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Validación electrónica de vehículos. Nuevas metodologías y posibles aportaciones al transporte sostenible

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Resumen

Los vehículos automóviles están adquiriendo una mayor complejidad electrónica debido al incremento del número de unidades electrónicas de control. Su número seguirá creciendo en el futuro debido a la integración de nuevas prestaciones vehículo cada vez más complejas como consecuencia de la llegada vehículo autónomo. Consecuentemente, las técnicas de validación del *software* resultan un elemento clave para los constructores automóviles con el fin de asegurar la calidad final y la seguridad del vehículo. A su vez, este proceso de validación conlleva unos costes elevados a los fabricantes que deben reducirse para asegurar una mayor rentabilidad.

Gran parte de los modelos de transporte sostenibles se basan en soluciones eléctricas o en otras, que impliquen la sustitución de trenes de tracción tradicionales por otros que generen menos emisiones locales. Un modelo de transporte puede ser innovador per se al ofrecer una solución hasta ahora no propuesta, o bien puede innovar al proponer aplicaciones que beneficien a la sostenibilidad, independientemente de usar modelos ya conocidos en la literatura, como bien pueda ser contribuciones al ecodiseño, a las técnicas *Vehicle-to-X*[1] (vehículo conectado), o por proponer mejoras a tener en cuenta en las actuales políticas europeas, como el *European Green Deal* (Pacto Verde Europeo), relacionadas con los modelos de transporte sostenibles existentes.

¿Cuál es el nexo entre la validación *software* de automoción y los modelos de transporte sostenibles? Pues bien, validando un *software* y añadiéndose nuevas funcionalidades, se pueden reducir los consumos energéticos y conseguir mejoras en las prestaciones de los transportes sostenibles. En esta tesis se ofrecen soluciones innovadoras de validación basadas en sistemas expertos. Se propone un modelo de transporte sostenible demostrando su viabilidad económica. Hecho esto, se evalúa las aportaciones del *software* de las unidades electrónicas de control de un vehículo eléctrico sobre la sostenibilidad, tales como disminución de emisiones durante el diseño de productos (ecodiseño) y reducción de consumo energético de edificios gracias a la técnica *Vehicle-to-Building* (vehículo conectado a edificio), todo ello con la finalidad de convertir los modelos de transporte en modelos aún más respetuosos con el medioambiente. Finalmente, se analiza el impacto de los sectores sociales sobre los modelos de transporte sostenible, realizando proposiciones a considerar en las actuales políticas medioambientales en discusión en la Unión Europea, como el *European Green Deal*, con el fin de mejorar la sostenibilidad de los modelos de transporte basados en movilidad eléctrica.

Palabras Clave— *Eco-routing (navegación ecológica), eco-charging (carga ecológica), eco-driving (conducción ecológica), validación de software, transporte sostenible*

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[1] En esta tesis, los términos técnicos en inglés que aparezcan son mostrados en la sección Nomenclatura con su correspondiente traducción. Posteriormente, se emplearán indistintamente en cualquiera de las dos lenguas. De términos ampliamente utilizados en el lenguaje corriente tales como software, test y hardware no se mostrará la traducción.

Abstract

Vehicles are becoming sophisticated electronic systems due to the fact that they are integrating a significant number of electronic control units. This trend will certainly continue in the year to come as more complex functions will be integrated in vehicles specially thanks to the autonomous driving. Consequently, software validation techniques are a key element for car manufacturers in order to ensure the quality of the vehicle which will be marketed. In turn, this validation process increases costs for manufacturers, and this must be reduced with the aim of improving the profitability of projects.

Most of the sustainable transport models are based on electric solutions or on similar solutions which imply that traditional powertrains are substituted by others those that generate fewer local emissions. A transport model can be innovative per se by offering solutions that have not been proposed so far, or it can innovate by offering applications on different fields such as eco-design, *Vehicle-to-X* technique or European policies (European Green Deal), which benefits sustainability based on models already described in the literature.

What is the link between automotive software validation and sustainable transport models? By validating software and adding new functionalities, energy consumption can be significantly reduced. Consequently, this thesis offers innovative validation solutions based on expert systems. A sustainable transport model is proposed, demonstrating its economic viability. Once this is done, it evaluates the contributions of the electronic control unit software of an electric vehicle (the main actor of sustainable transport models) on sustainability and society, such as the reduction of emissions during a product design (eco-design) and the improvements in the vehicle-to-building technique with the aim of making transport models even more eco-friendly. Finally, the impact of the social sectors on sustainable transport models is studied in detail, making proposals to be considered in the current environmental policies under discussion within the European Union, such as the European Green Deal, in order to improve the sustainability of transport models based on electric mobility.

