)	90.264	89.053
CO_2 Emissions ($kgCO_2/kWh$)	15.976	15.762
Energy Losses (kWh)	4.291	4.230
Energy Loss Cost (EUR)	0.595	0.587
EV lifetime (Years)	9.230	10.401

7.4.2. Second scenario

In this scenario, the PV, battery, and EV are integrated into the HEMS, where the EFMSA is implemented to achieve optimal energy flow.

Random ESSs parameters are assumed to evaluate the ESSs parameters optimization process by considering a battery size of 4.8 kWh and a DOD of 80%, while a DOD of 90% was considered for the

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EV's battery. It is found that the LCOS and life cycle of the battery are 0.076 EUR/kWh and 5,757 cycles, respectively. Likewise, the LCOS and life cycle of the EV's battery are 0.033 EUR/kWh and 4,750 cycles, respectively. Table 7.3 describes the results obtained considering the second scenario. Figures 7.6 and 7.7 present the system's energy balance for winter and summer seasonal conditions.

Table 7.3: The simulation results of the second scenario

	Winter	Summer
Cost (EUR)	5.210	5.083
Grid Imported Energy (kWh)	40.725	56.264
CO_2 Emissions ($kgCO_2$/kWh)	7.208	9.958
Energy Losses (kWh)	3.535	3.757
Energy Loss Cost (EUR)	0.462	0.517
EV lifetime (Years)	13.141	11.085
PV Daily Financial Contribution (EUR)	0.271	0.530
Battery Daily Financial Contribution (EUR)	0.226	0
EV Daily Financial Contribution (EUR)	1.019	0.337
Total Financial Contribution (EUR)	1.516	0.867

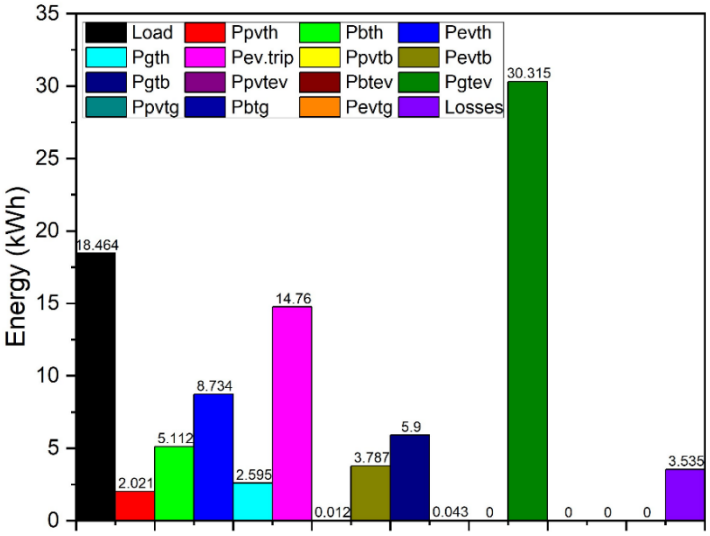

Figure 7.6: Energy balance for the second scenario in winter

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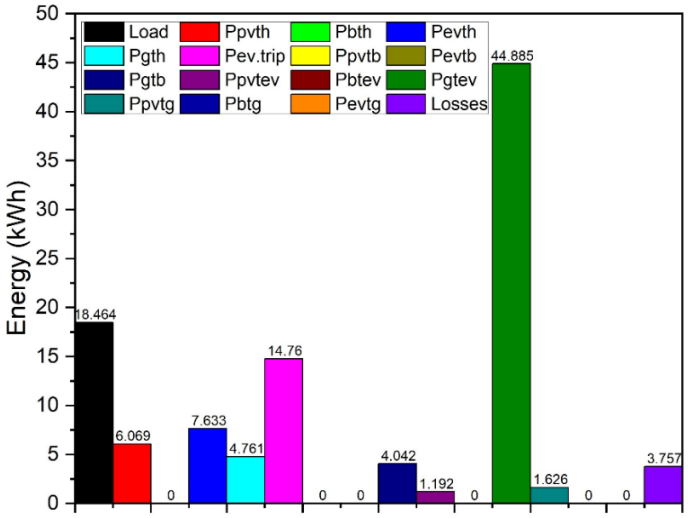

Figure 7.7: Energy balance for the second scenario in summer

7.4.3. Third scenario

In this scenario, the optimization of ESSs parameters is implemented using PSO. The results reveal that the optimal parameters for both winter and summer conditions are a battery size of 2.4 kWh with a DOD of 50%, and a DOD of 50% for the EV.

Table 7.4: The simulation results of the third scenario

	Winter	Summer
Cost (EUR)	4.905	4.831
Grid Imported Energy (kWh)	36.946	47.520
CO_2 Emissions ($kgCO_2$/kWh)	6.539	8.411
Energy Losses (kWh)	3.179	3.389
Energy Loss Cost (EUR)	0.387	0.459
EV lifetime (Years)	19.053	17.363
PV Daily Financial Contribution (EUR)	0.271	0.530
Battery Daily Financial Contribution (EUR)	0.129	0.007
EV Daily Financial Contribution (EUR)	1.237	0.418
Total Financial Contribution (EUR)	1.637	0.955

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As a result, the LCOS and life cycle of the battery are 0.056 EUR/kWh and 12,397 cycles, respectively. For the EV, the LCOS and life cycles of its battery are 0.023 EUR/kWh and 12,397 cycles, respectively. Table 7.4 describes the results obtained from the third scenario. Figures 7.8 and 7.9 show the energy balance of the system for winter and summer conditions.

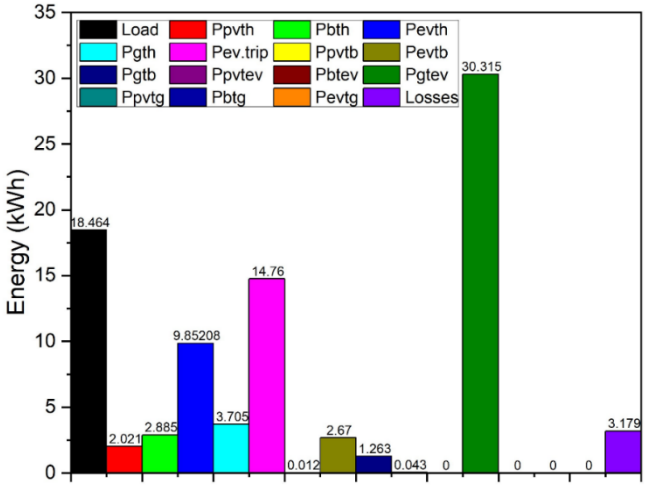

Figure 7.8: Energy balance for the third scenario in winter

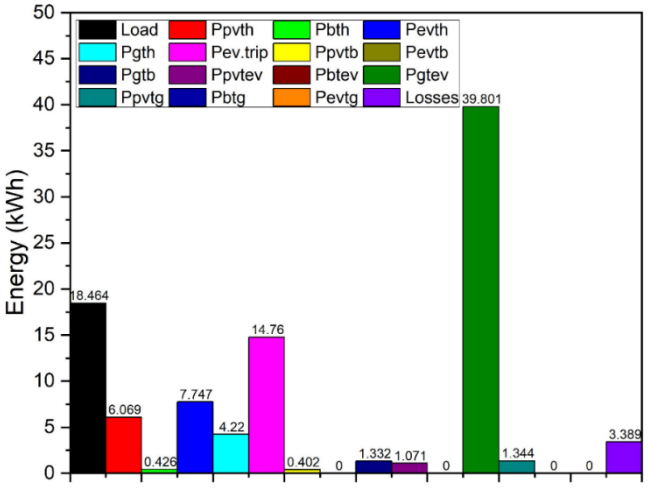

Figure 7.9: Energy balance for the third scenario in summer

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7.4.4. Fourth scenario

In this scenario, the household appliance scheduling is applied, where the optimized ESSs parameters serve as input for the optimization process. The findings and outcomes from the fourth scenario are comprehensively detailed in Table 7.5, providing a thorough overview of the results achieved. Figure 7.10 shows the convergence of the PSO for winter and summer. Figures 7.11 and 7.12 show the energy balance of the system for winter and summer. These visual representations contribute to a more holistic understanding of the optimization process and its implications in diverse climatic conditions.

Table 7.5: The simulation results of the fourth scenario

	Winter	Summer
Cost (EUR)	4.760	4.708
Grid Imported Energy (kWh)	36.364	47.879
CO_2 Emissions ($kgCO_2$/kWh)	6.436	8.474
Energy Losses (kWh)	3.143	3.284
Energy Loss Cost (EUR)	0.381	0.445
EV lifetime (Years)	19.120	17.687
PV Daily Financial Contribution (EUR)	0.267	0.631
Battery Daily Financial Contribution (EUR)	0.080	0
EV Daily Financial Contribution (EUR)	1.271	0.342
Total Financial Contribution (EUR)	1.618	0.973

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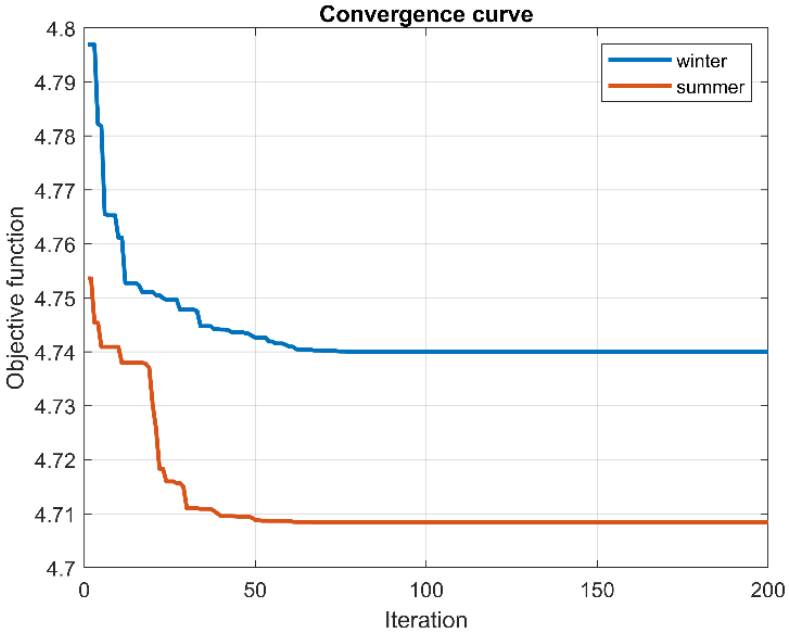

Figure 7.10: The convergence of the PSO for winter and summer scenarios

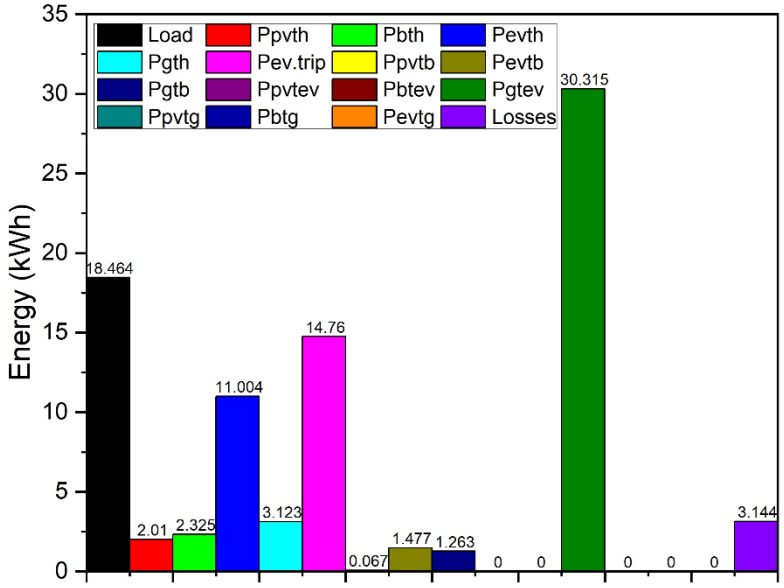

Figure 7.11: Energy balance for the fourth scenario in winter

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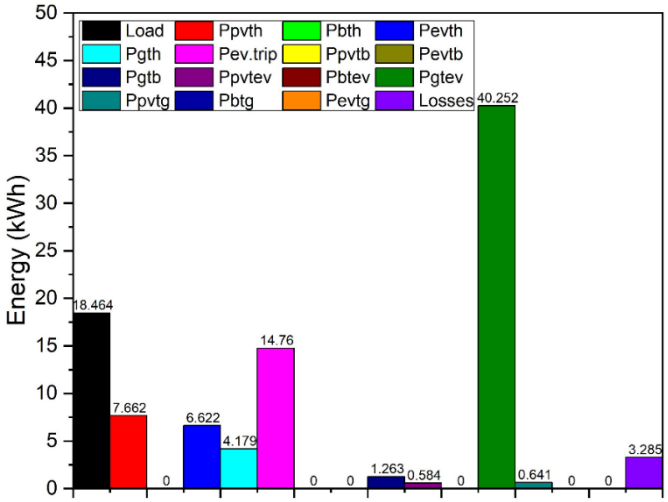

Figure 7.12: Energy balance for the fourth scenario in summer

7.5. DISCUSSION

7.5.1. Energy flow and energy usage prices

The EFMSA controls the energy flow in the integrated system, aiming to achieve maximum actual energy cost reduction. The fourth winter scenario is a representative example of discussing the optimal power flow to meet the energy consumption, as shown in Figure 7.13. Additionally, the third winter scenario is highlighted to discuss the battery and EV's energy exchange, see Figure 7.14.

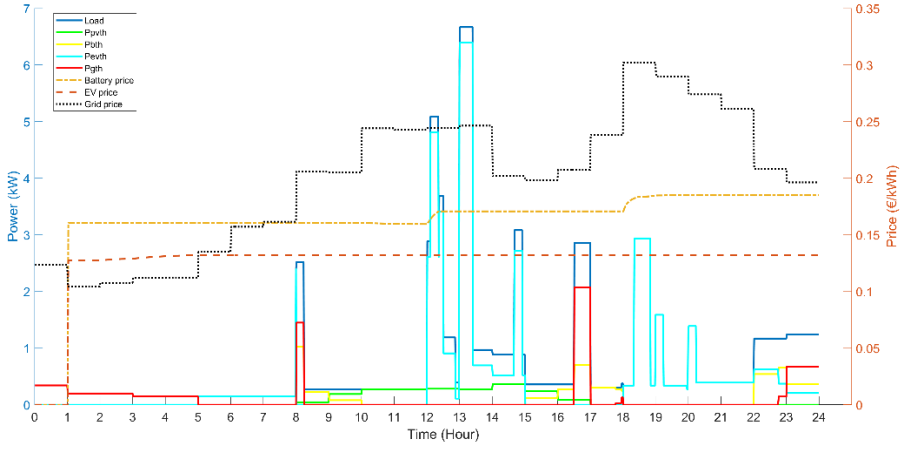

Figure 7.13: Power flow and energy prices of the fourth scenario in winter

In the event of excess PV generation, the PV system covers the load, as shown in the periods (10:00-12:00). The remaining excess energy is sent firstly to the EV in case it is connected to the system due to the low LCOS of the EV compared to the battery, so the stored energy will be used later with a lower price, ensuring higher energy cost reduction. While the EV is on a trip, excess PV generation is sent to the battery or the grid depending on the maximum financial option.

If PV falls short of meeting the load or during the absence of solar radiation at night, the EFMSA covers the remaining consumption using other available resources considering their energy usage cost. For example, in the periods (05:00-8:00, 12:00-15:00, and 18:00-22:00), the EV covered the remaining consumption since it had the lowest energy usage price. In the period (08:00-10:00), the battery covered the remaining consumption, where the EV is on a trip, and the grid price is higher than the battery's price. In the periods (00:00-05:00), the grid covers the remaining consumption due to its lower price, even though the battery or EV's battery has energy. In some cases, more than two energy systems covered the energy demand as illustrated in the periods (16:00-17:00 & 23:00-24:00).

Moreover, scenario three for winter is considered a representative example to discuss the battery and EV energy exchange dynamics, as detailed in Figure 7.14. The EV charged the battery in the period (12:00-12:51), where the amount of energy stored at this period is 1.279 kWh with a purchased price of 0.1883 EUR/kWh. This strategy is beneficial for cost reduction, where the battery can be discharged to the home in the upcoming periods as the grid price would be high and the EV would be on a trip (15:00-18:00) with a grid price ranging between 0.198 to 0.238 EUR/kWh. Similarly, the EV charged the battery intermittently for the same purpose during the period (18:00-22:07). However, there is no energy sent from the battery to the EV, which refers to the high battery energy usage cost, where it would not be beneficial for cost reduction. Moreover, due to the low grid sell price, no energy is sold from the battery and EV to the grid. The same charging strategy is established for charging the battery and EV's battery from the grid, considering the grid energy price during the upcoming periods. The proposed algorithm (EFMSA) achieves

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efficient energy flow within the integrated system, aligning with fluctuating energy prices and ensuring cost-effectiveness and sustainable utilization of the energy systems.

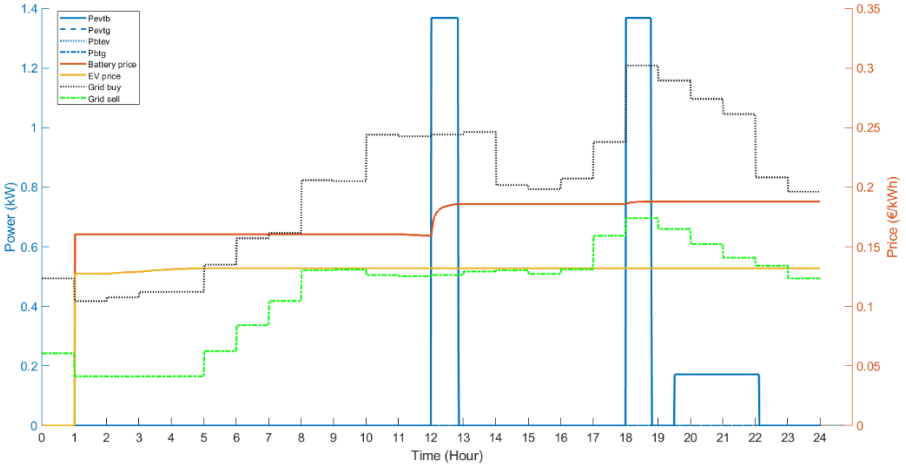

Figure 7.14: Battery and EV's battery energy exchange of the third scenario in winter

7.5.2. Energy cost

Table 7.6 outlines the simulation results of energy costs and reduction compared to the first scenario. The comparison results show the effectiveness of the proposed system in achieving maximum cost reduction, reaching 28% in winter and 17% in summer. By factoring in the installation and O&M costs, the cost reduction results provide household consumers with a clear insight into the advantages of adopting HEMS.

Table 7.6: The energy cost simulation

	Winter		Summer	
Scenario	Cost (EUR)	Cost Reduction (%)	Cost (EUR)	Cost Reduction (%)
1	6.620	-	5.723	-
2	5.210	21.299	5.083	11.182
3	4.905	25.906	4.831	15.586
4	4.74	28.398	4.708	17.735

Figures 7.15 and 7.16 illustrate the energy consumption with and without appliance scheduling for winter and summer, respectively. The operation time of household appliances is scheduled according to the availability of PV power, along with the battery, EV, and grid energy usage prices, which is reflected in the reduction of energy cost.

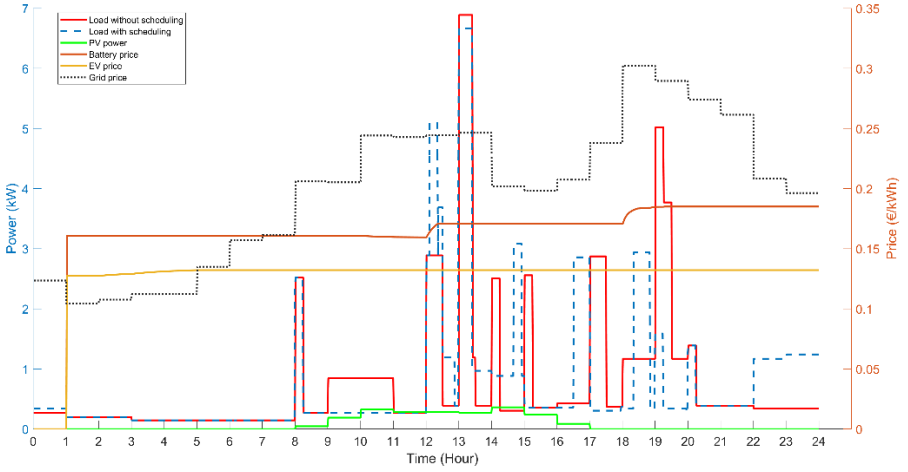

Figure 7.15: Energy consumption with and without scheduling in winter

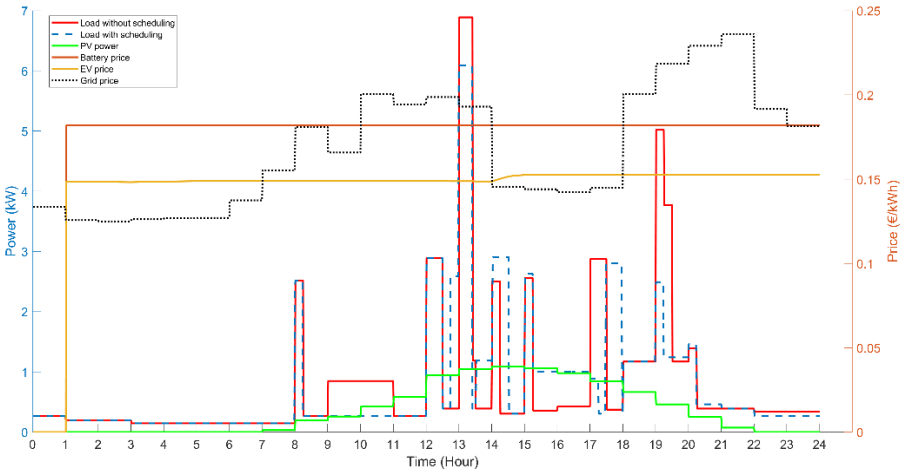

Figure 7.16: Energy consumption with and without scheduling in summer

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7.5.3. The ESS lifetime and energy losses

The study's outcomes shed light on the battery and EV's battery lifetimes and energy-saving aspects. Using the mathematical model detailed in section 7.3.7.4, Table 7.7 presents the simulation results of energy losses and their associated cost. In both winter and summer scenarios, the simulation results revealed valuable insights. The proposed system managed the operation time of the integrated system efficiently in terms of extending the lifetime and obtaining actual energy cost reduction.

The proposed system in the fourth scenario reduced the energy losses compared to the first scenario by 26.730 % and 22.340% in winter and summer, respectively. Consequently, the cost resulting from the energy losses is reduced by 35.966% and 24.190% compared to the first scenario in winter and summer, respectively.

Table 7.7: The simulation results of energy losses and energy losses cost

	Winter				Summer			
Scenario	Energy Losses (kWh)	Energy losses reduction (%)	Losses cost (EUR)	Losses cost reduction (%)	Energy Losses (kWh)	Energy losses reduction (%)	Losses cost (EUR)	Losses cost reduction (%)
1	4.291	-	0.595	-	4.230	-	0.587	-
2	3.535	17.618	0.462	22.352	3.757	11.182	0.517	11.925
3	3.179	25.914	0.387	34.957	3.389	19.881	0.459	21.805
4	3.144	26.730	0.381	35.966	3.285	22.340	0.445	24.190

Using the mathematical models detailed in sections 3.3.5 and 3.7.1, Table 7.8 shows the estimated lifetime of the EV's battery in summer and winter and the estimated battery lifetime in winter.

The proposed system in the fourth scenario achieved the most extended battery and EV lifetime. The EV's battery lifetime was extended compared to the first scenario by 107.144% in winter from 9.230 to 19.120 years, and 70.047% in summer from 10.401 to 17.687 years. Similarly, the battery lifetime was extended compared to the second scenario by 94.274% from 4.087 to 7.940 years in winter.

The utilization pattern of the battery differs from winter to summer. This variance can be attributed to the grid energy prices and LCOS of

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the battery and its energy usage cost, as well as the lack of battery charging amount from the PV, where the battery energy usage price was higher than the EV and grid energy usage prices. For that, the estimated battery lifespan in the summer scenario is undisclosed since the battery was not utilized to supply the energy demand, see Figures 7.7 and 7.12.

Table 7.8: The simulation results of the ESS lifetime

	Winter				Summer			
Scenario	EV lifetime (years)	EV lifetime extension (%)	Battery lifetime (years)	Battery lifetime extension (%)	EV lifetime (years)	EV lifetime extension (%)	Battery lifetime (years)	Battery lifetime extension (%)
1	9.230	-	-	-	10.401	-	-	-
2	13.141	42.374	4.087	-	11.085	6.576	-	-
3	19.053	106.425	5.967	44.999	17.363	66.934	-	-
4	19.120	107.144	7.940	94.274	17.687	70.047	-	-

This comprehensive evaluation offers valuable information for optimizing system parameters and operational strategies to enhance energy efficiency and extend the lifetime of the integrated energy system. Additionally, the proposed system affirms its capability to enhance operational longevity while minimizing energy losses across varied seasonal conditions.

7.5.4. The integrated energy system contribution

Through efficient integration of PV, battery, EV, and smart management, the system has demonstrated a capacity to optimize energy systems utilization, resulting in reduced energy costs and enhanced financial returns. The integrated energy system has exhibited commendable financial contributions over its operational lifetime, as inferred from the results shown in Table 7.9. The proposed system achieved the maximum economic benefits compared to the installation cost of the integrated energy system, with a daily contribution of 1.619 EUR in winter and 0.973 EUR in summer. Besides, using the mathematical model detailed in section 7.3.7.3 alongside the calculated battery and EV's battery lifetimes presented in the previous section

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7.5.3, the financial contribution of the integrated system throughout its operational lifetime was calculated, as summarized in Table 7.9. The results show an overall financial contribution of 11,546 EUR in winter conditions and 7,973 EUR in summer conditions, with an average contribution of 9,759 EUR during the integrated system operational lifetime. The EV's battery contributes more due to its low energy usage cost and high stored capacity. The PV system contribution shows better results in summer than winter, influenced by the amount of solar radiation and grid prices. The battery provides a financial contribution in winter due to the high grid prices and the amount of energy stored in it from the PV. However, the battery has the lowest contribution due to its high LCOS and not operating in the summer scenario.

These nuanced variations underscore the system's dynamic responsiveness to seasonal and contextual factors, optimizing economic benefits over its operational lifespan. As a result, the financial gains compared to the installation costs are further enhanced by extending the lifespan and enhancing the operation of energy systems including PV, batteries, and EVs, contributing to long-term cost savings and overall economic sustainability.

Table 7.9: The simulation results of financial contribution

	Winter					Summer				
Scenario	PV (EUR)	Battery (EUR)	EV (EUR)	Daily (EUR)	Operational lifetime (EUR)	PV (EUR)	Battery (EUR)	EV (EUR)	Daily (EUR)	Operational lifetime (EUR)
1	-	-	-	-	-	-	-	-	-	-
2	0.271	0.226	1.019	1.516	7,705	0.530	0	0.337	0.867	6,203
3	0.271	0.129	1.237	1.637	11,363	0.530	0.007	0.418	0.955	7,546
4	0.267	0.080	1.271	1.618	11,546	0.631	0	0.342	0.973	7,973

7.5.5. CO_2 emissions

Table 7.10 shows the simulation results of the CO_2 emissions from importing energy from the grid, revealing key insights into the environmental impact and providing a comprehensive overview of CO_2 emission reduction under varying conditions. The proposed system achieved a notable reduction in importing energy from the grid, resulting in a reduction of 59.713% and 46.234% in CO_2 emissions

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compared to the first scenario in winter and summer, respectively. In particular, the trend indicates that adopting PV, batteries, and EVs, coupled with smart home management, contributes to a substantial decrease in reliance on traditional carbon-intensive energy generation. The observed reduction in both winter and summer suggests that the benefits are not confined to specific seasons, highlighting the system's potential to contribute substantially to environmental sustainability throughout diverse seasonal conditions while enhancing the resilience of the household energy infrastructure.

Table 7.10: The simulation results of CO_2 emissions

	Winter		Summer		Average
Scenario	CO_2 ($kgCO_2/kWh$)	CO_2 reduction (%)	CO_2 ($kgCO_2/kWh$)	CO_2 reduction (%)	CO_2 reduction (%)
1	15.976	-	15.762	-	-
2	7.208	54.882	9.958	36.819	45.850
3	6.539	59.068	8.411	46.638	52.853
4	6.436	59.713	8.474	46.234	52.973

To sum up, besides its environmental benefits, the proposed system presents promising economic advantages that can translate into long-term cost savings for households. This dual impact positions the system as a compelling solution for households aiming to minimize their carbon footprint and achieve economic efficiency in their energy consumption practices. The decentralized and diversified nature of the system minimizes vulnerability to fluctuations in energy grids, contributing to increased energy security. This multi-faceted approach underscores the holistic benefits of the proposed system, making it a comprehensive and resilient solution for households navigating the complex interplay of environmental, economic, and energy security considerations.

7.6. CONCLUSION

This paper introduced an effective home energy management system for smart homes that integrates PV, batteries, and EVs. An energy flow

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management algorithm was developed to control modes of EV2G, EV2B, EV2H, B2G, B2EV, B2H, PV2H, PV2B, PV2EV, PV2G, G2H, G2B, and G2EV. Additionally, it introduced an optimization strategy using PSO to obtain optimal parameters for the battery (DOD & size) and EV's battery (DOD) and schedule the household appliances. The PV, battery, and EV energy usage cost models were formulated and introduced into the optimization process, considering each system's installation costs and lifecycle, resulting in an actual cost reduction compared to the installation costs and ensuring sustainable utilization of the integrated system throughout its operational lifetime. Four scenarios were simulated considering winter and summer weather conditions.

The proposed system aimed to reduce the actual energy cost, extend the ESSs lifetime, reduce energy losses, reduce CO_2 emissions, and maximize the financial returns from in-stalling the PV, battery, and EV at home. The results revealed that the proposed system achieved the study's objectives and its capability to deal with varied seasonal conditions, energy price variations, user preferences, and sustain energy systems utilization. Additionally, the results encourage household consumers seeking to reduce their environmental impact and increase their financial returns associated with investing in PV, battery, and EV energy systems at home, resulting in promoting sustainable and efficient energy practices at the household level.

In the future, the authors propose expanding the scope of the study by incorporating several homes in diverse geographical regions (energy demand patterns), considering monthly weather variations (seasonal dynamics), and investigating and optimizing various parameters of the integrated energy system to identify the most practical options for residential applications (scalability/replicability).

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CHAPTER 8. SOCIAL AWARENESS ABOUT ENERGY TRANSITION AND SUSTAINABILITY: THE ROLE OF VIDEO GAMES

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

- Title: Social Awareness About Energy Transition And Sustainability: The Role Of Video Games
- Authors: Al Muala, Z. A.; Sansó-Rubert Pascual, D.; Bello Bugallo, P.M.
- Publisher: HAL open science
- Book chapter: Simulation and Gaming for Social and Environmental Transitions (423-431)
- ISBN:979-10-415-2760-1
- Year of publication: 2023
- Contribution of the doctoral student: contribution to the development of the research and writing the paper.
- Authorization of the journal/publisher for the use of the publication in the doctoral thesis. URL: https://hal.science/?lang=en

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SUMMARY

Energy security and climate change concerns have emerged due to the world population growth and increasing energy demand. This requires taking measures to address these concerns, especially social awareness, as HECs can contribute to enhancing energy transition and sustainability. Besides, Video games play a key role as a tool for education, changing human behavior, and enjoyment. This study aims to investigate the influence of playing video games on HECs' awareness of energy transition and sustainability. A questionnaire was designed to evaluate the players' awareness of energy security, the environmental effect of using energy, the development of the renewable energy sector, and the economic benefit of managing energy consumption before playing a game. Moreover, another questionnaire to evaluate how their awareness was affected by playing a game was designed. To do so, The Power the Grid game was taken as a case study, and then ten experts in playing video games were invited to play the game. The players' awareness was compared before and after playing the game; the results showed that the players' awareness increased about energy issues, the role of HECs in the importance of managing energy because of its contribution to enhancing energy security, supporting the renewable energy sector, reducing the environmental impact of energy usage, and understanding the working principle of the smart meter. Based on the results, a set of proposals to expand the game's options and boost the players' awareness have been presented, especially about DR programs.

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8.1. INTRODUCTION

Sustainability refers to the responsible use of resources without compromising the ability of future generations to meet their own needs. This includes promoting renewable energy, economic development, and maintaining the environment. The world witnessed progress in the energy transition from dependence on fossil fuel to RESs, as the share of renewable energy in total final energy consumption in Europe increased from 10% to 22% between 2005 and 2021 [EEA, 2023b], which helped in reducing the annual CO_2 emissions by 19% [Ritchie et al., 2023].

However, with the increase in population and the technological development that leads to an increase in energy consumption, measures need to be taken to contribute more to increasing the penetration of RES into the electrical grid [Avtar et al., 2019]. As it is known, RES is primarily dependent on weather conditions. For that, the problem of balance between generation and energy demand emerged and led to calls for regulatory measures to solve this problem in case we want to increase renewable energy generation plants and enhance their penetration into the electrical grid. Among these measures is the involvement of energy consumers play a role in the process of enhancing energy transition and sustainability.

As a result, SG and the concept of DR have appeared, as decision-makers established an electric tariff system that would contribute to managing energy consumption in line with the state of the electrical grid (supply and demand), here data exchange between and supply and demand side is enabled [Siano, 2014]. In addition, the residential sector is one of the largest energy-consuming sectors, and hence managing energy consumption in the residential sector would contribute to improving energy security and the penetration of more RES into the electrical grid, thus reducing the environmental impacts of energy use.

Several studies have indicated the factors that affect consumers to make them manage energy consumption, participate in DR programs, and enhance the sustainability of the renewable energy sector. It was found that the economic factor in terms of financial income by reducing the cost of the electricity bill contributes significantly to making the consumer participate in DR programs [Gyamfi et al., 2011; Ferreira et

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al., 2018; Tantau et al., 2021]. It was also found that reducing carbon emissions would encourage them to participate in DR programs [Gyamfi et al., 2011; Ferreira et al., 2018; Tantau et al., 2021; Oprea et al., 2022]. Contributing to energy security is also an essential factor that plays a key role in participating in DR programs [Siano, 2014; Tantau et al., 2021; Oprea et al., 2022].

In addition, consumers' awareness of the importance of the sustainability and development of the renewable energy sector plays a positive role in participating in DR programs [Robert et al., 2018; Abdolmaleki et al., 2021; Tantau et al., 2021; Oprea et al., 2022]. Moreover, installing devices that provide consumers with information about their consumption and electricity prices, such as smart meters increases participation in DR [Tantau et al., 2021; Ferreira et al., 2018; Li et al., 2019; Oprea et al., 2022]. Therefore, participating energy consumers in DR programs requires efforts to increase social awareness.

Nowadays, video games have become widespread worldwide and they have become a wide part of the lives of almost all children and adolescents, and a vibrant medium of human self-expression [Egenfeldt-Nielsen et al., 2020]. In addition to entertainment, video games can be used for educational and developing skills, especially in decision-making [De Aguilera et al., 2003; Cheng et al., 2015; Hamari et al., 2016]. On the other hand, video games contribute to the social aspect through friendships, and therefore it is likely that people who play beneficial games have a favorable impact on others [Trepte et al., 2012].