Keywords— *Eco-routing, eco-charging, eco-driving, software testing, sustainable transport*

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NOMENCLATURA

ACC	*Adaptive Cruise Control*	Control Adaptativo de Crucero
ADAS	*Advanced Driving Assistance Systems*	Sistemas de Ayuda a la Conducción
ASIL	*Automotive Safety Integrity Level*	Nivel de Integridad de Seguridad en automoción
AUTOSAR	*AUTomotive Open Systems Architecture*	Arquitectura abierta de sistemas de Automoción
BEMS	*Building Energy Management System*	Sistema de control de la gestión de energía del edificio
CAN	*Controller Area Network*	Controlador Area Local
DLLs	*Dynamic-link libraries*	Biblioteca Dinámica de datos
EC	*Eco-Charging*	Carga Ecológica
ECU	*Electronic Control Unit*	Unidad de Control Electrónica
EDR	*Eco-Driving*	Conducción Ecológica
EEPROM	*Electrically erasable programmable read-only memory*	Memoria de solo lectura programable eléctricamente
EGD	*European Geen Deal*	Pacto Verde Europeo
EGR	*Exhaust Gas Recirculation*	Recirculación de gases de escape
ER	*Eco-Routing*	Navegación Ecológica
ESP	*Electronic Stability Program*	Programa de Estabilidad Electrónica
EV	*Electric Vehicle*	Vehículo Eléctrico
EX	*Expert System*	Sistema Experto
HIL	*Hardware-in-the-loop*	Hardware en el bucle
LIN	*Local Interconnect Network*	Red Local de Interconexión
LSTM	*Long Short-Term Memory*	Red Neuronal de Memoria grande de corto plazo
NAR	*Nonlinear autoregressive neural network*	Redes Neuronales no lineales autorregresivas
RE	*Renewable Energy*	Energía Renovable
SAE	*Society of Automotive Engineers*	Sociedad de Ingenieros de Automoción
SG	*Smart Grid*	Red Inteligente
SM	*Software Module*	Módulo Software
TC	*Test-case*	Caso de test

TIR	*Internal Return Rate*	Tasa Interna de Retorno
USB	*Universal Serial Bus*	Bus Serie Universal
VAN	*Net Present Value*	Valor Actual Neto
VCU	*Vehicle Control Unit*	Unidad de Control Vehículo
V2B	*Vehicle-to-Building*	Vehículo Conectado a edificación
V2G	*Vehicle-to-Grid*	Vehículo Conectado a Red
V2H	*Vehicle-to-Home*	Vehículo conectado a casa

1. PREÁMBULO

El *software* se encuentra cada vez más presente en nuestras vidas. Es complicado encontrar aparatos electrónicos en la vida diaria que no lleven integrado un *software* embebido de mayor o menor complejidad. Antes de la comercialización de todo producto, se ha de llevar a cabo un exhaustivo control y validación del sistema, incluido el *software* y su impacto en la electrónica [1, 2]. Este proceso de validación conlleva un coste importante para las empresas que debe ser reducido para mejorar la rentabilidad del proceso de desarrollo de un producto [3, 4]. Por tanto, actualmente las empresas se encuentran en la encrucijada de encontrar técnicas de validación que aseguren reducir el tiempo necesario para asegurar su calidad y fiabilidad a la vez que se reduzcan los costes. Este aspecto se hace mucho más presente a medida que el producto electrónico va adquiriendo complejidad, como es el caso del sector de la automoción donde existen una gran cantidad de unidades electrónicas de control *(ECUs)* encargadas de controlar funciones, en algunos casos críticas, con fuerte impacto en la seguridad del vehículo y de sus pasajeros [5, 6].

Por otra parte, la sostenibilidad es un factor esencial para asegurar la conservación de los recursos naturales. De hecho, es un tema ante el cual la sociedad muestra una gran sensibilidad. Si bien este campo es amplio, uno de los puntos más trabajados es la proposición de modelos de transporte sostenibles basados, en la mayoría de los casos, en soluciones eléctricas por su no generación de emisiones [7]. Sin embargo, la sostenibilidad del transporte y los modelos no deben ir únicamente centrados en esas soluciones, pues el uso del vehículo eléctrico *(EV)* implica mejoras en ámbitos más amplios como el ecodiseño, técnicas como el *Vehicle-to-Building* (*V2B*), etc. En otras palabras, el transporte sostenible tiene un impacto mucho mayor que la propia disminución de la generación de emisiones locales.

Otra importante cuestión es cómo ligar el transporte sostenible y la validación del *software*. La validación del *software* requiere integrar el concepto de sostenibilidad durante su realización, campo que no ha sido explorado con detalle [8, 9]. A su vez, el *software* validado integrándolo con módulos *software (SMs)* específicos, puede proporcionar una herramienta muy importante a la sostenibilidad y a sus modelos de transporte. Como ejemplo, vehículos con algoritmos desarrollados de *Eco-Driving* (*EDR*), *Eco-Routing (ER)* o incluso algoritmos que realicen estimaciones de la generación de energía y contribución de las energías renovables *(REs)* en la generación de electricidad. En esta tesis, se presenta un modelo de transporte sostenible económicamente viable[2]. Se demuestra que el *software* de automoción validado y modificado[3], al integrar nuevos *SMs*, genera reducciones de consumo energético que repercuten en hacer más limpio aún los modelos de transporte sostenible reduciendo, por ejemplo, las emisiones en otras actividades de la sociedad como es el diseño de productos más verdes (ecodiseño)[4] o mejorar las aportaciones a la técnica *V2B*[5]. A su vez, se demuestra también en esta tesis, que, gracias al *software* validado y modificado, se puede conseguir que los procesos de carga de los *EVs* sean aún más limpios al informar al conductor sobre los momentos del día en los que la aportación de *REs* es más elevada. Finalmente, gracias al muestreo de cómo son usados los *EVs* por los diferentes sectores sociales considerados (autónomos, trabajadores locales o trabajadores que trabajan fuera de una determinada ciudad), la presente tesis ofrece proposiciones para los legisladores europeos de tal manera que las nuevas políticas se centren sobre los sectores sociales que más pueden contribuir a la sostenibilidad y a los modelos de transporte sostenibles para que sean aún más verdes y respetuosos con el medioambiente[6]. Consecuentemente, la validación *software*, el propio desarrollo del *software*, los modelos de transporte y la sostenibilidad están íntimamente unidos tal como se demuestra en esta tesis y en las publicaciones que la acompañan.

Finalmente, es vital exponer de manera sucinta la relación existente entre esta tesis doctoral y los cambios legislativos actuales. Tal como ha sido publicado recientemente, la Unión Europea prohibirá en 2035 la venta de vehículos de combustión [10]. Esto, sin lugar a duda, implica la necesidad de fomentar el *EV* de manera urgente. Esta tesis se centra fuertemente en este aspecto pues:

a) Promueve aplicaciones del *EV* en tecnologías futuras clave para la sostenibilidad como es el caso de *V2B, Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H)* y *Smart Grid (SG).*
b) Las propuestas innovadoras de validación *software* son válidas tanto para vehículos de combustión como para *EVs.* Tal como se detallará a lo largo de esta tesis doctoral, estas

[2] Este aspecto queda recogido en la siguiente publicación *"Macro-economic impact,* reduction *of fee deficit and profitability of a sustainable transport model based on electric mobility. Case study: City of León (Spain)"*, publicado en la revista Energy.

[3] Este aspecto queda recogido en las siguientes publicaciones:
"Application of rule-based expert systems in hardware-in-the loop simulation case study: Software and performance validation of an engine electronic control unit" publicado en *The Journal of Software: Evolution and Process*

[4] Este aspecto queda recogido en la siguiente publicación *"Contribution of Driving Efficiency and Vehicle-to-Grid to Eco-Design"*, publicado en Energies.

[5] Este aspecto queda recogido en la siguiente publicación *"Contribution of Driving Efficiency to Vehicle to Building"*, publicado en Energies.

[6] Este aspecto queda recogido en la siguiente publicación "*Can Eco-routing, ¿Eco-driving and Eco-charging Contribute to the European Green Deal?",* publicado en Energy

técnicas se basan en el uso de modelos Simulink® empleados para codificar el *software.* Por tanto, es indiferente si estos modelos se refieren a una *ECU* de un *EV* o bien a un sistema de iluminación siempre y cuando las especificaciones se hayan modelado con Simulink®.

2. INTRODUCCIÓN

2.1 El sector de la automoción

El sector de la automoción lleva haciendo frente a crisis importantes desde el año 2008 así como a continuas necesidades de fuerte reconversión para mantener su competitividad. En el citado año 2008, se produjeron desplomes de ventas que llegaron a convertirse en los peores datos registrados en la historia del sector. Este hecho hizo que algunos constructores, muy centrados en aquellos momentos en los mercados europeos y con escasa globalización en sus ventas, llegaran a sufrir serias pérdidas económicas y falta de circulante que pusieron en riesgo su viabilidad [11]. Tal fue el caso de PSA Peugeot Citroën que, para asegurar su actividad, en el año 2012 firmó un acuerdo con el gigante General Motors, gracias al cual se conseguirían alcanzar sinergias para ambas empresas cercanas a los 2.000 millones de dólares mediante el desarrollo de 4 plataformas conjuntas que implicarían ahorro de costes tanto en compras como en el desarrollo de los productos [12]. Ni siquiera este acuerdo tan interesante para PSA Peugeot Citroën fue suficiente para su viabilidad, de tal manera que la marca china Donfeng Motors adquirió una parte importante de su accionariado. No solamente esta empresa francesa ha sufrido la crisis del sector automóvil. Otras como Opel o Vauxhall sufrieron cambios de accionariado al necesitar un importante cambio de rumbo y estrategia debido a las pérdidas económicas constantes que venían sufriendo. Mucho más reciente, es la fusión de Fiat y PSA para conseguir sinergias de desarrollo y ahorro de costes para asegurar la rentabilidad de ambas marcas [13]. Por último, el impacto de la pandemia actual no es un elemento que se deba olvidar, pues ha golpeado triplemente a este sector al impactar su cadena de suministros, se han producido cierre de fábricas parciales o totales, como es el caso de Nissan en Barcelona, y, finalmente, ha habido un colapso en la demanda. Por tanto, y, en resumen, el sector de la automoción es altamente sensible a todo lo que le rodea, pero ha mostrado una gran capacidad de adaptación para sobrevivir a las crisis económicas y sanitarias que, por desgracia, se han sufrido en los últimos años