Besides, in game designing and development, the developers must have feedback from the players to know their interests and the quality of video games, especially at the beginning. Developing games in line with advancements in real life is essential, and paying attention to game content is a priority. However, some of them are still in the stage of growth and development. Alongside this, the DR part in energy games is uncommon, and the utilization of energy-smart tools in video games is still limited [Schweiger et al., 2020].

As a result, it is necessary to study the role of DR in video games by developing a viable pathway. Then, we may anticipate that

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incorporating this concept into games will help to clarify the importance of participation in DR and managing energy consumption in addition to their enjoyment of playing video games. Therefore, the purpose of this study is to investigate the influence of playing video games on HECs' awareness of their essential role in managing energy consumption to enhance energy transition and sustainability.

8.2. MATERIALS AND METHOD

To discuss how playing a game affects people's awareness of energy transition and sustainability together and the growth of the renewable energy sector, this study implements the following methodology: exploring the factors that might affect HECs to manage their energy consumption, searching for a video game whose content includes energy production and consumption options as a case study for this work, creating questionnaires to investigate the influence of playing a video game on awareness of energy issues, suggesting tools based on the results to be added to the selected game regards increasing social awareness.

8.2.1. The game selection

To choose a game as a case study for this work, it has been searching for a video game that provides access and control in the energy management process and illustrates the importance of energy consumers' role in energy transition and sustainability. Google was used to find the best-fitted game (by searching in digital platforms that serve as PC game distributors and gaming forums).

To understand better how a video game works, YouTube was used to watch videos posted by designers. This study uses a game as an example to understand better, how video games contribute to society's changing energy consumption behavior. Power the Grid Game is a real-time-strategy tycoon game that simulates the power grid. This game offers multiple power plants to cover the energy demand during the day.

The players' role is to keep balancing between supply and demand, so the players have to observe the state of the production and demand at each time and for the coming hours too, to predict the optimal amount of energy that needs to be produced. Moreover, it offers to buy and

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establish renewable energy plants. As long as the players keep the grid stable, they earn money, where the money needs to be spent wisely on establishing the power plants and buying fuel and coal to operate the plants. Besides, in the case of a power shortage, the players have a specific time to recover the grid stability by operating more power plants. With time, the city is developing and expanding, and thus the energy demand increase. In the end, the players seek to establish a 100% renewable energy system that covers the energy demand during the day.

8.2.2. Questionnaires

The investigation procedure of this work (Figure 8.1) is as follows: two questionnaires were created; the first questionnaire was conducted before the participants played the game, aiming to measure their awareness about energy issues. The questions were simple to give an impression of the participating players' knowledge.

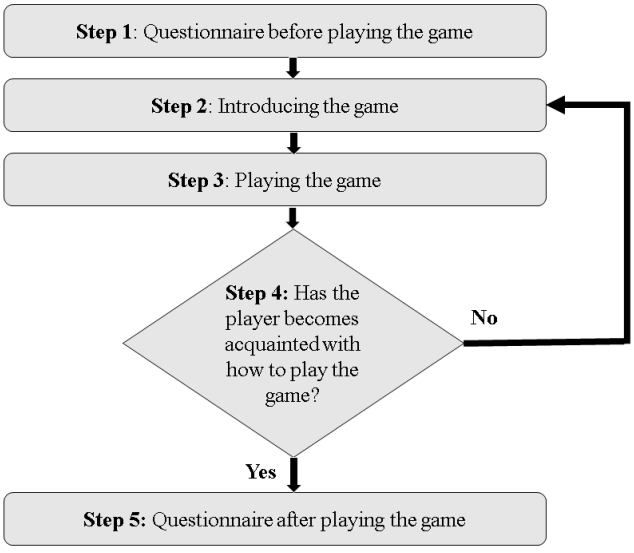

Figure 8.1: The flow chart for the procedure of the questionnaires

Before playing the game, a detailed explanation of the game rules through a lecture in a computer lab where the players play the game is given. Then, the players play the game several times until they become

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familiar with the game's options thus leads them to complete the mission. Meanwhile, the players can communicate with the supervisor to clarify any doubts about the game's rules. Where the duration of the game and rounds depends on the performance of the players, the players who become familiar with the game's rules complete the mission in a shorter time than the players who are not familiar with the game's rules. This is reflected in the results, where more players' familiarity with the game provides more realistic results. After that, the second questionnaire is conducted after completing playing the game to measure the effect of playing this game on increasing their awareness about energy issues and compare it with the results of the first questionnaire as shown in Table 8.1. In the second questionnaire, the questions were asked in more detail to obtain more accurate results, assuming that the participating players' knowledge of the electrical system operations increased after playing the game.

Table 8.1: Questionnaire form

Stage	Nº	Question
Before playing the game	Q1	My knowledge level about energy issues (availability, affordability, and efficiency) is extensive
	Q2	I think that HECs can contribute to energy security
	Q3	I think that HECs can contribute to developing the renewable energy sector
	Q4	I think that HECs can contribute to improving the environment
	Q5	I think that HECs can contribute to reducing electricity prices
	Q6	I think I am knowledgeable about the function of the smart meter and that it can contribute to managing energy consumption effectively
After playing the game	Q7	I have gained a better understanding of energy issues (availability, affordability, and efficiency) after playing the game

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Stage	Nº	Question
	Q8	I think that HECs can contribute to energy security (such as grid stability, and uninterrupted availability of energy sources) in the short and long term
	Q9	I think that HECs can contribute to increasing the penetration of renewable energy plants into the main grid and reducing fossil fuel plants
	Q10	I think that HECs can contribute to reducing the environmental impact of using energy, such as by reducing the CO_2 emissions
	Q11	I think that HECs can contribute to reducing electricity prices (demand side and supply side)
	Q12	I think that smart meters can provide valuable information about the demand and supply state, which contributes to managing energy consumption effectively
	Q13	I think that HECs' awareness of the importance of managing their energy consumption will improve after playing this game

After that, a discussion to gain a deeper understanding of the players' point of view about adding some features to the game is conducted that would contribute to players' awareness of energy issues. In addition to bringing more enjoyment to the game. The survey of 13 questions divided into two questionnaires with a 7-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree) was answered by the participants.

8.2.3. Participants

This work is a primary study; the participating players were ten Ph.D. students from the Faculty of Science at La Universidade de Santiago de Compostela. They have selected based on their tendency to play video games regularly, not sporadically. 30% of the participants' players have experience playing energy video games, and their average age was 29.

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8.3. RESULTS AND DISCUSSION

8.3.1. The depth of players' knowledge of energy issues before playing the game

This section describes how knowledgeable the participating players are about energy issues, the environment, and the renewable energy sector before playing the Power the Grid game. Figure 8.2 shows the percentage of answers to questions 1 to 6. In the first question, which measures the knowledge of the participating players about energy issues, it is clear that only 10% of the players have sufficient knowledge and 10% have little knowledge, while the rest show a low level of knowledge. Similarly, the answers to the second question indicate that the players' knowledge of HECs' role in enhancing energy security is limited. Regarding the role of HECs in contributing to the development of the renewable energy sector, the answers to the third question indicate that the players show a better understanding compared to the answers to the previous questions. However, their knowledge is still somewhat low.

Concerning contributing to improving the environment, the results from the answers to the fourth question indicate that there is a lack of awareness of the role of HECs in enhancing the environment, as 60% of the participants do not have knowledge (10% strongly disagreed and 30% disagreed and 20% are undecided). As discussed earlier, HECs play a crucial role in reducing electricity prices. However, the answers to the fifth question indicate that only 40% somewhat agreed and 10% strongly agreed. Moreover, the results show a lack of awareness of the participating players involved in the working principle of the smart meter and its role in energy management at home; 10% showed that they agreed somewhat with the importance of the smart meter, and 10% agreed strongly.

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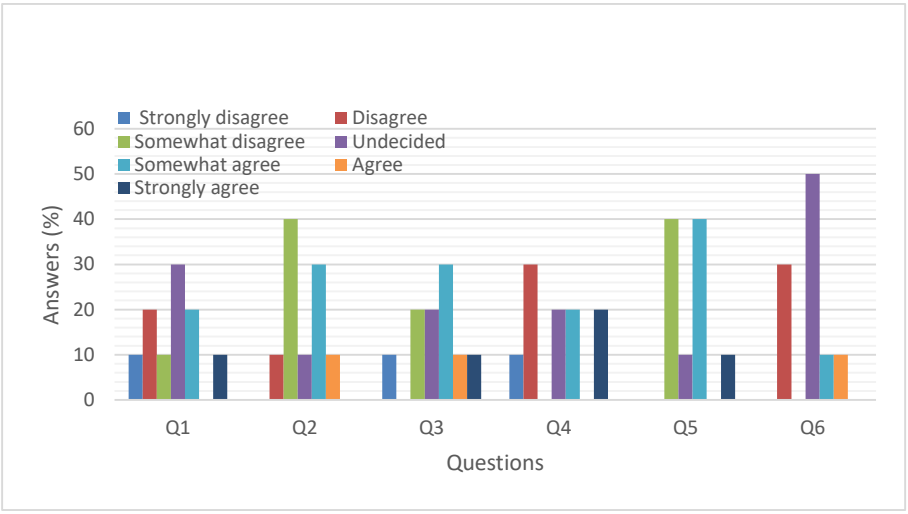

Figure 8.2: Distribution of the participating players' answers to the first questionnaire

8.3.2. The effect of playing the Power the Grid game on players' awareness of energy issues

Before the participating players started playing the Power the Grid game, the game rules, constraints, and tools were explained in detail. The second questionnaire was conducted, which contains seven questions from 7 to 12 to measure players' awareness after playing the game. The results of the level of players' awareness after playing the game were compared to the results of the last section to understand the impact of playing the game on the players' awareness.

It is clear from Figure 8.3 that the awareness of the players has increased after playing the game. As their awareness about energy issues increased, 30% indicated that they have little knowledge, 30% have good knowledge, and 10% have sufficient knowledge. Whereas before playing the game, only 10% had comprehensive knowledge, and 10% had low knowledge of energy issues. Likewise, the answers to the Q8 indicated an increase in participating players' awareness of the essential role of HECs in promoting energy security; 20% strongly agreed with this, 30% agreed, and 10% agreed somewhat, while before playing the game only 10% agreed, and 30% somewhat agreed.

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The results also indicated an increase in awareness about the essential role of HECs in promoting the renewable energy sector, where all players agreed on their crucial role in enhancing the renewable energy sector and reducing fossil fuel power plants. Whereas some of them did not agree with that before playing the game. Before playing the game, the participating players showed some awareness about the role of HECs in enhancing the environment. However, after playing the game, 90% of the participating players (50% agreed, 40% strongly agreed) agreed that HECs contribute to reducing the environmental impact of using energy.

As known, HECs contribute to reducing electricity prices by managing their energy consumption based on the grid status and the amount of energy generated from renewable energy plants and thus contribute to reducing the electricity bill and reducing fossil fuels used by the supplier. Before playing the game, 50% of the participating players showed a lack of awareness of this aspect (disagreeing and undecided). However, after playing the game, it was found that only 10% are unaware of this aspect, which indicates that the game has a significant effect in increasing awareness. The smart meter is crucial in energy management, as it displays the electricity consumption and prices, moment by moment so that the consumer can manage energy easily.

In the Power the Grid game, the electricity consumption is shown, which contributes to helping the consumer understand the working principle of the smart meter in reality. Before starting the game, the participating players showed an insufficient understanding of the working principle of the smart meter and the importance of its role. However, after the game, they all indicated that they agreed with the importance of the smart meter in energy management and that they became aware of its working principle (70% strongly agreed, 20% agreed, and 10% somewhat agreed).

Concerning the role of playing the Power the Grid game in improving the players' awareness of energy issues, question 13 was asked. The participating players showed their complete conviction that the game had an influential role in raising their awareness about the importance of energy management due to its contribution to enhancing

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energy security, the environment, and the renewable energy sector; 70% strongly agreed, 20% agreed, and 10% somewhat agreed.

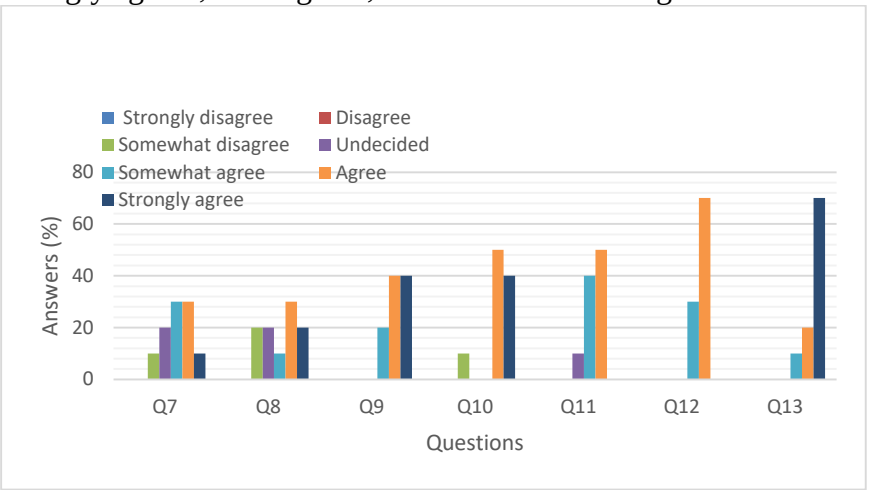

Figure 8.3: Distribution of the participating players' answers to the second questionnaire

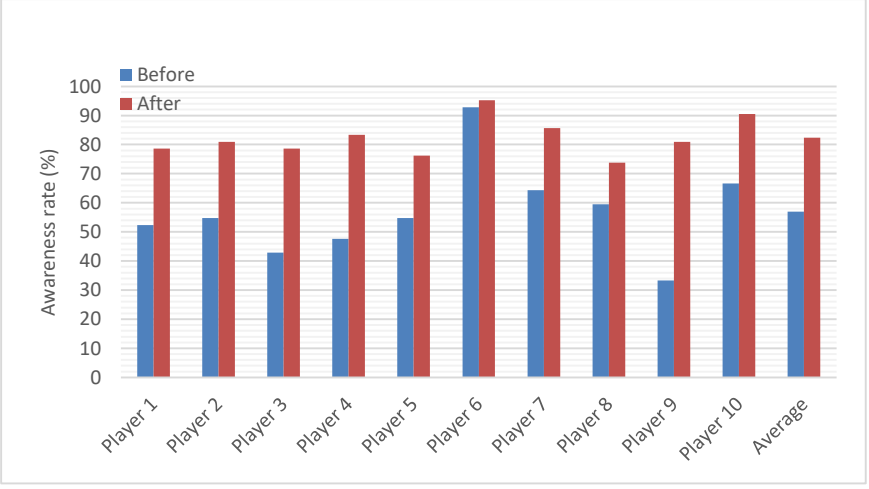

Figure 8.4: The awareness rate of the participating players before and after playing the game

Moreover, Figure 8.4 shows the level of awareness of the participating players about the importance of the role of HECs in energy

management before and after playing the game. The effect of the game on increasing awareness is clearly shown. Before playing the game, the awareness rate of 30% of the players was less than 50%, the awareness rate of 60% of the players was between 50% and 70%, and the awareness rate of 10% of the players was more than 90%.

However, after playing the game, it was noticed that the awareness increased clearly, as the lowest awareness rate was 73.8% for player number eight. Whereas the percentage of players whose awareness percentage was less than 80% was only 40% and 40% whose awareness percentage was between 80-90%. In addition, the awareness rate of 20% of the players was higher than 90%.

8.3.3. Recommendation for improving the Power the Grid game

The Power the Grid game contains various features that simulate reality, bring fun and suspense, and encourage players to think deeply. Figure 8.5 shows the Power the Grid game modes and the suggested recommendations.

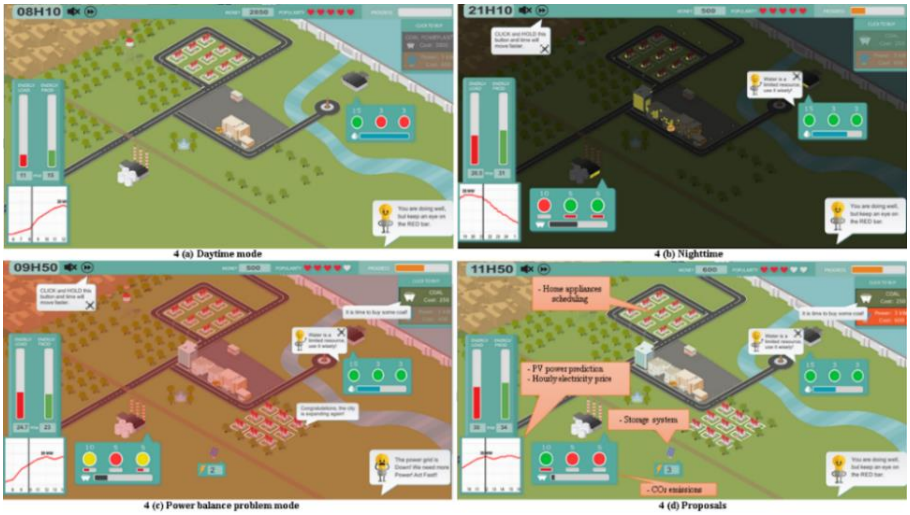

Figure 8.5: Power the Grid game, source [Gamejolt, 2023]

Figure 8.5(a) shows the daytime mode; the city's infrastructure, the amount of energy produced, and the expected electricity consumption are displayed. In addition to the power plants (the hydroelectric power plant) and the gross of available fuel. It is noted that energy

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consumption increases with time during the daytime hours, and the player manages the energy for this city accordingly. Figure 8.5(b) shows the nighttime mode, a coal power plant has been purchased and established. With the increase in the demand for energy due to the city expansion, the lack of fuel stocks, and the slow establishment of power plants, a power balance problem occurs, thus leading to a power outage in the city, as shown in Figure 8.5(c), as the energy was poorly managed.