Sin lugar a duda, se trata de un sector fascinante al ser capaz de estar luchando por su viabilidad para asegurar la supervivencia de los constructores, pero al mismo tiempo, es capaz de proponer soluciones tecnológicas altamente complejas que, hace unos años, los clientes no hubieran imaginado. Es evidente que en este punto nos referimos al vehículo autónomo, producto en el que todos los constructores y proveedores como Bosch o Valeo, están invirtiendo cantidades ingentes de dinero para su rápida comercialización [14, 15]. Entre todas estas tecnologías se puede destacar el avance en tratamiento de imágenes y uso de sensores como los radares, lidar y cámaras con el consiguiente impacto en los sistemas de trenes de tracción, frenada, seguridad (ISO 26262) y columna de dirección. Dicho esto, es conveniente exponer en párrafos posteriores un mayor detalle de estos aspectos para una mejor comprensión.

La *SAE* internacional, antes conocida como la Sociedad de Ingenieros de Automoción (*Society of Automotive Engineers*), propuso una clasificación de niveles de conducción autónoma en función de la intervención humana, para establecer cuán autónomo podía llegar a ser un vehículo [16]. Estos niveles abarcan desde el 0, en el cual no existe ningún tipo de conducción autónoma, hasta el nivel 5 donde existe ya una automatización total. Entre los citados niveles se encuentra el nivel 1, en el que los vehículos integran ya algunas funciones de asistencia a la conducción como el regulador de velocidad, el nivel 2 con una automatización parcial integrando funciones como *Adaptive Cruise Control (ACC)* sin tener en cuenta el entorno del vehículo, el nivel 3 donde se incorpora ya la automatización condicional teniendo en cuenta las condiciones de la vía de circulación y, el nivel 4 donde no se requiere la intervención del conductor. ¿Cuál es la diferencia entre un nivel 4 y 5? Pues bien, la respuesta si bien es futurista, es tan simple como que en un vehículo autónomo nivel 5 sólo habrá asientos para los ocupantes, y no existirán ni volante ni palanca de marcha. Es complicado saber en qué fecha se podrá llegar a un nivel 5, si bien se espera que se pueda estar en un nivel 4 en fechas cercanas a 2030. Cabe mencionar un aspecto fundamental y es que no sólo el vehículo autónomo se enfrenta a barreras puramente técnicas, sino a barreras de otro tipo no menos importantes, como es el caso de la seguridad, aspectos legales, económicos y éticos. Desde un punto de vista ético, es posible que, en una circunstancia dada, el vehículo tenga que decidir entre salvar la vida a su conductor a costa de la de un peatón. El análisis de todos estos factores excede el objetivo de esta tesis, si bien el lector puede encontrar informes donde se detallan las perspectivas y lo que se espera del coche autónomo en el periodo 2020-2040 [17, 18, 19].

Desde un punto de vista puramente tecnológico, resulta claro que la complejidad electrónica de los vehículos va aumentando poco a poco, de tal manera que el número de *ECU*s se está incrementando de manera sustancial. En este punto conviene aclarar que, por *ECU*, esta tesis se refiere a todo sistema embebido que se utiliza para controlar un determinado sistema mediante el uso de sensores y actuadores que ejecutan las órdenes que envía el *software* que compone la *ECU*. Consecuentemente, es el elemento clave de esta tesis, así como el *software* que ejecuta. A su vez, teniendo en cuenta el gran número de *ECU*s que integran un vehículo, la validación del *software* de una *ECU* se convierte en un elemento crítico, cuya validación y aseguramiento de la calidad resulta fundamental para garantizar la integridad del pasajero. Debido a la gran cantidad de líneas de código presentes en el *software* de las *ECU*s y a la dificultad que conlleva su validación, la importancia de éste será descrita en el próximo apartado con detalle.

2.2 El *software* en automoción

El desarrollo de *software* es un elemento clave en automoción para asegurar el buen funcionamiento de las *ECU*s dentro de la arquitectura electrónica que presenta el vehículo. Debe imaginarse el funcionamiento de una red de este tipo como una orquesta en donde los músicos (las *ECU*s) deben funcionar de manera coordinada para que la información transmitida en tiempo real garantice que cualquier coche (sea *ADAS*[7] nivel 0 o superior) responda adecuadamente en todas las circunstancias. A modo de ejemplo, y para una mejor comprensión del lector, la función *ACC* necesita la colaboración de múltiples calculadores. En primer lugar, esta función (en su versión más simple) permite que, una vez establecida una velocidad objetivo por parte del conductor, el coche la mantenga o la reduzca su velocidad en función de la distancia con el vehículo que la precede. Lógicamente, estas prestaciones se ven mejoradas en niveles de automatización superiores permitiendo el cambio de carril. Dicho esto, para poder llevar a cabo esta función, el coche necesita un calculador encargado de procesar la información relativa al vehículo que lo precede. Para ello, entre otras cosas, necesita la información proporcionada por el calculador *Electronic Stability Programm (ESP).* El calculador motor, dicho con otras palabras, la *ECU* encargada de controlar el par que se va a aplicar sobre el motor térmico, *VCU (Vehicle Control Unit)* en su versión *EV*, tiene que procesar toda la información procedente de todos los calculadores y el estado del motor para elegir el par final que se va a aplicar sobre el motor. Esto es lo que técnicamente se suele denominar cadena de arbitraje de par. Esta descripción sucinta le permite al lector tener una idea de la complejidad que entraña las redes electrónicas de vehículos en las que el *software* juega un papel determinante.