Based on the results of the last sections, which showed the impact of the game in raising players' awareness, this work suggests expanding the game's options and covering the options that do not exist in the game. The suggestions would significantly boost the awareness of players in keeping with the technological development in real life, in addition to increasing the fun of playing the game. (See Figure 8.5(d)).

First, the amount of energy expected to be generated from renewable energy systems such as the solar system, which depends on solar radiation. Secondly, adding an option to install an ESSs, so the player can store energy in cases of excess energy generated from renewable energy systems and use it later instead of using fossil fuel plants, thus reducing the energy usage cost and reducing the environmental impact.

Third, adding a DR strategy; allows the players to schedule the operating times of some appliances in homes, machines in factories, and city lighting depending on the available produced energy. In addition, express the cost of energy usage from the power plants hourly; by adding a smart meter that displays the electricity prices besides the hourly energy consumption. Thus, the player can manage energy by scheduling consumption at different intervals based on the amount of energy generated by renewable energy plants, the amount of energy stored in the storage system, and the electricity prices of other fuel plants.

Fourth, adding a CO_2 emissions measurement device that counted the amount of CO_2 emissions caused by the use of fossil fuels in power generation. Adding this tool would raise players' awareness of the environmental impact of using this fuel and thus guide them to manage energy usage environmentally.

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8.4. CONCLUSION

This study presents an investigation of the role of video games focusing on social awareness, taking into account energy transition and sustainability. In line with the technological development in the energy sector and the increase in concerns about energy security and climate change, this study was carried out to investigate how video games might affect HECs' awareness of their role in contributing to energy security, reducing the environmental impact of using energy, and reducing electricity prices. First, a questionnaire was conducted to measure the awareness, and then the game rules were explained, and the players started playing. After that, another questionnaire was carried out after playing the game to measure the effect of playing the game on increasing awareness. The Power the Grid game was chosen as a case study with the participation of ten players.

The results showed a significant and remarkable role of playing this game in raising social awareness and educating HECs about energy issues compared with their awareness before playing the game.

Accordingly, several options were proposed to be added to the game, which would enhance social awareness of their essential role in ensuring a secure energy future and a better environment, in addition to the accessibility of electrical power at reasonable prices. The content of these proposals revolves around the execution of the DR strategy, which has begun to be applied in several countries. This study recommends increasing the interest in supporting game designers and facilitating the marketing of such games to increase the number of their goers because of their positive impact.

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CHAPTER 9. THE SMART INDUSTRIAL REVOLUTION INTO ENGINEERING CURRICULA: LINK THEORY TO PRACTICE FOR FUTURE ENGINEERS PREPARATION

SUMMARY

The smart industrial revolution (Industry 4.0) promotes the use of ICTs in the industry for efficient production processes and energy consumption, where engineers play a key role in applying ICTs and performing many tasks, such as process optimization, energy recovery, monitoring and management, and data analytics and automation. In this context, employees' educational quality has been proven to improve society's economic sustainability growth and the innovation performance of the industrial sector. Curriculum modernization to make education closer to industrial practice and reduce the gap between theory and practice knowledge, to adequately prepare future engineers became important. A new teaching style has been implemented by introducing the industrial production systems course into the engineering curricula. This approach aims to link theoretical knowledge with the production processes in manufacturing companies to provide good preparation for future engineers. The present work describes the course teaching approach during the academic semester; it went smoothly since it accounted for the students' perception variations and was diverse, containing a theoretical side, a mathematical and analytical side, case studies, and field visits. A feedback questionnaire was designed at the end of the academic semester to investigate the students' perspectives on the course. Furthermore, the students' grades in the academic years 2022-2023 and 2023-2024 are analyzed to evaluate course effectiveness. The results show positive student feedback and high grades, highlighting its success in meeting objectives and providing educational content that effectively addressed real-world applications. The integration of theoretical knowledge with practical

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experiences, such as case studies and field visits shows the highest student agreement, indicating its role in enhancing their understanding of industrial production processes. This underscores that university teaching is a valuable approach to exposing students to real-world applications and immersing them in actual manufacturing systems. Furthermore, the interaction in the classroom, the insightful discussion with the industrial experts, and the overall satisfaction indicate the value and the successful teaching procedure of this course.

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9.1. INTRODUCTION

Manufacturing is the process of creating goods or converting raw materials into goods for the fulfillment of human needs, which involves skilled labor and specialized equipment to ensure efficient production. These processes involve various stages, from design and prototyping to mass production, highlighting the fusion of human creativity and technological innovation [Kalpakjian et al., 2020; Kenton, 2022]. Manufacturing contributes to technological progress, forming a strong link between innovation and production [Obradović et al., 2021]. Production activities in companies are their reason for being, making effective and efficient manufacturing management imperative, where the vitality of factories relies on the effective execution of diverse functions to adequately manage production. Manufacturing stands as the primary driving force behind the national economy, wielding significant economic influence [Szirmai et al., 2015; Marconi et al., 2016]. According to statistical data, it constitutes 14.46% of Europe's Gross Domestic Product (GDP) and 18% of total employment in Europe [Storrie, 2019; The Global Economy, 2023].

Technological advancements gave rise to the fourth industrial revolution, known as Industry 4.0, characterized by the mass employment of smart objects. The key vision of Industry 4.0 is to make factories use of smart production systems and close to full automation, to ensure efficient performance using advanced ICTs. Besides, for energy consumption in the industry, SG contributes to promoting Industry 4.0, known as the Smart Grid Industry (SGI 4.0) by utilizing data provided by smart meters and consumption statistics to be used by machine learning to provide advanced decision-making [Qarabsh et al., 2020].

The European Commission established the "Sustainable and Efficient Energy Use in Industry" working group in 2016 and revised it in 2021 to be aligned with recent research, innovation, and policies such as the EU Green Deal. It aims to help industries become less energy, resources, and emissions-intensive and more competitive [European Commission, 2024a]. Achieving energy efficiency entails a multifaceted approach encompassing various activities, where the central role of engineers emerges as paramount. Engineers can drive

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significant improvements in sustainability, cost-effectiveness, and competitiveness within the manufacturing industry. Their contributions span essential tasks such as equipment selection, process optimization, energy recovery, monitoring and management, employee engagement, regulatory compliance, and data analytics and automation [Tanner, 2020].

Engineers' role encompass several activities in the industry sector, contributing to manufacturing processes, problem-solving, process analysis, and the creation of innovative ideas and designs [Lucena et al., 2022]. The comprehensive preparation of undergraduate students enhances their professional and technical skills, which significantly boosts their opportunities within the industrial sector and serves as the essential key for economic and sustainability development [Uhlemann et al., 2020; Hidayatuloh et al., 2021; Alam et al., 2022a, 2022b].

The role of education and the significance of the symbiotic relationship between universities and industries in countries' development in recent times has come as a major catalyst for countries' development [Chryssolouris et al., 2013; Agasisti et al., 2022]. It is found a significant relationship between educational quality and economic growth, underscoring the role of human capital in fostering nations' growth [Hanushek et al., 2007; Department for Business, Innovation & Skills, 2009]. Universities contribute to intellectual growth and innovation, preparing future workforce, producing skilled professionals, and groundbreaking research [Etzkowitz et al, 2017]. The collaboration between academic institutions and industries creates a dynamic system leading to a seamless flow of knowledge, with academia addressing real-world challenges and industries benefiting from research and a skilled workforce [Freitas et al., 2013]. This partnership not only enhances the quality of education by providing practical insights, but also accelerates countries' development, and promotes manufacturing quality [Flegel et al., 2005].

The effective preparation of future engineers relies on quality education at universities. However, theoretical knowledge within the confines of a classroom is insufficient, education must transcend theoretical concepts and be linked to real-world applications [Biggs et al., 2022]. This integration is significantly influenced by the curricula

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implemented for the bachelor's degree; educational curricula should not only convey theoretical foundations but also incorporate practical experiences, ensuring that students develop a comprehensive understanding that can be readily applied in the workplace [Rentzos et al., 2014; Sackey et al., 2017]. Hence, a challenge arises in moving towards a new approach to manufacturing education that integrates education, research, and innovation [ManufuturePlatform High Level Group, 2006].

To address the abovementioned concern, the academic staff at the Universidade de Santiago de Compostela has taken proactive measures. The industrial production systems course has been introduced into the bachelor's curriculum of the engineering degree. This innovative course transcends traditional styles of teaching, where it provides a holistic approach. Students are not only taught theoretical knowledge but are also guided to broaden their thinking horizons by bringing practice knowledge to the course. The initiative reflects a commitment to equipping students with practical insights and fostering skills for problem-solving.

This course delves into the fundamentals of industrial production processes, enhancing a comprehensive understanding through analyzing real-world cases. By combining theoretical insights with practical applications, students engage in mathematical exercises to simulate operational performance, enhancing their grasp of real-world industrial production dynamics. Beyond the classroom, the course incorporates learning experiences, including field visits to diverse factories, which offer students an exploration of production processes, bridging the gap between theory and practice. Furthermore, industry specialists enrich the learning experience by visiting the university to deliver lectures, providing valuable insights from the industrial sector, and establishing a meaningful connection between academic knowledge and industry realities.

In line smart industrial revolution and how education can contribute to enhancing future engineers' preparation, this paper takes the teaching style of the industrial production course as a presentative example, which presents a comprehensive initiative aimed at integrating theoretical education and practical knowledge. This paper

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suggests a unified approach that brings together academia and industry to create a synergistic learning environment, ensuring that graduates are well-equipped for the challenges of the professional world.

9.2. METHODOLOGY

To accomplish the objectives of this work, the methodology undertaken is as follows:

1. Carrying out a review of courses and methods for educating future engineers.
2. Course description including objectives establishment, learning outcomes determination, course structure, teaching methodology, and the evaluation system.
3. Dynamic classes and tutorial activities Implementation.
4. Course effectiveness and teaching style assessment.

9.3. DEVELOPMENT

9.3.1. Literature review

In higher education, there is a growing emphasis on transitioning from lecture-based teaching to evidence-based and student-centered approaches. The European Union supports this shift, it has launched several actions aimed at enhancing the quality of education [EU, 2017]. Besides, several research demonstrated enhanced student outcomes in environments that modernized teaching style [Dębiec, 2017; Derting et al., 2010].

The prosperity of the industry needs the education of engineering students. Therefore, it is essential to make today's university students understand the importance of their role in developing and adopting efficient tasks in real-world manufacturing and applications. Moreover, engineering curricula contain different forms of knowledge and concomitant practices: from science to engineering science and on to the application, underscoring its role in bridging the gap between theory and practice [Shay et al., 2016].

Engineers learn fundamental concepts, theories, and engineering process calculation during their degree journey. However, most of the required knowledge and skills for their profession in real-world applications are gained through on-the-job training [Fletcher et al.,

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2017; Grant et al., 2006]. This is rooted in a lack of effective integration of this knowledge into practical skills and competencies essential for professional success in the field [El-Sayed et al., 2004; Grant et al., 2006; Markes, 2006; Nair et al., 2009; Kondo et al., 2017]. Besides, employers tend to favor skilled college graduates over their non-skilled counterparts, as companies often invest significant time and resources into training new hires [Saunders et al., 2010].

The modernization of engineering curricula has been a focal point of research and innovation in recent years, with various approaches aimed at enhancing the educational experience for students. At Brigham Young University, the "Global Product Development" course was designed and offered to introduce engineering students to manufacturing issues within real-world productions. The course encompassed classroom and group studies, seminars, and travel studies, and since the class was devoid of textbooks, students were expected to search out diverse resources, such as handbooks and online materials [Todd et al., 2005]. Efforts at Kansas State University included modernizing the "Introduction to Manufacturing Processes and Systems" course by adding the concept of green energy manufacturing involving metals, ceramics, plastics, and composites. The course was limited to classroom lectures and movies to provide the frame for class discussion [Pei et al., 2011]. To keep in line with contemporary challenges, the academic staff of the School of Environmental and Materials Engineering at the Shanghai Second Polytechnic University emphasized the importance of teaching the principle of chemical engineering in the environmental engineering major. They suggested adjusting the course content considering the practical problems, arousing students' interest in the teaching process, ongoing research and technology advancement, reviving class discussion, utilizing media and blackboard, and implementing experiments aligned with chemical and environmental engineering [Sun et al., 2015]. Similarly, at the School of Chemical Engineering, Xi'an Jiaotong University, the "Optimization Method and Applications in the Chemical Industry" course was reformed to be internationalized [Yang et al., 2017]. This involved a bilingual course, a new syllabus and teaching plan, and a course website with rich content, however, the course was limited to classrooms.

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Additionally, researchers such as Khadom et al. (2020) and Alvarez (2021) suggested modernizations to bridge the gap between theoretical knowledge and practical application in chemical engineering education and critical thinking about chemical processes. They highlighted the importance of making the curriculum content coherent, hands-on experience, and experiential learning [Khadom et al., 2020, Alvarez, 2021]. Furthermore, initiatives at Taiyuan University of Technology's College of Chemical Engineering focused on equipping students with automation and computer knowledge to tackle complex industrial problems [Zhang et al., 2023].

Regarding teaching methods, a variety of approaches have been implemented to enhance learning outcomes. Xiao et al. (2018) advocated for project-based teaching to promote engagement and practical application in courses such as equipment design [Xiao et al., 2018], while at the University of Pittsburgh, Johnson et al. (2019) integrated Simtronics software to facilitate theory-practice integration and skill development [Johnson et al., 2019]. Similarly, at the Universidad Complutense de Madrid, Domínguez et al. (2021) utilized Jupyter Notebook software to enhance learning material accessibility and interactivity in "Introduction to Chemical Engineering" classes [Domínguez et al., 2021]. Hart et al. (2021) and Torrecilla et al. (2021) implemented methods such as flipped classrooms, virtual reality-enhanced learning, and thinking-based learning to foster critical thinking and deeper understanding among students in manufacturing processes [Hart et al., 2021; Torrecilla et al., 2021].

Site visits emerged as an effective tool for providing real-world context and practical experience in engineering education. Wolff et al. (2018) and Dorfling et al. (2019) highlighted the value of integrating site visits and design projects into the curriculum, enabling students to apply theoretical knowledge in practical systems and develop essential skills in planning, execution, and reporting [Wolff et al., 2018; Dorfling et al., 2019].

Safety education has also been a focus, with researchers such as Zeng et al. (2017) and Pollock et al. (2021) proposing comprehensive approaches to integrating safety concepts into the curriculum. These approaches encompassed various strategies such as pre-class review

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sessions, brainstorming tasks, and project-based assessments, aimed at instilling a culture of safety consciousness and competence among future engineers [Zend et al., 2017; Pollock et al., 2021].

To sum up, designing skills-oriented teaching for engineers seems to be a contribution that could bridge the gap between theory and practice. This work focuses on expanding the range of the teaching approach by bringing classroom instruction, seminars, teamwork, lectures by invited industrialists, and industrial visits together within a unified teaching framework. The focus also includes modernizing the curriculum by introducing the "Industrial Production Systems" course, emphasizing real-world application and industry relevance. Furthermore, it incorporates a feedback questionnaire that gauges student satisfaction and refines teaching quality.

9.3.2. Course description

The "Industrial Production Systems" course is part of the third year of the bachelor's degree in Chemical Engineering at the School of Engineering at La Universidade de Santiago de Compostela, Spain. This course is attended by around 60-70 students a year, with 4.5 ECTS credit hours.

9.3.2.1. Course aim

The course aims to provide students with a comprehensive understanding of manufacturing processes, offering insights into the practical realities of manufacturing. It encompasses essential topics such as the significance of materials, their classification, a detailed exploration of potential manufacturing processes, and an overview of industrial production systems. Beyond these fundamentals, the course equips students with insights into support systems and the effective management of production processes, ensuring a well-rounded comprehension of the intricacies involved in real-world manufacturing scenarios.

9.3.2.2. Expected learning outcomes

The expected learning outcomes of an industrial production course represent the foundational building blocks upon which students embark

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on a transformative journey into the world of manufacturing and operations. This course is designed to provide undergraduate students with a solid foundation in the principles and practices of industrial production. The expected learning outcomes of this program have been carefully crafted to empower students with the knowledge, competencies, and expertise needed to thrive in the field, that is essential for success in the dynamic world of manufacturing and production systems. From understanding the principles of production systems to cultivating expertise in quality management, supply chain dynamics, and sustainable manufacturing practices, this course offers a comprehensive educational experience. Moreover, it places emphasis on problem-solving, teamwork, and ethical considerations to ensure that graduates are well-prepared to make significant contributions to the industrial sector, drive innovation, and meet the challenges of today's ever-evolving production landscape. After completing the course, the students shall be able to demonstrate many skills. Figure 9.1 describes the Expected Learning Outcomes (ELO) including basic and general skills (ELO1, ELO2), transversal skills (ELO3, ELO4, ELO5, ELO6, ELO7), and specific skills (ELO8, ELO9).

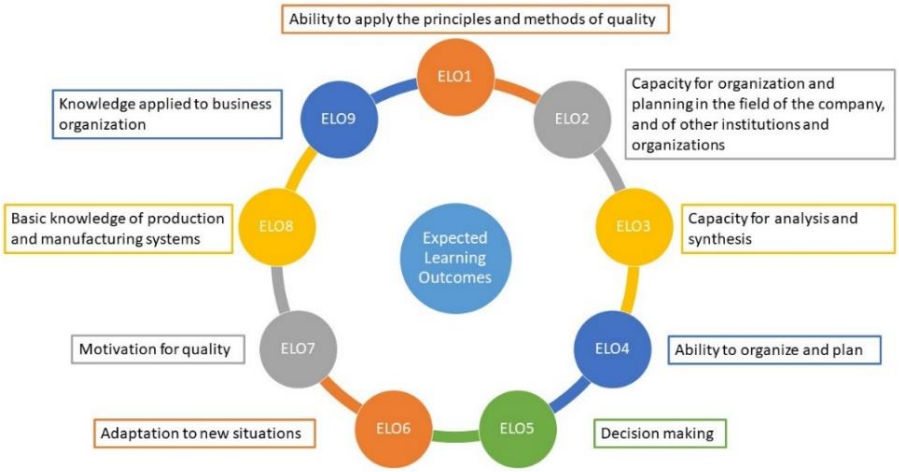

Figure 9.1: Expected learning outcomes

9.3.2.3. Course structure

The course covers the manufacturing process principles and focuses on the procedures that take place during the production processes that affect the possibilities for achieving high-performance, cost-effective production systems, and efficient production systems. The course structure has two main subjects to focus on; each one includes several topics, as shown in Figure 9.2.

Firstly, in "Manufacturing and Industrial Production Systems", students explore the foundational principles of manufacturing. This segment begins with "Introduction to Manufacturing", providing students with a solid entry point into the dynamic realm of production. It then delves deeper into the core of manufacturing with "Manufacturing Processes", where students gain insight into the techniques and technologies that drive industrial production. Lastly, it explores "Manufacturing Systems", offering a holistic view of how the various components come together to form efficient, responsive, and sustainable production systems.

Secondly, "Manufacturing Support Systems" ushers students into the essential facets of support and optimization in industrial production. It encompasses "Process Planning and Production Control", providing students with the tools to strategize, plan, and manage production processes effectively. Simultaneously, "Quality Control and Inspection" equips students with the knowledge and methodologies necessary to maintain and enhance the quality and precision of manufactured products.

This structure ensures that students not only gain a solid foundation in the fundamental principles of manufacturing but also acquire the knowledge needed to optimize processes, control quality, and contribute to the advancement of industrial production.

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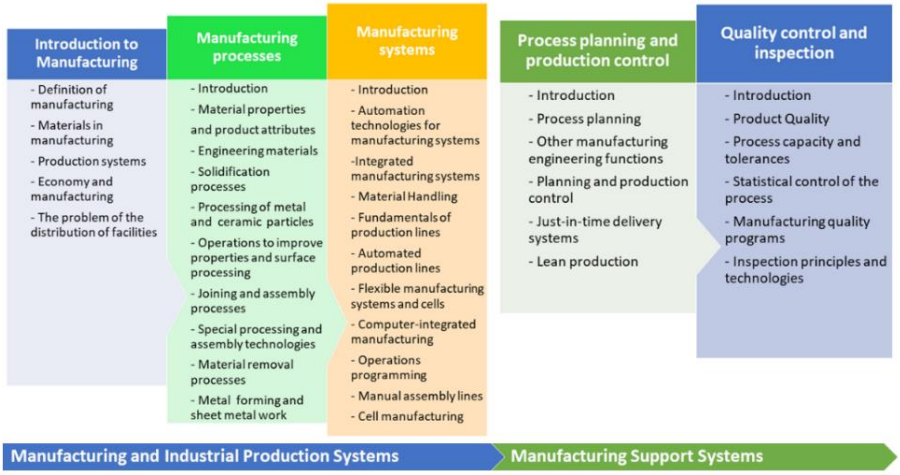

Figure 9.2: Course structure

9.3.2.4. Teaching methodology

The teaching approach encompasses classroom lectures, featuring both expository lectures and interactive seminars. Additionally, the course incorporates a practical dimension aimed at bridging the gap between theoretical knowledge and real-world applications. This involves on-site visits to industrial companies and lectures by industry specialists, to share their experiences with students. Furthermore, students are expected to complete mandatory individual assignments and group projects throughout the semester, contributing to a well-rounded learning experience.

Expository lectures encompass the presentation of course content along with solving typical problems facilitating the studied concepts. The interactive seminar classes conclude each subject with one or two seminars, focusing on activities related to the proposed problems for each topic, as well as engaging in other evaluation activities. Besides, to promote classroom interaction, a set of voluntary tasks is suggested for students to undertake and submit to the corresponding mailbox. These activities include partial evaluation tasks such as short in-class questions and timed tests. These assessments take place after finishing teaching each subject and are discussed during interactive classes to address queries and foster further interaction.

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The tutorials have two distinct activities: a) sessions on existing industrial production systems with invited industrialists held in the classroom, and b) on-site industrial visits. Before the industrialists' visit, an in-depth study of the specific industrial production system is implemented. These activities are evaluated with the preparation of a document on aspects related to the taught subjects. Additionally, mandatory assignments, either individually or in pairs, require students to analyze the industrial fabric of the geographical region. This entails selecting a specific production system and progressively examining it throughout the course. Each student's analysis of the chosen system is to be submitted at the end of the subject teaching. Submissions should be made through a designated mailbox on the virtual platform provided for this purpose.

Furthermore, mandatory group projects are considered throughout the course, with the teacher randomly selecting both the subject and the group members. These group projects unfold progressively during expository classes, aligning thematically with the subjects covered in the course. Once completed, students submit their work to the teacher, who provides approval for presentation during either expository or interactive classes. All projects are related to the course content and supervised and guided by the teacher throughout the course. Evaluation criteria for these projects include the team's efficiency, working time from proposal to completion, synthesis, and the overall quality of the presentation.

9.3.2.5. The course evaluation system

The course evaluation comprises various components, each contributing to the overall evaluation. These include a) exams, accounting for 60% of the final grade; b) works/activities, which consist of individual work (10% in the final grade), group work (10% in the final grade), and student activity throughout the course in specific activities such as questions and tests (10% in the final grade), making up 30% of the final grade; c) tutorials, with the teacher's report (5%) and interaction in the class (5%), making up 10% of the final grade. The total of these evaluations determines the student's final grade in the class. To successfully pass, a student must achieve at least 50% overall

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and obtain a minimum grade of 3.5 (out of 10) in each evaluative component, including the exam, assignments/activities, and tutorials.

9.4. INDUSTRIAL PRODUCTION COURSE CLASSES AND TUTORIAL ACTIVITIES

The subject's theoretical content is taught through expository classes. At the beginning of each lecture, the teacher engages in a general discussion, reviewing information covered in previous lectures and priming students for the upcoming topic. Both the blackboard and a presentation tool (data show) serve as supportive materials, as depicted in Figure 9.3.

Interactive seminars delve into various study and analysis topics. These seminars address the mathematical aspects of production processes and enhance understanding of the production process. Key areas covered include industrial production systems, analysis of production cycle times, manual assembly lines, and automatic production lines.

To fulfill the objectives of this course and bridge the gap between theoretical classroom knowledge and practical real-world applications, two distinct activities were implemented. Firstly, a visit was made to a prominent industrial company specializing in ceramics manufacturing, located in Vigo, Galicia (NW Spain). The field visit was supervised by specialists from the manufacturing facility who provided a detailed explanation of the production process. This walkthrough covered the initial stage involving the preparation of fundamental materials for manufacturing, followed by processing operations leading to the final product, involving the applied ICTs in the production system, as illustrated in Figure 9.3. The visit also facilitated engaging interaction between the specialists and students through questions and discussions.

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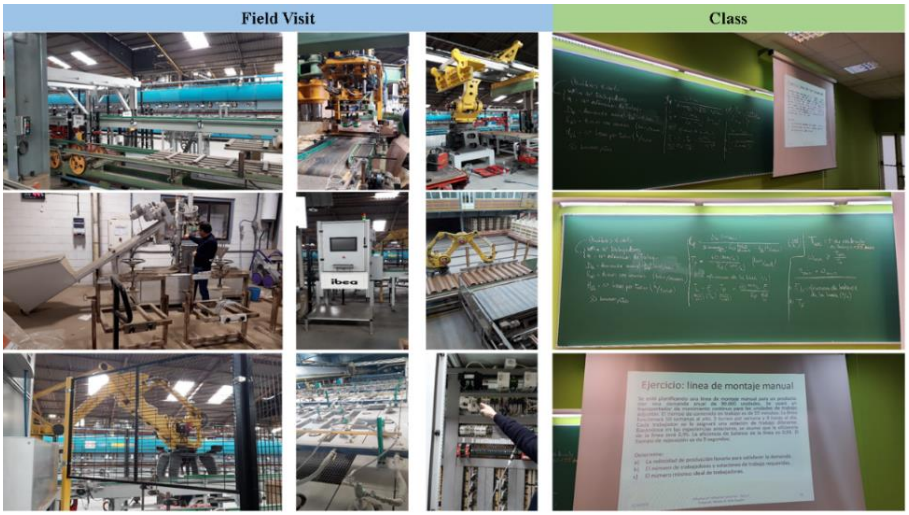

Figure 9.3: Industrial production systems course activities

Secondly, representatives from a company conducted informative lectures within the classrooms to elucidate the production processes at their manufacturing facility. The company specializes in the creation and design of high-performance multi-purpose four-wheel drive and military trucks with advanced technology. During these lectures, expert industrialists shared comprehensive details about the company, covering key activities such as design, production, marketing, and the ICT applications in these stages. Each aspect was thoroughly explained, including insights into the company's quality and standards procedures aimed at maintaining efficient workflow and high productivity. Besides, the structure of the company was detailed, encompassing aspects such as the total area, storage facilities, and assembly lines. Furthermore, the production scenario was elucidated, involving production capacity, product types, their applications, and the overall production strategy. Following each lecture, students inquired various questions related to the application of the company's products, the functioning of production lines, the applications of ICTs, and consumer satisfaction. The specialist industrialists adeptly addressed all inquiries and engaged in extensive discussions with students to clarify any aspects that may have been unclear.

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9.5. TEACHING METHOD EVALUATION

The Industrial Production Systems course serves as a component in the curriculum for third-year engineering students at the University of Santiago de Compostela. This comprehensive course aims to equip students with the essential knowledge and skills needed to bridge the gap between theoretical knowledge and practice in industry.

At the end of the course, an insightful feedback questionnaire was designed and implemented to measure the students' perspectives on the course. The implemented questionnaire served as an instrument through which the students delivered their insights, covering a set of aspects. The questionnaire was prepared using a five-point Likert scale (Strongly Agree, Agree, Undecided, Disagree, and Strongly Disagree) and classified into ten main aspects. The course objectives, scrutinize the alignment between the intended outcomes and the actual learning experience. The course content evaluation assessed the relevance and depth of the material in covering the industry needs and real-world applications while teaching methods analysis sought to identify the effectiveness of employed instructional approaches. The course structure evaluation gauged the coherence and sequence of topics, assignments, and assessments. The importance of teamwork was highlighted in the questionnaire, emphasizing collaborative learning experiences. Resources, including technological aids and reference materials, were evaluated for adequacy and accessibility. Moreover, the questionnaire probed into the industrial visits and specialized lectures, aiming to understand their impact on the student's comprehension and achieving the course's objectives. The assessment and evaluation aspect considers that the evaluation methods employed were fair, transparent, and aligned with the course objectives. The overall satisfaction was assessed to provide a holistic view of the students' sentiments toward the course. Besides, a comments and suggestions section offers insights into the students' thoughts, opinions, and experiences. It also helps to discover unexpected perspectives that might not covered in the questionnaire's questions.

The academic performance based on the students' grades is used as an assessment metric to evaluate the course's effectiveness. This can be done by analyzing grade distributions and the percentage of students

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who successfully pass the course on their first chance. Finally, the professor's perspective is considered by describing the workload and the efforts required in teaching this course.

9.6. RESULTS

The results section presents a comprehensive overview of students' overall grades and feedback questionnaire results, offering a thorough course evaluation. Students' academic performance and feedback results figure out their perspectives, shedding light on the effectiveness of the course in meeting its objectives, enabling a nuanced understanding of the impact and success of the industrial production systems course, and discovering aspects for improvement. Figures 9.4 and 9.5 present the feedback analysis results. The questionnaire was delivered in person in the classroom, 59 students participated in the feedback process with a response rate of 87%, offering a rich perspective. The data collected from the questionnaire served as a valuable tool for introspection and improvement for enhancing the course curriculum.

In Figure 9.4, the survey results reflect a prevailing sentiment among students regarding the course's significance, efficacy, and instructional quality. Specifically, a substantial majority of students, comprising 86.44%, expressed agreement regarding the course's achievement of its intended objectives. An overwhelming 91.525% of students demonstrated that the course content effectively addressed industry needs and real-world applications, underscoring its practical relevance. Besides, 62.712%, affirmed that the teaching methodology, encompassing lectures, seminars, group discussions, and hands-on activities, facilitated comprehension of course material.

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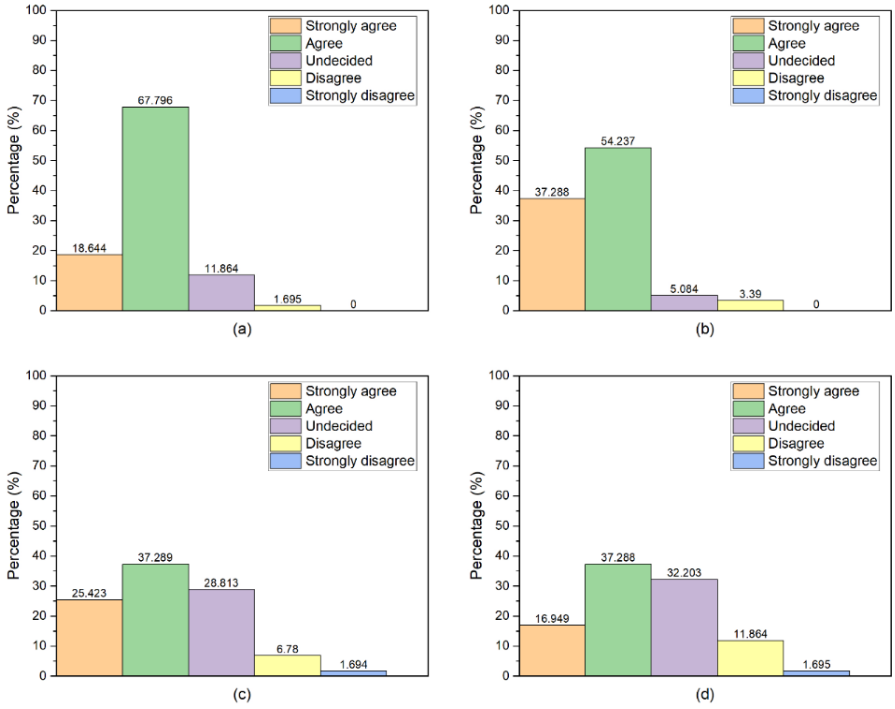

Figure 9.4: Students' perception of the quality of (a) course objectives, (b) course content, (c) teaching method, and (d) course structure

While a majority of 54.237% acknowledged that the sequence of topics, assignments, and assessments is well organized. However, a few proportions of the students were undecided and disagreed with some aspects of the course. It was found that 11.864% of the students were undecided, and 1.695% expressed disagreement regarding the course's alignment with its intended objectives. In terms of whether the course content adequately addressed industry needs and real-world applications, 5.084% were undecided and 3.390% disagreed. For teaching effectiveness, 28.813% of students were uncertain, and 8.474% leaned towards disagreement or strong disagreement about the efficacy of teaching methods in facilitating comprehension. Regarding the organization of topics, assignments, and assessments, 32.203% were undecided, and 13.559% leaned towards disagreement or strong disagreement.

In Figure 9.5, a significant majority of students, representing 84.745%, acknowledged the role of teamwork in group activities and discussions, underscoring its value in enriching their learning experience. Moreover, 67.795% of respondents affirmed the adequacy, relevance, and accessibility of provided learning resources, including textbooks and online materials. An overwhelming 96.609% of students agreed about the educational merit of industrial visits and lectures led by industry specialists, underscoring their effectiveness in bridging theoretical knowledge with real-world applications and bolstering comprehension. Additionally, 67.795% of participants lauded the fairness and transparency of evaluation methods employed, noting their efficacy in enhancing comprehension of course concepts and accurately assessing students' understanding of the material.

Besides, the analysis revealed that a portion of students had reservations about certain aspects of the course. Specifically, 8.474% of students were undecided, with 5.084% and 1.695% expressing disagreement and strong disagreement, respectively, regarding the significance of teamwork in enriching their learning journey. When considering the accessibility and sufficiency of provided resources, 28.813% were undecided, and 3.390% expressed disagreement. Moreover, in terms of the educational value derived from industrial visits and specialized lectures, 1.695% of students were undecided, and 1.695% leaned towards disagreement regarding the contribution of this component to educational enrichment and knowledge expansion. Concerning the evaluation methods employed, 22.034% were undecided, with 10.17% leaning towards disagreement regarding their effectiveness in enhancing comprehension of course concepts.

Ultimately, the results revealed that the majority of students, approximately 78%, expressed overall satisfaction with the course, acknowledging its effectiveness in enhancing both theoretical understanding and practical knowledge.