[7] El acrónimo ADAS es ampliamente utilizado en el mundo de la automoción. Sus siglas significan Advanced Driver-Assistance Systems.

Existen muchas metodologías de desarrollo de *software* tales como el ciclo en V o, más modernas, los métodos ágiles [20, 21]. En cualquier caso, a partir de unos requerimientos escritos de lo que se espera del producto, se debe conseguir proporcionar un *software* que funcione correctamente y con la fiabilidad esperada. La cuestión obvia es ¿cómo garantizan los fabricantes esa fiabilidad y que el *software* responde a lo esperado? Aquí de nuevo se introduce un elemento clave en esta tesis: la validación del *software*. Si bien todo esto se detallará en próximos apartados de esta tesis doctoral, este proceso consiste en la creación de bibliotecas de *tests*, técnicamente designado como generación de *Test-Cases (TCs)* con el fin de comprobar si dada unas condiciones iniciales del sistema y unas acciones a realizar, el sistema responde acorde a lo esperado. Este proceso requiere de muchos aspectos a tener en cuenta, entre ellos, conocimientos técnicos detallados sobre el funcionamiento de los *SMs* a testear, recursos económicos importantes para la adquisición de vehículos prototipo, así como simuladores *hardware-in-the-loop (HIL)* para comprobar la correcta integración del *software* y el *hardware*, etc. [22, 23]. El lector puede deducir que las inversiones y el tiempo necesario para validar el *software* de una *ECU* son elevados, si bien no es lo mismo validar una *ECU* encargada de controlar la iluminación interior de un vehículo que una *ECU* encargada de controlar un motor térmico, donde intervienen una gran cantidad de *SMs* y variables físicas que, sin duda, hacen de esta *ECU* una de las más complicadas de validar. Por tanto, uno de los ejes fundamentales ligados a la validación del *software* de automoción no es otro que reducir al máximo las horas de validación y los recursos necesarios para la disminución de los costes económicos que lleva asociada esta actividad al igual que asegurar que dicha reducción no repercuta en la calidad y fiabilidad del *software*. Este aspecto es un eje clave tratado en esta tesis doctoral.

Por último, es importante destacar que la validación *software* hace frente a retos relacionados con la generación de *TCs* adecuados y pertinentes para asegurar que el *software* se prueba en condiciones representativas de funcionamiento, así como a problemáticas técnicas asociadas a la simulación *HIL* [21, 22, 23]. Referente al primer punto, la inteligencia artificial propone soluciones para la generación de *TCs* en tiempo real. Referente al segundo punto, la dificultad actual a la hora de automatizar *TCs* no es otra que la interacción de los *SMs* de tal manera que los resultados esperados indicados en el *TC* podrían ya no ser válidos. Consecuentemente, el ingeniero de validación o bien el script de automatización no sería capaz de discernir si el *software* se ha comportado correctamente o no. Esta tesis doctoral muestra cómo las bibliotecas dinámicas de datos *(Dlls)* juegan un papel esencial para mejorar la automatización de *TCs*.