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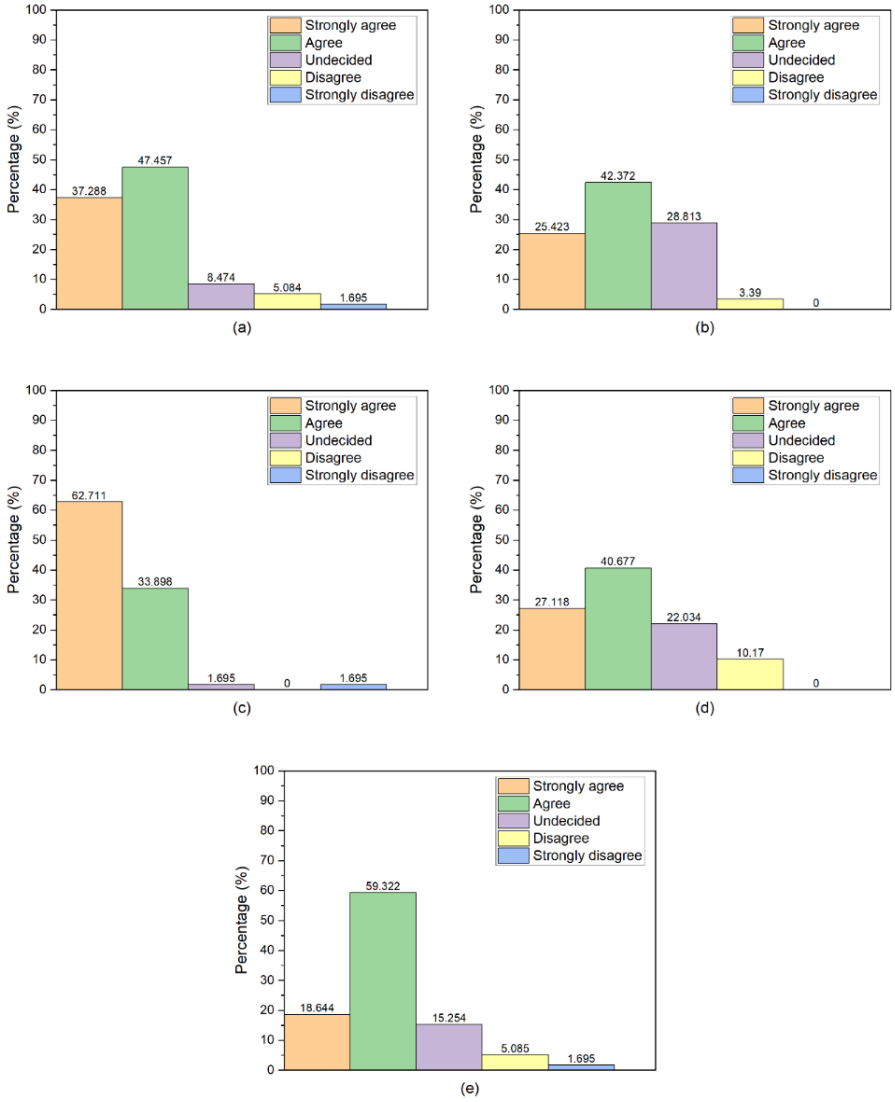

Figure 9.5: Students' perception of the quality of (a) teamwork, (b) resources, (c) industrial visits and specialized lectures, (d) assessment and evaluation, (e) overall satisfaction

Students' grades were analyzed to evaluate the course effectiveness and development during the academic courses 2022-2023 and 2023-2024. Figure 9.6 shows the results of the percentage of students who

passed the course, grade distributions, and average grades. In the academic course 2022-2023, the analysis of students' grades revealed an average score of 7.2, with 90.45% of students successfully passing the course on their first chance. Furthermore, there was a notable distribution of grades, 6.9% fail, 25% pass, 55.6% remarkable, and 12.5% outstanding, where three students were awarded an "Honours degree". In contrast, the academic year 2023-2024 exhibited an improvement in overall performance, with the average grade increasing to 7.6. Additionally, the percentage of students passing the course on their first chance rose to 95.16%. The grades distribution ranged between 15.3% pass, 76.3% remarkable, and 8.4% outstanding with no failed case, where three students were awarded an "Honours degree".

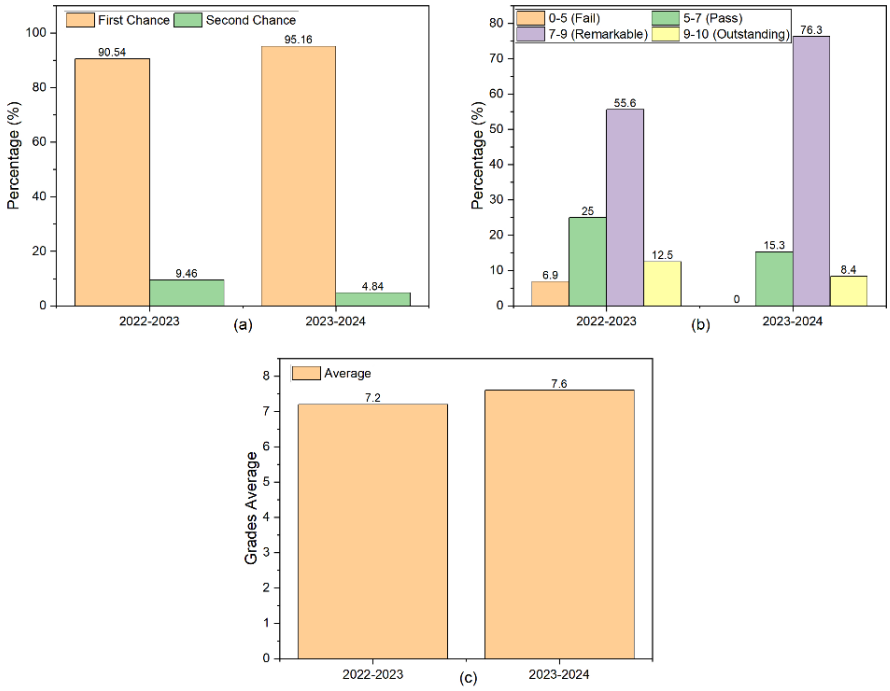

Figure 9.6: The results of (a) the percentage of students who passed the course (b) grade distributions (c) average grades

When asked about the workload associated with the course and the efforts needed to teach this course, the professor provided insight into the nature of the workload and acknowledged that teaching this course

demands significant effort. This includes activities such as lesson planning, providing support to students, supervising projects, grading assignments, organizing on-site visits and industrialists invitations, feedback provision, and staying updated with relevant advancements in the field. Besides, through the commitment to providing a rich learning experience and ensuring student comprehension, the professor demonstrates a dedication to overcoming the challenges associated with teaching this course effectively.

9.7. DISCUSSION

The findings reflect the overall effectiveness of the course in various key aspects, such as fostering student engagement and comprehension, practical application of course content, and preparing them for real-world challenges. It also underscores the multifaceted approach to learning and assessment employed within the educational framework.

The high percentages of agreement indicate that the majority of students found these elements valuable and beneficial to their learning experience, demonstrating the course's success in fostering student engagement, comprehension, and practical application of course content. However, it is important to address the concerns raised by some students regarding certain aspects of the course. For instance, the reservations about instructional delivery, course organization, resource accessibility, and assessment and evaluation suggest areas for refinement and enhancement. Ensuring transparency and offering opportunities for feedback about the teaching style can improve overall satisfaction with the course, ultimately ensuring a more fulfilling learning experience for all students. To do so, students were encouraged to provide open-ended comments and suggestions, fostering the discovery of their thoughts about the course and unexpected perspectives that may not have been addressed by the structured questions in the questionnaire. The typical comments provided by the students revolved around: ‘I found this course very useful and satisfying’, which agreed with the results (see Figure 9.5(a), Figure 9.5(b), Figure 9.6(c) Figure 9.6 (e)); ‘The PowerPoint slides provided in the classroom need to be better organized’, which is agreed with the results (see Figure 9.5 (c)).

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Our results are aligned with previous studies, Havenga et al. (2022) underscored that integrating real-world applications into the course content promotes the students' knowledge and skills (see Figure 9.4 (b)) [Havenga et al., 2022]. Jain et al. (2020) indicated that the teaching methodology contributes to facilitating understandability and promoting student outcomes (see Figure 9.4 (c)) [Jain et al., 2020]. Arshad et al. (2021) found that a well-organized course structure contributes to a better understanding of the material, higher grades, and overall satisfaction (see Figure 9.4 (d)) [Arshad et al., 2021]. Ercan et al. (2017) revealed that teamwork in engineering education enhances the learning experience (see Figure 9.5 (a)). Shukla (2022) identified that the adequacy, relevance, and ease of access to resources can enhance the quality of teaching, resulting in better student understanding (see Figure 9.5 (b)). For on-site visits and invited industrialist lectures, many studies confirmed that these approaches facilitate the course material understanding, enhance students technical knowledge, and learn health and safety aspects in real-world applications (see Figure 9.5 (c)) [Markom et al., 2011; Nordin et al., 2012; Wolff et al., 2018]. A study demonstrated that the quality and fairness of evaluation systems are strongly linked to learning outcomes (see Figure 9.5 (d)) [Struyven et al., 2005]. In Engineering Education, overall course satisfaction is directly linked to several key aspects, such as the quality of course content, teamwork, teaching methodology, and the integration of real-world applications and problem-solving into the curriculum (see Figure 9.5 (e)) [Gonzalez-Rogado et al., 2014; Lynch et al., 2017].

The high students' grades in both academic years indicate the student's interest in the course and successful teaching style. Besides, the notable improvement in student grades from an average of 7.2 in the academic year 2022 to 7.6 in 2023 signifies a continuous enhancement in the teaching style. In addition to, the absence of failing cases, coupled with an increase in remarkable grade percentages and a decrease in pass degree percentages during the 2023 academic year.

The results provided a nuanced understanding of the course's strengths and areas that required enhancement. The feedback received was not only a testament to the student's engagement with the material

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but also a reflection of the course's effectiveness in meeting its educational objectives. This feedback, rooted in the students' experiences and opinions, reinforced the academic staff's commitment to continuous improvement in delivering quality education. The insights garnered from the feedback process would undoubtedly contribute to refining and optimizing the Industrial Production course for future cohorts, ensuring its continued relevance and effectiveness in preparing students for the dynamic challenges of the industrial landscape.

As a result, in line with the smart industrial revolution (Industry 4.0) and the widespread adoption of smart control systems using ICTs in the industry, this work affirms that university teaching is a valuable approach to exposing students to real-world applications and immersing them in actual manufacturing systems. The feedback results of on-site visits and industrialists' lectures serve as evidence of improving students' knowledge and skills. Through these visits, students learn how smart control systems within ICTs are integrated into manufacturing processes to improve efficiency, quality, and productivity. They observe how sensors, actuators, and automated systems work together to optimize production lines and respond dynamically to changing demands. Exposing to real-world applications, helps students gain insights into the practical application of the concepts they learn in class, preparing them to tackle challenges and innovate within the manufacturing sector.

9.8. CONCLUSION

Industry 4.0 coupled with SGI 4.0 contribute together to enhance the industrial production processes, resulting in sustainable economic and social development. Since engineers constitute a fundamental segment of this sector, well education and preparation for engineers contribute significantly to the industrial sector development and make them integrate easily into the job market. For this purpose, the industrial production systems course has been introduced into the Bachelor's Degree Curriculum to enhance the quality of the graduates and keep abreast of the job market. This work focuses on modernizing curricula in teaching industrial production principles and production processes,

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as well as the link between teachings in the classroom with practicing in reality. A feedback questionnaire was designed to assess the effectiveness of the teaching methodology, the overall student satisfaction, and identify potential areas for course improvement.

The results demonstrate the efficacy of the course design in meeting its intended objectives. Students were equipped with the necessary skills by integrating theoretical instruction with practical applications, analyzing systems, and addressing problems mathematically. This holistic approach facilitated a deeper comprehension of the course and prepared students to navigate real-world applications effectively.

This course effectively bridged the gap between theoretical study and practical application by introducing the students to prominent companies in their field and region. A feature of the course was visiting a manufacturing company, where both the teacher and industrialist experts facilitated a seamless link between classroom learning and real-world production processes. This experience enriched students' understanding of engineering processes and provided insights into their practical implementation. Moreover, students had the opportunity to engage with specialists from a renowned European company. Expert-led sessions were carried out in the classroom, fostering lively discussions and exchanges between students, experts, and the instructor. Besides, during the two academic years, the active participation, overall student satisfaction, and good grades underscore the students' appreciation and interest in the course.

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CHAPTER 10. TOWARD SUSTAINABILITY: A REVIEW OF TEACHING OPTIMIZATION AND SIMULATION TOOLS, ENERGY FLOW MANAGEMENT STRATEGIES, AND BATTERY MANUFACTURING

SUMMARY

Sustainability has gained significant attention due to the fact of limited resources on the planet and climate change concerns. This has promoted sustainable practices and carried out research, driving advancements across various sectors. This paper presents a review of literature focusing on recent studies in sustainability-related topics spanning from 2014 to 2023. The research framework implemented a selection process using the Web of Science database, refining criteria based on specific keywords in titles, abstracts, and topics. The literature review has three main sections including teaching optimization and simulation tools, energy flow management strategies, and battery manufacturing in terms of sustainability. The review reveals the widespread applications of simulation software, optimization tools, and sustainability principles in theoretical and on-ground research in energy management and battery manufacturing. This emphasizes the role of engineers in fostering sustainability advancement and the importance of equipping future engineers with the necessary skills for real-world applications, such as optimization techniques.

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10.1. INTRODUCTION

In light of preserving resources challenges and environmental concerns confronting humanity today, the urgency of sustainability has emerged [Kuhlman et al., 2010]. Sustainability can be defined as meeting present needs without compromising the ability of future generations to meet their own needs [Hallin et al., 2021]. Therefore, there is a necessity to transition towards sustainable development pathways that reconcile economic growth with ecological integrity and social well-being. This has garnered attention across diverse sectors, such as energy, education, manufacturing, environmental science, economics, and social policy.

Raising awareness plays a key role in sustainability advancement. Societies contribute to sustainability through many activities in several sectors, such as energy (efficient energy consumption), transportation (adoption of electric cars), manufacturing and industry (circular economy principles), construction and infrastructure (green buildings), waste management and recycling (waste-to-energy technologies), and education and research (integration of sustainability principles in curricula) [Lee et al., 2017; Tang et al., 2020; Sanchez-Carrillo et al., 2021].

Education serves as a means to raise awareness of individuals, communities, and institutions to become active agents of change, ranging from early childhood education to lifelong learning initiatives. Educational institutions such as universities can equip students with the competencies needed to deal with sustainability challenges through the integration of sustainability principles and the application of real-world applications into the curriculum [Tasdemir et al., 2020]. Engineers play an important role in sustainability, underscoring the importance of well-prepared future engineers. Optimization and simulation are important topics to be taught to undergraduate engineers, which are increasingly utilized across engineering and manufacturing to improve efficiency, solve complex problems, and make informed decisions [Ghasemi et al., 2024].

Besides, while the world is moving towards renewable energy, optimizing the energy flow within the integrated system is necessary to have the full potential of renewable energy. Energy management has a significant focus from scholars due to its role in sustainability

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advancement; it centers on efficient utilization and conservation of energy resources and optimizing energy, generation, transmission, and distribution [Alam et al., 2019]. This involves SG, DR programs, RESs, ESSs, and optimization techniques aiming to enhance energy system stability and reduce reliance on fossil fuels.

ESSs have emerged as an integral part of advancing sustainability; they facilitate the penetration of RESs into the main grid and realize the full potential of sustainable energy transition [Denholm et al., 2010]. Consequently, growing attention is paid to various aspects of battery manufacturing improvement. This includes recycling and optimizing the metals used in battery manufacturing to preserve resources, reduce environmental impact, and enhance performance and longevity [He et al., 2020; Mao et al., 2022; Brandão et al., 2023]. Additionally, the affordability of batteries, to promote their spread and adoption by consumers [Mauler et al., 2021].

This review paper attempts to bring together the implemented research that contributes to the discussion on sustainability in terms of education, energy flow management, and battery manufacturing. It also attempts to figure out the intersections between these topics, thereby, promoting the formulation of initiatives spanning from educating future engineers to carrying out research and experiments for a more sustainable future.

10.2. MATERIALS AND METHOD

This section reviews a number of approaches to teaching simulation and optimization tools for undergraduate students, home energy management strategies, and battery manufacturing. The selecting papers process is carried out on the Web of Science, between 2014 and 2023, with specific criteria in the title and then refined with specific criteria in the abstract and topic for each section. Finally, articles are selected for each section by reading the abstracts to identify those that are in this study's scope.

The optimization and simulation tools criteria are "teaching" in the title, then refined with the criteria "optimization" and "simulation" in the abstract" and "students" in the topic. For the second section, the criteria are "energy management" in the title, then refined with the

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criteria "home energy management" in the abstract, and "optimization" and "energy storage" in the topic. Finally, the third section criteria are "battery performance" in the title, then refined with "production" in the abstract and "sustainable" in the topic.

10.2.1. Optimization and simulation tools

Simulation software and optimization techniques serve as tools for evaluating and improving the performance of real-world systems across various sectors. Recognizing their significance, curriculums are being taught these tools for undergraduate students to skill them up and prepare them for the workforce.

The PSO algorithm was taught to students and utilized through a project, to perform an open loop step system in the course of Modeling and Control Systems. Positive student feedback highlights the teaching effectiveness in understanding and applying PSO for real-world problem-solving [Oliveira et al., 2014]. Babia (2015) proposed a task-based approach to teaching a sustainable design process [Babia, 2015]. It has 12 tasks revolving around sustainability from the raw materials stage to the final product and waste through an optimization process. Students learned how to express and solve this problem mathematically considering its constraints, where the optimization problem is defined as a Mixed Integer Non-Linear Programming Problem (MINLP). Another work focused on virtual prototyping technology by utilizing simulation software such as Automatic Dynamic Analysis of Mechanical Systems (ADAMS) and ENSIGHT to study and analyze vehicle motion to overcome obstacles and design optimization [Meng et al., 2016]. A MATLAB-based HMETS hydrological model to simulate the streamflow of a watershed was used to teach civil engineering students. The approach includes optimization algorithms, five different objective functions, and 14 parameters to be calibrated [Martel et al., 2017]. De Moura Oliveira (2018) proposed a teaching approach for electrical and computer engineering students about optimization. The principles of the PSO algorithm were taught using videos, followed by testing on benchmark functions, and implementation in designing a Proportional-Integral-Derivative (PID) controller [de Moura Oliveira, 2018].