2.3 El *software* y la sostenibilidad

Desde hace años, el concepto de la sostenibilidad está ligado al mundo de la ingeniería. Consecuentemente, resulta fundamental definir este concepto de una manera simple e intuitiva. Básicamente, la sostenibilidad consiste en atender las necesidades actuales sin comprometer la capacidad de las generaciones futuras de satisfacer las suyas, garantizando el crecimiento económico, el cuidado medioambiental y el bienestar social. Estos tres aspectos es lo que se suele conocer como la triple vertiente de la sostenibilidad. No es complicado deducir que todas las actividades ingenieriles, y la automoción impactan de manera directa sobre la sostenibilidad. El uso abusivo de materiales o bien materiales que sean difíciles de reciclar, el diseño de procesos altamente consumidores de energía, etc. implican claramente una repercusión directa sobre la sostenibilidad. En este punto, aparecen conceptos importantes tales como el ecodiseño, consistente en incorporar criterios ambientales en la fase de concepción y desarrollo de un producto, bien o servicio, de tal manera que se tomen las medidas preventivas adecuadas con vistas a mitigar los impactos ambientales en las diferentes fases del ciclo de vida de un determinado producto, desde su fase de concepción, continuando por su producción y finalizando con la eliminación del mismo [24]. Centrándonos en la parte de diseño, y más concretamente en la validación del *software*, es altamente importante centrarse en las repercusiones que tienen estas actividades en el medioambiente [8, 9]. Más específicamente, el proceso de validación de *software* implica el uso de simuladores *HIL y* rodajes durante una gran cantidad de kilómetros para asegurar la calidad del *software* antes de su comercialización. Consecuentemente, el proceso de validación *software* conlleva la generación de emisiones tanto debido al uso de simuladores *HIL* como por la fabricación de vehículos prototipo. En este punto, es conveniente hacer hincapié en el hecho de que validar un *software* de una *ECU* con una alta complejidad de diseño, implica una gran cantidad de horas de validación que, necesariamente, conlleva un elevado consumo eléctrico. Como consecuencia, la integración de las *REs* junto con una adecuada planificación del proceso de validación del *software* reduce las emisiones. En lo referente al uso de vehículos prototipo, éstos son imprescindibles para poder realizar las actividades propias de puesta a punto del *software*, más conocido como *tuning activities* en terminología técnica anglosajona, así como la validación *software* en condiciones reales, es decir, cuando el *software* del calculador en cuestión interactúa directamente con el resto de las *ECUs* de la red electrónica del vehículo. La elección adecuada y óptima de los *TCs* que deben ser ejecutados utilizando vehículos prototipo y cuáles mediante simulación *HIL* repercute en una disminución de los tiempos de validación, una necesidad menor de vehículos prototipo, así como una mejor integración de las *REs*, tal como se analiza ampliamente en esta tesis doctoral. Para conseguir esto, se han de proponer técnicas de validación de *software* que permitan la reducción de costes, mejorar la calidad del *software*, que permitan elegir los medios óptimos de validación y contribuir a una mejor integración de las *REs* en el proceso de diseño sin olvidar en ningún momento la sostenibilidad o, dicho con otras palabras, el impacto económico y medioambiental de este proceso. Este punto clave es tratado en esta tesis doctoral.

2.4 El vehículo y la sostenibilidad

Los vehículos realizan una función clave en la sociedad actual, y resulta ciertamente inimaginable un mundo sin coches. Esta realidad obliga a los ingenieros a buscar soluciones que impliquen una disminución de los impactos medioambientales de las actividades relacionadas con la automoción. Cuando se menciona el concepto de reducción de emisiones ligadas a los coches, una de las primeras imágenes que viene a la mente es el *EV*, principalmente por su no generación de contaminantes a nivel local [25, 26]. Para considerar verde al *EV* se han disminuir las emisiones ligadas al proceso de generación de energía eléctrica para la carga de las baterías. La mejor integración de las *REs* no queda reducida a las emisiones cero locales, sino que influyen de manera importante en despliegues de tecnologías llamadas a jugar un papel primordial en el futuro como son las *SG*, *V2G* y *V2H* [27, 28, 29, 30, 31]. Una pregunta importante que esta tesis doctoral trata de estudiar es ¿cómo el vehículo y su *software* pueden participar en la reducción de emisiones durante el diseño de un producto? Esta tesis doctoral se centra en el concepto de *ER*, *Eco-Charging* (*EC*) y *EDR* [32] que combinados adecuadamente con la distribución geográfica de los ingenieros que participan en un proyecto de diseño, contribuyen a mejoras importantes en cuanto a la disminución de emisiones asociadas al proceso de desarrollo del producto. Este punto, tal como se analiza en esta tesis doctoral, resulta de gran innovación, pues actualmente los estándares y directivas ligadas al ecodiseño no contemplan en estos factores [33]. Para una mejor comprensión de este aspecto, es conveniente definir de manera sucinta estos conceptos. *ER* trata de establecer una ruta para desplazarse de un punto origen a un punto destino teniendo en cuenta las recomendaciones del algoritmo encargado de planificar la ruta, de tal manera que se minimice el impacto medioambiental. La manera de minimizar este impacto suele ir íntimamente ligada a la disminución de combustible [34]. El concepto de *EDR* se centra en la planificación de rutas de navegación teniendo en cuenta los hábitos de conducción del conductor de tal manera que se minimice el impacto medioambiental [35]. En consecuencia, la planificación de las rutas es a la carta, pues se tienen en cuenta datos como el uso del pedal del acelerador, velocidades medias a las que suele rodar el conductor, etc. Actualmente, es sencillo encontrar en los coches comerciales esta función de tal manera que al finalizar el desplazamiento de un punto origen a un punto destino, el vehículo muestra una nota numérica que informa al conductor sobre la eficiencia energética en cuanto a su modo de conducción. Sin embargo, cuando se trata de *EVs* resulta claro que no sólo el modo de conducción es el único factor que influye en dicha eficiencia energética. De nada sirve conducir eficientemente si, posteriormente, se realiza el proceso de carga en el momento en que la mayoría de la electricidad que se está produciendo deriva del carbón o de otras fuentes de energía no renovables. Desgraciadamente, este factor no se tiene en cuenta en los vehículos actuales, de manera que el conductor no tiene ningún tipo de información al respecto. Finalmente, el *EC* busca conseguir cuál es el momento óptimo para realizar el proceso de carga. Un aspecto importante es cómo relacionar estos tres factores simultáneamente y en concreto, qué innovaciones técnicas se pueden proponer para conseguir que los conductores reciban informaciones sobre la integración de las *REs* y poder planificar los momentos óptimos para realizar la carga. El resultado de todo esto, sería una información al conductor sobre su eficiencia en el modo de conducción basada en los conceptos de *ER* y *EDR*. La presente tesis doctoral se centra en este punto, proponiendo soluciones basadas en redes neuronales para proponer soluciones a la problemática anteriormente expuesta. El uso de *ER*, *EDR* y *EC* no sólo tiene influencia en una disminución de las emisiones durante el diseño, también impacta en una mejora de las emisiones de las edificaciones gracias al uso conjunto de *ER*, *EDR*, *EC*, *V2B* y *EVs* tal como se detalla en esta tesis doctoral.