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Engineers require a strong foundation in mathematics, it provides essential tools for problem-solving, modeling, and analyzing systems. Asmuss et al. (2019) discussed teaching mathematical modeling and optimization tools and explained how they can be effectively used for facilitating theoretical understanding and solving problems in real-world applications. This includes software such as GeoGebra, Mathematical Visualization Toolkit, and Java modeling tools with specific problems from mathematical analysis and optimization [Asmuss et al., 2019]. In line with the technology development and sustainability concerns, simulating real-world systems and optimizing their operation becomes necessary. In this context, the Model Predictive Controller (MPC) is widely used in engineering and automation systems. Keller et al. (2020) presented a teaching approach about MPC principles and application for master students. This approach includes theoretical teaching about modeling, simulation, and optimization, followed by implementation by simulating an MPC model of a real internal combustion engine on Matlab [Keller et al., 2020]. Another study focused on energy sustainability, highlighting the need for skilled engineers specialized in renewable energy to align with technological advancements and facilitate the transition towards a cleaner energy future. The study recommended that simulation and optimization tools are necessary to be taught to enhance engineering students' skills [Jafarinejad et al., 2021]. For sustainable buildings, several optimization, simulation, and prediction tools are used by architects to obtain an efficient design in terms of consuming lower energy and household comfort. To facilitate early education in building design, a comprehensive framework has been developed for integrating these tools into teaching practices [Wang et al., 2022b]. A CoppeliaSim as a virtual environment, coupled with MATLAB for simulation and optimization, was employed to teach students the PID control theory. The Embodied Voice Assistant (EVA) mobile robot was taken as a practical case study for comprehensive learning [Pastrana et al., 2023].

10.2.2. Energy flow management

In the literature, there have been several solutions for optimal energy flow management. The scope of this work is the residential sector;

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HEMSs within the solar panel and battery systems including energy flow management and home appliance scheduling.

Zhang et al. (2015) proposed a multi-objective function considering energy cost and user comfort using an improved PSO algorithm, where the simulation, data forecasting, and optimization were done in C language in Microsoft Visual Studio [Zhang et al., 2015]. Another work modeled a multiple knapsack problem solved using GA, binary PSO, and Ant Colony Optimization (ACO) algorithms. Various scenarios involving population size and iterations were considered to target the reduction of energy costs and enhancement of user comfort. The study utilized Matlab for simulation and optimization purposes [Rahim et al., 2016]. Another work tackled energy costs, user comfort, and PAR in the optimization problem. GA, the Cuckoo Search Optimization Algorithm (CSOA), and the Crow Search Algorithm (CSA) were implemented to solve the optimization problem in Matlab under RTP and Critical Peak Pricing (CPP) [Aslam et al., 2017]. Javaid et al. (2018) developed a Genetic Wind-Driven Optimization algorithm (GWDO) to solve a multiple knapsack optimization algorithm in Matlab, focusing on energy costs, user comfort, and PAR. This study combined An Inclined Block Rate scheme (IBR) with RTP to effectively manage energy consumption [Javaid et al., 2018]. Lee et al. (2019) proposed a Q-learning method in Matlab to solve a MILP problem, aiming to optimize energy costs and comfort level, combined with an artificial neural network to predict indoor temperature [Lee et al., 2019]. A weighting method was implemented to determine the optimal weight variables of PSO and BPSO that achieve the best energy costs and PAR reduction considering selling energy to the grid. PSO and BPSO were applied to continuous and binary variables, respectively [Dinh et al., 2020]. A study proposed a novel ESSs charging/discharging scheme combined with an appliance scheduling strategy considering energy costs, PAR, and customer dissatisfaction. The multi-objective optimization problem with a weighting sum method was solved using BPSO in Matlab [Mohammad et al., 2021]. An optimization strategy using the GWO and a weighting sum method was applied to a multi-objective problem. It aims to reduce energy costs and PAR considering the efficient use of RESs and ESSs

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in Matlab [Mohammad et al., 2022]. Al Muala et al. (2023) proposed an optimization strategy in Matlab using PSO and AGWO algorithms to solve a linear optimization problem. They aimed to reduce energy costs, considering the installation cost and lifespan of the energy systems [Al Muala et al., 2023].

10.2.3. Battery manufacturing

Batteries are used in a wide range of applications, with the electro-mobility sector and high penetration of RESs being the main contributors to the increasing demand predicted for the next decade.

In the context of battery manufacturing, using renewable materials and applying sustainable approaches are being taken in many studies. Zhang et al. (2015) presented a new sustainable method by using an agricultural byproduct from crop stalks as a porous template for manufacturing cathode materials. They revealed the potential of crop stalks as a sustainable, dependable, and eco-friendly resource for producing high-performance lithium-ion batteries [Zhang et al., 2015]. In a study focused on sustainability in terms of petrochemical wastes, Ko et al. (2016) explored the utilization of Pyrolysis Fuel Oil (PFO) as a carbon source in manufacturing anode materials for lithium-ion batteries. The findings proved that PFO presents a high performance and holds promise as a sustainable resource for the commercial manufacturing of anode materials [Ko et al., 2016]. Similarly, Xianga et al. (2017) derived porous carbon nanosheets from a natural silk cocoon for manufacturing advanced lithium-sulfur batteries. The proposed work showed high battery performance and highlighted its contribution to sustainability in terms of cost, preserving resources, and large-scale manufacturing [Xianga et al., 2017]. A simple and sustainable approach to manufacturing silicon nanorods from natural sepiolite was implemented to develop a sustainable and efficient anode material for lithium-ion batteries [Chen et al., 2018]. A sustainable and cost-effective approach was developed for manufacturing anode materials using natural graphite. The findings showed a high performance exhibited by these materials within lithium-ion batteries, emphasizing their potential significance in advancing lithium-ion battery technology [He et al., 2019]. In another work focused on

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industrial waste, Wu et al. (2020) proposed a recycling approach to extract anode materials from silicon industrial waste for manufacturing lithium-ion batteries [We et al., 2020]. Zhang et al. (2021) directed efforts toward sustainable development in the agriculture sector; they developed a cost-effective and sustainable approach by leveraging rice husks for the anode materials extraction in lithium-ion battery production [Zhang et al., 2021]. Wang et al. (2022) introduced a sustainable method for manufacturing anode materials in lithium-ion batteries through biomass fermentation treatment, utilizing wheat flour fermentation. This approach presented a high battery performance with cost-effectiveness and scalability [Wang et al., 2022c]. The solid-state synthesis method was used to recycle the failed lithium-ion batteries under optimal repair conditions. This sustainable approach proved its high performance and efficient environmental and economic features in regenerating cathode materials [Kong et al., 2023].

10.3. RESULTS AND DISCUSSION

In this review paper, several topics are considered related to sustainability. Various studies focused on educating simulation and optimization tools to future graduates in line with technology development and sustainability practice in real-world applications. The literature shows the possibility of enhancing education through teaching simulation and optimization tools due to their spread usage in real-world applications and their role in sustainability improvement. This is aligned with a previous study by Sadollah et al. (2020) underscoring the strong relationship between optimization tools and sustainability and their application in various sectors [Sadollah et al., 2020]. Besides teaching optimization and software, where most of the literature focuses on teaching optimization algorithms, the sustainable industry requires skilled engineers; this can be done by modernizing curricula and integrating the principles of machine learning, automation, and data analysis software. This is supported by Hernandez-de-Menendez et al. (2020) highlighting the role of educating future engineers on these tools and preparing them for the workforce. Moreover, Software such as Matlab is widely used in simulating and optimizing energy systems operation, thereby, it should be taught in the curriculum due to its ease

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of use and broad-scope application. However, compared to the large number of published works that used optimization, simulation, and machine learning and their widespread application in real-world applications, there is a lack of published work about simulation software and optimization techniques in higher education, indicating a few consideration of these tools in educating future engineers. This gap should be bridged through modernizing the curriculum and teaching approaches.

Energy management significantly contributes to sustainability, where several studies proposed optimization techniques focused on energy cost, PAR, and user comfort. However, some sustainability aspects are not included in the literature; the installation cost of the integrated system, realistic energy selling approaches, and extended energy exchange models within the integrated system, such as between electric vehicles and batteries are poorly considered. Additionally, the lifespan and the operation of ESSs in terms of optimal charge/discharge rate, depth of discharge, and operation temperature are not widely considered.

Since ESSs contribute to sustainability and enhance the penetration of RESs into the main grid, sustainability is also considered in ESSs manufacturing. The literature shows efforts in developing sustainable approaches and utilizing renewable materials in manufacturing ESSs. It delves into utilizing several resources such as agriculture, industry, fuel wastes, and nature and recycling failed batteries for extracting anode and cathode materials, where most studies focused on lithium batteries. Besides, in manufacturing ESSs, focusing on the lifecycle outcomes according to different operation conditions, such as charge/discharge rate and depth of discharge is an important aspect due to their widespread usage in the residential and commercial sectors. For optimizing ESSs manufacturing, engineers can implement the optimization principles in the production process by considering influenced factors, such as material properties and process parameters (weight and capacity).

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10.4. CONCLUSION

This study underscores the importance of educating/training future engineers, particularly in sustainability principles, optimization techniques, and software applications, where engineers significantly contribute in two key areas that have a strong correlation with sustainability. The first aspect is the role of engineers in the field of energy flow management, whether by carrying out research or projects on the ground. Where the literature shows that applying optimization techniques and modeling real-world systems in software are widely used in research. The second aspect involves the application of sustainability and optimization principles in manufacturing processes to ensure green manufacturing. This includes the selection of optimal materials and parameters for better performance and longevity, especially concerning batteries, due to their contribution to moving toward a secure and sustainable energy system.

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CHAPTER 11. CONCLUSION

As the world faces challenges related to climate change, growth in population and energy demand, and energy security, there is a shift towards energy transition and sustainable energy practices. Governments, industries, and communities worldwide are increasingly recognizing the importance of reducing reliance on fossil fuels and embracing RESs. Initiatives such as the European Green Deal, NZE Scenario, EAP, and the Paris Agreement underscore the global commitment to achieving net-zero emissions and fostering a more sustainable energy future. At the core of this transition lies effective demand side management, which encompasses optimizing energy consumption, integrating renewable energy sources, and ensuring grid stability. Societies can pave the way for a more resilient and sustainable energy landscape by implementing policy frameworks, harnessing SG infrastructure and DR programs, and fostering consumer engagement.

This thesis has traversed a multifaceted journey, navigated through three distinct parts, each contributing essential findings, insights, and recommendations. Through this journey, the thesis investigated the key drivers of adopting HEMSs and tackled optimal demand side management strategies head-on. It also sought to enlighten society on energy-related issues through innovative gamification methods and highlighted the importance of the university's curriculum in the realm of the smart industrial revolution and teaching optimization tools and simulation software to train future engineers.

In Part 1, a comprehensive **investigation** was carried out to understand household perspectives and intentions about adopting HEMSs after the new DR program in Spain. An extended model of TAM was proposed for this purpose. Based on the literature review, the perceived customer’s environmental awareness and family’s economic benefits were added to TAM. The study was done in Galicia, Northwest Spain. After gathering the data, it underwent analysis using Amos 20. The data analysis results fulfilled the research objectives, providing

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valuable insights into the influence of each factor on the intention to use HEMSs. The study elucidated the impact that various factors exert on shaping the attitude toward and intention to use HEMSs. The results show a positive impact of the consumers' environmental awareness and family's economic benefits on the attitude toward using HEMSs. In addition, the results show a direct positive effect of usefulness and attitude toward use on the intention to use HEMSs. It is worth noting that the higher the economic benefits and environmental awareness, the more attitude to use HEMSs, which in turn leads to formulating positive intention to use HEMSs. The perceived family's economic benefit stands out as the most important factor in improving consumer acceptance, which is consistent with the function of HEMSs; saving energy and consuming energy in the low-price periods reduces the bill. Likewise, the influence of environmental awareness on the attitude toward using HEMSs holds notable significance. In other words, energy consumers are willing to manage their energy consumption to preserve the environment. This willingness is contingent upon them gaining adequate awareness of climate change issues and realizing their essential role in participating in DR aimed at environmental enhancement. Besides, the results reveal that usefulness has a positive and direct impact on intention to use, and the attitude does not mediate the relation between usefulness and intention to use. Hence, the higher the usefulness of using HEMSs in enhancing life quality, the more intention to use HEMSs. While the perceived ease of use and usefulness have insignificant effects on the attitude toward use. This indicates that the perceived ease of turning on/off the appliances and the usefulness of managing energy consumption in response to electricity prices are not directly affecting consumers' attitudes. In light of the findings, policymakers ought to place a focus on these factors by offering financial incentives, encouraging the installation of local RESs at home, and reducing taxes on saving-energy appliances. And clarify the benefits of managing energy consumption according to the new electricity prices on the future economic and environmental trajectory of Spain. Furthermore, efforts should be directed towards enhancing consumer awareness regarding the risks associated with fossil fuel usage, the advantages of using RESs, and the importance of using

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HEMSs to preserve the environment and enhance energy security. These endeavors can be facilitated through various channels such as social media, informative articles, the inclusion of relevant content in university curricula, and the organization of scientific symposiums and seminars. The researchers can use the above-mentioned findings as a foundation to further develop the proposed model and explore additional factors that could potentially impact consumer acceptance in Spain. By doing so, researchers can offer policymakers a richer understanding of the factors at play, thereby assisting in the formulation of more effective strategies aimed at enhancing consumer acceptance of the new electricity tariff.

In Part 2, the focus shifted towards the demand-side management **strategies** in the residential sector, with consideration given to the above-mentioned explored factors in the development of strategies. Three home energy management strategies were developed in Matlab, incorporating applying optimization techniques such as PSO and AGWO algorithms. Besides, to obtain realistic results, a real case study of a residential home, weather data, households' preferences, the costs associated with installing solar panels and battery energy systems, the replacement cost of EVs' batteries, and energy usage tariff in Spain are taken:

1. This thesis introduced an innovative energy flow management strategy aimed at optimizing energy distribution within the residential sector. A key aspect of this strategy involved developing a comprehensive energy usage cost model for both PV and BESS, which factored in installation expenses and life cycle considerations. Through simulation analysis, the effectiveness of this approach was demonstrated, particularly in achieving tangible cost reductions and maximizing the operational efficiency of PV and battery storage systems. The strategy prioritized conserving battery reserves during periods of PV power shortfall, prioritizing importing energy from the grid when grid prices offered more favorable returns than battery usage costs, and prioritizing discharging operations when grid price outweighs battery energy usage price. Moreover, the research findings shed light on the economic inefficiency of selling surplus energy back to the grid, highlighting the superior financial benefits of self-

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consumption within homes. By showcasing actual reductions in energy costs associated with PV and battery installations, this study promotes the adoption of localized energy solutions among consumers, emphasizing the importance of efficient energy management and resource optimization. Ultimately, these findings underscore how the decentralized energy systems contribute to bolstering both energy security and environmental sustainability, paving the way for a more resilient and eco-conscious energy landscape.

2. This thesis has introduced an innovative strategy for energy optimization within the residential sector, centered on an efficient energy flow management system and appliance scheduling optimization method. The proposed framework addresses key considerations such as PV and battery life cycles, as well as installation costs. This holistic approach ensures that energy consumption is optimized to minimize costs while maximizing efficiency and sustainability. The incorporation of battery and PV energy usage pricing models into the optimization strategy and energy flow management system offers a holistic solution for enhancing energy efficiency and cost-effectiveness to the framework, enabling more accurate and informed decision-making regarding energy usage patterns. The proposed strategy was developed in Matlab and AGWO and PSO algorithms to further enhance the efficiency and effectiveness of the optimization process, ensuring optimal outcomes for energy management within homes. This strategy provides practical insights and solutions that resonate with Spanish energy consumers, particularly in the context of the new electricity tariff, by utilizing real data from a home in Vigo, Spain. The simulation analysis extends beyond mere cost considerations, encompassing broader sustainability metrics such as battery lifetime, CO2 emissions, the breakeven point of the integrated energy system, and quantifying energy losses and their associated costs. This analysis provides a holistic understanding of the sustainability, economic, and environmental implications of the proposed strategies. In evaluating the effectiveness of the proposed energy management strategy, a comprehensive comparison was carried out with a previous model of energy management strategy. The results underscored the superior performance of the proposed strategy across multiple key

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metrics. It achieved a greater reduction in both cost and energy losses compared to the previous model. This indicates the efficiency and effectiveness of the optimization methods employed within the proposed framework. Moreover, the proposed strategy demonstrated a notable extension to the lifespan of the battery lifetime. By optimizing the usage patterns and charging/discharging cycles, the system effectively mitigated factors contributing to battery degradation, thereby enhancing its overall longevity. This aspect is particularly significant as it not only improves the economic viability of battery integration but also contributes to sustainability efforts. Furthermore, the proposed system exhibited a shorter time to reach the breakeven point compared to the previous model strategy. This suggests that the investment in implementing the proposed system yields tangible benefits in a relatively shorter timeframe, making it a more attractive option for energy consumers seeking cost-effective solutions. The proposed strategy encourages more sustainable energy consumption practices, by emphasizing the economic and environmental advantages of scheduling appliances in tandem with utilizing PV and batteries throughout their lifespan. This not only benefits energy consumers in terms of cost savings but also contributes to broader societal goals of reducing carbon emissions and enhancing energy resilience.