2.5 Modelos sostenibles de transporte

El aumento de ventas de los *EVs* influye y debe influir en el futuro en mejoras medioambientales por la reducción de emisiones locales. Teniendo en cuenta lo expuesto en apartados anteriores, la combinación adecuada y óptima de *SGs* y *EVs* es una solución a medio plazo que, en el futuro, tendrá una importancia significativa en la sostenibilidad. La cuestión importante es analizar la viabilidad de los modelos de transporte sostenibles basados en movilidad eléctrica, teniendo en cuenta factores como la degradación de la batería, ganancias del propietario del *EV* por su participación en la cesión de la energía almacenada mediante *SGs* así como las ganancias que puede tener las comercializadoras eléctricas en estos modelos [36]. En este punto, conviene tener en cuenta que, debido al déficit tarifario existente en España, estos modelos pudieran no ser viables en nuestro territorio. En este punto se centra esta tesis doctoral, analizando la viabilidad de los modelos de transporte sostenibles basados en *EVs* analizando su compatibilidad teniendo en cuenta el déficit tarifario de España.

2.6 Prohibición de los vehículos de combustión en 2035

En el pasado mes de julio de 2021, la Unión Europea ha anunciado su intención de prohibir los vehículos de combustión en 2035 apostando fuertemente por el *EV* [10]. Este hecho ha desatado una fuerte controversia ya que los constructores han mostrado mayoritariamente sus reticencias. El hecho de fomentar el *EV* implica la necesidad de instalar una gran cantidad de puntos de carga. Bruselas plantea la obligación de instalar puntos como máximo cada 60 km, lo cual implicará un coste no despreciable. Como consecuencia de todo esto, las investigaciones futuras deben ir encaminadas a las mejoras de las prestaciones del *EVs* y a sus aplicaciones como son las *SG, V2G* y *V2H* entre otros. Dado que gran parte de esta tesis se centra en investigaciones donde el elemento principal ha sido el *EV*, los resultados mostrados en esta tesis adquieren una mayor significación.

2.7 Nueva legislación de las tarifas en el sistema eléctrico

Desde el 1 de junio se están aplicando la nueva normativa basada en la TED/371/2021 [37]. El punto más importante de esta normativa es la agrupación de los peajes existentes (2.0 A, 2.0 DHA, 2.0 DHS, 2.1 A, 2.1 DHA y 2.1 DHS) en uno único (2.0 TD). Como recordatorio, para potencias inferiores a 10 kW se disponía de la opción 2.0 A (precio fijo), 2.0 DHA (discriminación horaria con dos periodos) y 2.0 DHS (discriminación horaria con tres periodos) [37, 38]. Finalmente, para potencias comprendidas entre 10 kW y 15 kW, se disponía de la tarifa 2.1 A (precio fijo), 2.1 DHA (discriminación horaria con dos periodos) y 2.1 DHS (discriminación horaria con tres periodos) [37, 38]. A partir del 1 de junio, gracias a la utilización de 2.0 TD, se tendrá una discriminación horaria de tres periodos [37, 38]:

a. Punta, de lunes a viernes de 10:00 a 14:00 y de 18:00 a 22:00.

b. Llano, de lunes a viernes de 8:00 a 10:00 y de 14:00 a 18:00 y de 22:00 a 00:00.
c. Valle, de lunes a viernes de 00 :00 a 8 :00 así como las 24 horas de los fines de semana o los festivos nacionales.

El objetivo fundamental de esta nueva legislación no es otro que penalizar los consumos que se producen en los momentos de mayor demanda con vistas a mejorar la estabilidad de la red. Otro punto importante es que la nueva tarifa posibilita elegir un término de potencia por cada tramo horario.

Dicho todo lo anterior, las ventajas principales para el usuario del *EV*, no será otra que una disminución del precio de carga de carga en las horas valle, es decir, de 00:00 a 8:00. Verdaderamente, ¿es esta política la acertada para conseguir la promoción de los *EVs*, la mejor integración de las *REs* y el fomento de las técnicas *V2H*, *V2G* y *V2B*? La respuesta es negativa tal como se desarrolla a lo largo de la tesis doctoral, amparando esta afirmación en las publicaciones científicas obtenidas.