3. The thesis has introduced an innovative home energy management system tailored for smart homes, leveraging the integration of PV, BESSs, and EVs. Central to this system is the development of an advanced energy flow management algorithm, which manages the energy distribution among various components and modes of operation. These include EV2G, EV2B, EV to home, battery to grid, battery to EV, battery to home, PV to home, PV to battery, PV to EV, PV to grid, grid to home, grid to battery, and grid to EV. Moreover, this paper has introduced an optimization strategy harnessing the feature of PSO to adjust key parameters, such as the DOD and size of the battery system, as well as the DOD of the EV's battery. Additionally, the optimization framework extends to scheduling household appliances, ensuring optimal energy utilization while balancing user preferences and energy demand. The PV, battery, and EV energy usage cost models were formulated and introduced into

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the optimization process, considering each system's installation costs and lifecycle. This approach represents a significant milestone in advancing HEMSs and achieves a more comprehensive understanding of the economic implications associated with energy consumption and utilization. In the culmination of this study, four scenarios were simulated, each accounting for the varying weather conditions during both winter and summer. The overarching objective of these simulations was to evaluate the efficacy of the proposed home energy management system across diverse operational contexts. At the core of this strategy lies a multifaceted approach aimed at achieving several objectives. Firstly, the system is developed to significantly reduce the actual energy cost, thereby delivering tangible financial benefits. Secondly, the system seeks to extend the operational lifetime of ESSs, ensuring long-term sustainability and reliability. Thirdly, through the optimization of energy usage and distribution, the system effectively minimizes energy losses, enhancing overall system efficiency. Moreover, a central focus of the proposed system is its capacity to mitigate environmental impact. Ultimately, the system was designed to maximize the financial returns associated with the installation of PV, battery, and electric vehicle components within the home. By carefully balancing energy supply and demand, the system aims to optimize the utilization of these resources, ensuring that homeowners derive maximum value from their investment in clean energy technologies. The findings underscored the effectiveness of the proposed home energy management system in achieving its intended objectives. They also highlighted the importance of fine-tuning parameters such as DOD, battery size, and charging/discharging schedules to achieve optimal performance and efficiency. By carefully adjusting these parameters, homeowners can realize significant savings on energy costs, minimize their carbon footprint, prolong the lifespan of ESSs, and maximize financial returns over the long term. The simulation analysis across diverse seasonal conditions and energy price variations demonstrated the proposed strategy's adaptability to real-world scenarios. Moreover, by considering user preferences and optimizing energy usage, the system effectively schedules appliances and promotes sustainable and efficient energy practices. Notably, the EV's battery contributed to

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financial savings more than PV and battery energy systems due to its low energy usage cost and high stored capacity. Its versatility in providing power to both the home demand and the grid during peak demand periods offers energy consumers a practical solution for maximizing financial benefits while contributing to a more sustainable and resilient energy infrastructure. The key insights gleaned from the results is the system's ability to empower household consumers to make environmentally conscious decisions while simultaneously maximizing their financial returns, extending energy systems' lifetime, integrating PV, battery, and EVs, and contributing to grid security.

In Part 3, the thesis provided **approaches** revolved around knowledge and skills for the energy and industry sectors' advancement. Through three distinct case studies, the thesis illuminated contributions towards achieving these objectives. The first case study utilized video game technology to raise awareness about energy transition and sustainability using SG, engaging individuals in a dynamic and immersive learning experience; the second case study delved into the realm of the smart industrial revolution, focusing on equipping future engineers with the requisite knowledge and skills to be in line with evolving technology and deal with real-world applications; the third case study carried out a literature review on sustainability-related topics to highlight the necessary skills for engineers to perform an efficient practice in their profession:

1. The thesis delved into the exploration of video games as a tool for fostering social awareness, particularly concerning energy transition and sustainability. Against the backdrop of rapid technological advancements in the energy sector and increasing concerns regarding energy security and climate change, this research sought to explore the potential impact of video games on enhancing HECs' awareness, thereby paving the way for more sustainable energy practices and behaviors. In the initial phase of this study, a questionnaire was carried out to gauge participants' baseline awareness levels regarding energy-related issues. Following this, participants were provided with a comprehensive explanation of the game rules, after which they engaged in gameplay. Subsequently, another round of questionnaires was conducted to assess the impact of gameplay on participants' awareness

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levels. The Power the Grid game was selected as a case study, and the involvement of ten participants provided valuable insights into the potential efficacy of gaming as an educational tool for enhancing awareness of energy-related topics. Through this structured approach, the thesis sheds light on the effectiveness of gamification in fostering awareness and understanding of complex energy concepts among participants. The findings of this study underscored the substantial impact of engaging in the Power the Grid game on enhancing social awareness and educating HECsabout energy issues. Before playing, participants had varying levels of knowledge, with some indicating limited understanding. However, after playing, there was a marked improvement in understanding the essential role of HECs in promoting energy security and the renewable energy sector, as well as in environmental conservation. The game also effectively highlighted HECs' contribution to reducing electricity prices and emphasized the significance of the smart meter in energy management. Overall, players unanimously agreed that the Power the Grid game significantly raised their awareness of society role importance in enhancing energy security, environmental conservation, and the renewable energy sector. In light of the findings, the study suggested developing the game with additional features aimed at further enhancing social awareness regarding the pivotal role of energy management in fostering a secure energy future and a healthier environment, while also ensuring access to affordable electricity. These proposed enhancements center on the implementation of DR programs, a growing practice adopted in various nations to balance energy supply and demand more efficiently. By integrating DR concepts into the game's framework, players can gain insights into the real-world applications of such strategies, thereby deepening their understanding of energy management principles and their broader implications for sustainable energy systems. The outcomes emphasized the potential of interactive gaming experiences to effectively convey complex concepts and foster a deeper appreciation for energy transition and sustainability. Furthermore, the findings suggested that gamification strategies hold promise for facilitating broader societal engagement and involvement in addressing pressing energy challenges. This study recommends fostering support for game

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designers and facilitating the marketing of educational games to broaden their reach and impact. This recommendation highlights the need for collaborative efforts among game developers and marketing professionals to elevate the visibility and accessibility of educational games, thereby harnessing their potential to drive meaningful change and engagement in energy transition and sustainability.

2. In line with the smart industrial revolution and the application of ICTs, the thesis delved into the aspect of enhancing engineering education to adequately prepare future engineers for challenges in the manufacturing sector. The introduction of the industrial production systems course into engineering curricula represented a significant step toward achieving this goal. This approach effectively linked theoretical knowledge with practical production processes, better preparing students for integration into the job market and making curricula more relevant to professional practice. This study described various aspects of the industrial production course in detail. This included course objectives, expected learning outcomes, and teaching methodologies. The course content encompassed theoretical, mathematical, and analytical components, as well as practical case studies and field visits. These elements were carefully designed to provide students with a comprehensive understanding of industrial production processes and their application in real-world scenarios. As part of the evaluation process, a feedback questionnaire was administered to students at the end of the academic semester and students' grade analysis was carried out for two academic years. This questionnaire sought to gather insights into students' perspectives on the industrial production course, including their perceptions of course content, teaching methods, and overall learning experience. The results of the feedback questionnaire revealed several key findings regarding the effectiveness of the course design. The majority of students expressed satisfaction with the course, indicating that it met their expectations and provided valuable learning experiences and the course objectives were successfully achieved. Furthermore, the feedback highlighted the importance of integrating theoretical knowledge with practical experiences. Students appreciated the opportunity to apply their learning in real-world settings, such as through case studies and field visits. These experiences enhanced their

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understanding of course material and provided valuable insights into the complexities of industrial production processes. Additionally, the feedback indicated that students found the teaching methodologies employed in the course to be effective. Besides, the grades analysis results underscored the students' interest in the topic, showing high grades with an improvement in students' performance during two academic years. The combination of lectures, discussions, and hands-on activities helped to reinforce learning and fostered a deeper engagement with course material. Moreover, students valued the opportunity to interact with industry professionals during field visits and guest lectures, as it provided them with valuable insights into current industry practices and trends. Ultimately, the course effectively equips students with the skills and knowledge needed to excel in their future careers, as such, the integration of the industrial production course into chemical engineering curricula represents an advancement in engineering education and sets the stage for sustained advancement in the field.

3. A literature review was carried out on teaching optimization tools and simulation software in universities, energy management strategies, and battery manufacturing. The selecting papers process was carried out on the Web of Science, between 2014 and 2023, with specific criteria in the title and then refined with specific criteria in the abstract and topic for each section. Finally, articles were selected for each section by reading the abstracts to identify those that are in this study's scope. The optimization and simulation tools criteria are "teaching" in the title, then refined with the criteria "optimization" and "simulation" in the abstract" and "students" in the topic. For the second section, the criteria are "energy management" in the title, then refined with the criteria "home energy management" in the abstract, and "optimization" and "energy storage" in the topic. Finally, the third section criteria are "battery performance" in the title, then refined with "production" in the abstract and "sustainable" in the topic. The study aimed to figure out the intersection between these topics in terms of sustainability and to demonstrate how are the wide usage of teaching optimization tools and simulation software in real-world applications. The literature review examined universities' courses in teaching

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different simulation tools and simulation tools in several engineering majors. Besides, it showed that simulation tools such as optimization algorithms and machine learning and simulation software such as Matlab are widely used in developing energy management strategies. For battery sustainable manufacturing, a notable improvement is being achieved in using renewable materials and sustainable approaches for manufacturing battery's cathode and anode materials. The literature revealed a lack of teaching optimization tools and simulation software compared to the published work on using these tools in energy management strategies. In contrast, the study underscores the possibility of enhancing education by modernizing curricula and integrating the principles of optimization, machine learning, automation, and data analysis software. Besides, the study shed light on some overlooked sustainability aspects in energy management such as investment cost, realistic energy selling prices, and the lifespan and the operation of ESSs in terms of optimal charge/discharge rate, depth of discharge, and operation temperature. Regarding battery manufacturing, it showed the possibility and feasibility of utilizing several resources such as agriculture, industry, fuel wastes, and nature and recycling failed batteries for extracting anode and cathode materials, where most studies focused on lithium batteries. Engineers can apply optimization principles to refine key factors, such as material properties and process parameters (weight and capacity).

Once the results of each of the three parts of the thesis are obtained, as previously and consecutively explained, specific objectives related to each of them are achieved, giving the following related conclusions:

1. The thesis investigated the key drivers for adopting efficient energy practices using HEMSs, which contribute to understanding the challenges and opportunities in sustainable energy practices adoption within the residential sector. It found that enhancing environmental awareness and family economic benefits significantly contributes to the use of HEMSs. This helps policymakers draw up policies to encourage energy consumers to use HEMSs, resulting in energy costs and carbon emissions reduction and enhancing energy security.
2. Besides, the thesis proposed innovative demand-side management strategies within SG delves into the application of

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advanced technologies and methodologies. The developed strategies considered electricity tariff incentives, energy consumers' preferences, preserving the environment, and energy systems life cycle. The thesis showed how these strategies provide benefits for energy consumers, the environment, and the overall electrical system by reducing energy usage costs, carbon emissions, and reliance on fossil fuels while simultaneously extending energy systems' lifetime and saving energy.

3. In addition, the thesis focused on utilizing technologies to raise awareness of energy consumers about their role in energy transition. It elucidated that video games of energy raise individuals' awareness and encourage active participation and responsible energy behavior leading to establishing a sustainable energy system. Besides, It highlighted the role of education in equipping future engineers by modernizing curricula, efficient teaching methods, teaching optimization and software tools, and on-site visits.

In conclusion, we can tell that the thesis provided practical solutions for moving toward energy sustainability and transition in terms of demand-side management in SG technology, raising awareness, and educating future engineers. It proposed efficient demand side management strategies to integrate RESs and ESSs, raised society's awareness of energy consumers' role in energy sustainability, highlighted how the residential sector contributes to this endeavor, and underscored the importance of educating future engineers to achieve efficient and sustainable tasks in scientific research and their professions, which are aligned with the objectives of the "European Green Deal", "Paris Agreement", "NZE scenario", and "EAP". In other words, this work showed how the integration of clean energy systems, batteries, and electric vehicles drives sustainability and offers contributions to human wellbeing (reducing energy costs and independent self-consumption), preserving the environment (reducing carbon emission), and enhances overall energy systems (energy efficiency and energy security). This thesis brought theory regulations, policies, and knowledge to real-world applications, offering a contribution for both individuals and policymakers in terms of moving toward sustainability and energy transition.

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DIFFUSION OF RESULTS

PUBLICATIONS IN SCIENTIFIC BOOKS AND JOURNALS

(The required information is included in the title page of the corresponding chapter)

Al Muala, Z. A., Bany Issa, M. A., Bello Bugallo, P.M. (2024). Integrating Life Cycle Principles in Home Energy Management Systems: Optimal Load PV-Battery-Electric Vehicle Scheduling. Batteries, 10 (4), 138. https://doi.org/10.3390/batteries10040138. (see Chapter 7)

- Affiliation: TECH-NASE Research Group, Department of Chemical Engineering, Universidade de Santiago de Compostela, 15705 Santiago de Compostela, Spain.
- Publisher: MDPI
- Journal: Batteries
- eISSN: 2313-0105
- Impact Factor: 4.6 in 2023 (Database: Web of Science)
- Category: Electrochemistry (Database: Web of Science)
- Relative position: Q2 (16/45) in 2023 (Database: Web of Science)
- DOI: https://doi.org/10.3390/batteries10040138
- Year of publication: 2024
- Article views: 1102
- Contribution of the doctoral student: contribution to conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing— review and editing, visualization, and project administration.
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Al Muala, Z. A.[1], Bany Issa, M. A.[1], Rodriguez, J.[2], Bello Bugallo, P.M[1]. (2024). Antecedents of energy consumption intention to usage by home energy management system: a case study of Galicia's homes in Spain. Renewable Energy and Environmental Sustainability, 9, 3. https://doi.org/10.1051/rees/2024004. (see Chapter 4)

- Affiliation: [1]TECH-NASE Research Group, Department of Chemical Engineering, Universidade de Santiago de Compostela, Spain.
  [2]Department of Public Law and Political Theory, Universidade de Santiago de Compostela, Spain.
- Publisher: EDP Sciences
- Journal: Renewable Energy and Environmental Sustainability.
- eISSN: 2493-9439
- Impact Factor: 2.5 in 2021(Database: Exaly)
- Category: Renewable energy (Database: Exaly)
- Relative position: Q1 (5/31) in 2021(Database: Exaly)
- DOI: https://doi.org/10.1051/rees/2024004
- Year of publication: 2024
- Article views: 730
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Al Muala, Z. A.[1], Bany Issa, M. A.[1], Sansó-Rubert Pascual, D.[2], & Bello Bugallo, P. M[1]. (2023). Realistic Home Energy Management System Considering the Life Cycle of Photovoltaic and Energy Storage Systems. Sustainability, 15 (14), 11205. https://doi.org/10.3390/su151411205. (see Chapter 6)

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  [2]Department of Legal and Political Sciences, Universidad Europea, 28670 Madrid, Spain.
- Publisher: MDPI
- Journal: Sustainability
- eISSN: 2071-1050
- Impact Factor: 3.3 in 2023 (Database: Web of Science)
- Category: Environmental sciences (Database: Web of Science)
- Relative position: Q2 (159/358) in 2023 (Database: Web of Science)
- DOI: https://doi.org/10.3390/su151411205
- Year of publication: 2023
- Citations: 5 in Google Scholar, 3 in MDPI, 1 in Web of Science
- Article views: 1662
- Contribution of the doctoral student: contribution to conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing— original draft preparation, writing— review and editing, visualization, and project administration.

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Al Muala, Z. A.[1], Sansó-Rubert Pascual, D.[2], Bello Bugallo, P.M[1]. (2023). Social Awareness about Energy Transition and Sustainability: The Role of Video Games. Simulation and Gaming for Social and Environmental Transitions: In the Proceedings of the 54th Conference of the International Simulation and Gaming Association, (pp. 423-431). (HAL open science). ISBN: 979-10-415-2760-1. (see Chapter 8)

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  [2]Department of Legal and Political Sciences, Universidad Europea, 28670 Madrid, Spain
- Publisher: HAL open science
- Book chapter: Simulation and Gaming for Social and Environmental Transitions (423-431)
- ISBN:979-10-415-2760-1
- Year of publication: 2023
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PRESENTATIONS IN INTERNATIONAL CONFERENCES

Costa, R., Brandão, A. T., Al Muala, Z. A., Parajó, J. J., Bello Bugallo, P.M, Silva, A. F., Pereira, C. M. Rethinking Circularity of Electrified Interfaces for Sustainable Energy Storage Devices. The 29th EUCHEM Conference on Molten Salts and Ionic Liquids, Universidade de Santiago de Compostela, Spain, April, 22-26, 2024.

Al Muala, Z. A., Sansó-Rubert Pascual, D., Bello Bugallo, P.M. Social Awareness about Energy Transition and Sustainability: The Role of Video Games. The 54th edition of the International Simulation and Gaming Conference, La Rochelle University, France, July, 4-7, 2023.

Al Muala, Z. A., Bello, H. J., Bello Bugallo, P.M. Realistic Home Energy Management System Considering the Life Cycle of Photovoltaic and Energy Storage Systems. World Renewable Energy Congress XXI, Murdoch University, Australia, December, 4-9, 2022.

Al Muala, Z. A., Rodriguez, J., Bello Bugallo, P.M. Antecedents of Energy Consumption Intention to Usage by Home Energy Management System: A Case Study of Galicia. World Renewable Energy Congress XXI, Murdoch University, Australia, December, 4-9, 2022.

Lage-Díaz, M., Al Muala, Z. A., Sansó-Rubert Pascual, D., Salgado, J., Bello Bugallo, P.M. Sustainable Use of Batteries According to the Electricity Prices: Energy Management and Lifespan. XXVI Galician-Portuguese Chemistry Meeting, Universidade de Santiago de Compostela, Spain, November, 16-18, 2022.

Bello Bugallo, P.M, Al Muala, Z. A., Yesodharan, Y. Renewable Energy, Climate Change and Sustainable Development: Training Professionals and Researchers for a Sustainable Future. International Conference on Sustainable Energy Education (ICSEE), University of Kerala, India, January, 10-12, 2022.

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The thesis focuses on advancing energy transition and sustainability. It investigates the factors that might affect households to adjust energy consumption. It also proposes demand side management strategies in the smart grid. These strategies provide benefits for energy consumers and the electric grid by reducing electricity costs, extending the lifetime of local energy systems (solar panels and energy storage systems), and enhancing grid stability. Besides, it proposes approaches for raising awareness about the role of energy consumers in enhancing energy transition and sustainability and training future engineers to enhance their knowledge and skills in line with technology development.