2.8 Contexto personal

Desde el año 2014, el autor de esta tesis doctoral lleva realizando actividades relacionadas con la concepción de sistemas embebidos centrados en aplicaciones de control motor tanto diésel como gasolina, *ECU* telemáticas y diseño de sistemas de iluminación interior de vehículos. En lo referente a control motor, ha participado en 4 proyectos de concepción de un calculador motor en diferentes constructores como PSA Peugeot Citroën y Renault en sus centros de diseño de La Garenne-Colombes (Isla de Francia) y Lardy (Isla de Francia) respectivamente. En cuanto a las concepciones de sistemas telemáticos, ha participado en el diseño de una *ECU* telemática para la nueva generación de camiones Volvo en centros de diseño de Toulouse y Suecia. Finalmente, ha realizado funciones de jefe técnico de proyectos electrónicos, siendo en la actualidad jefe de proyecto de I+D relativos a la concepción electrónica, óptica, mecánica y de *software* de sistemas de iluminación en Valeo Iluminación en su planta de Martos (Jaén).

3. FUNDAMENTOS TEÓRICOS Y ANTECEDENTES

En las siguientes subsecciones se engloban aspectos teóricos importantes que son base para la comprensión de los artículos publicados como consecuencia de los avances y logros descritos en esta tesis doctoral.

3.1 Motores de combustión interna

Para una comprensión adecuada de la presente tesis doctoral, resulta importante realizar una breve introducción a los motores de combustión. Si bien la clasificación de los motores es bastante más compleja y amplia, desde un punto de la automoción se pueden establecer las cadenas de tracción de gasolina y diésel (si bien en las cadenas de tracción híbridas se pueden encontrar también motores de combustión).

3.1.1 Funcionamiento de los motores y del *software*

3.1.1.1 Proceso de combustión de un vehículo de gasolina

Como norma general, existen cuatro fases en el cilindro para transformar la energía química en mecánica: admisión, compresión, expansión y escape (Fig.1) [39]. En el caso de los motores de encendido provocado (motores gasolina), en el cilindro se inyecta aire procedente del circuito de admisión, así como combustible inyectado por los inyectores, todo ello en la fase de admisión. Posteriormente, se produce un proceso de combustión donde las diferencias de temperatura y velocidad relativas tanto del fluido como de la pared no son muy elevadas. Este proceso tiene una duración corta. Es importante recalcar que, durante la fase de compresión, la presión es prácticamente constante. Cuando finaliza la compresión se produce la activación de la bujía (expansión), momento en el cual el pistón desciende a su posición inferior. Finalmente, el pistón retorna a su posición superior, eliminando los gases restantes que quedaron en el cilindro por el proceso de combustión [39]. A modo de ejemplo, se muestra en la Fig. 2 el ciclo presión-volumen de este motor.

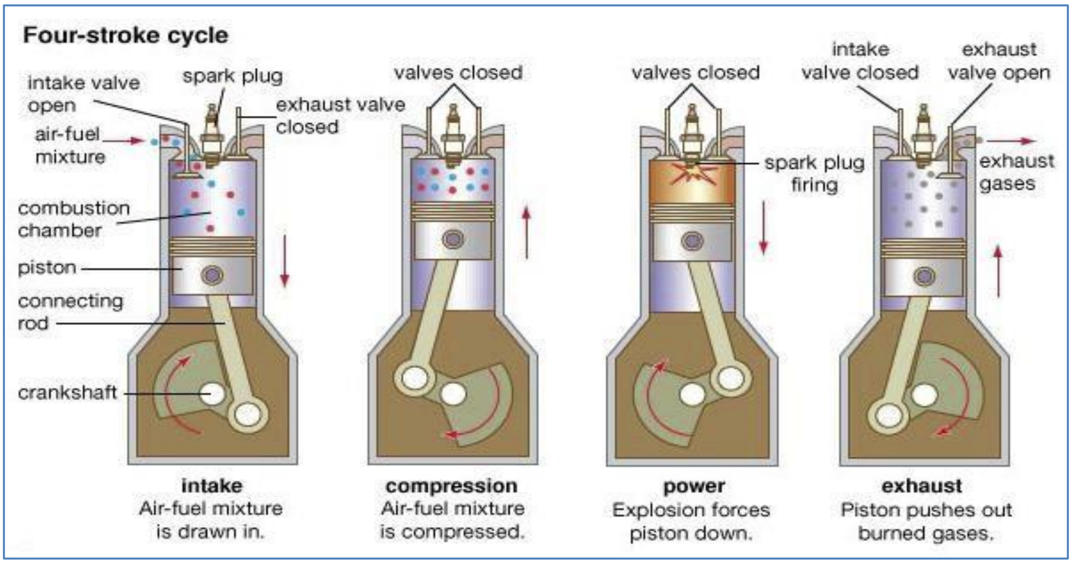

Figura 1. Fases de un cilindro. Fuente PSA Peugeot Citroën

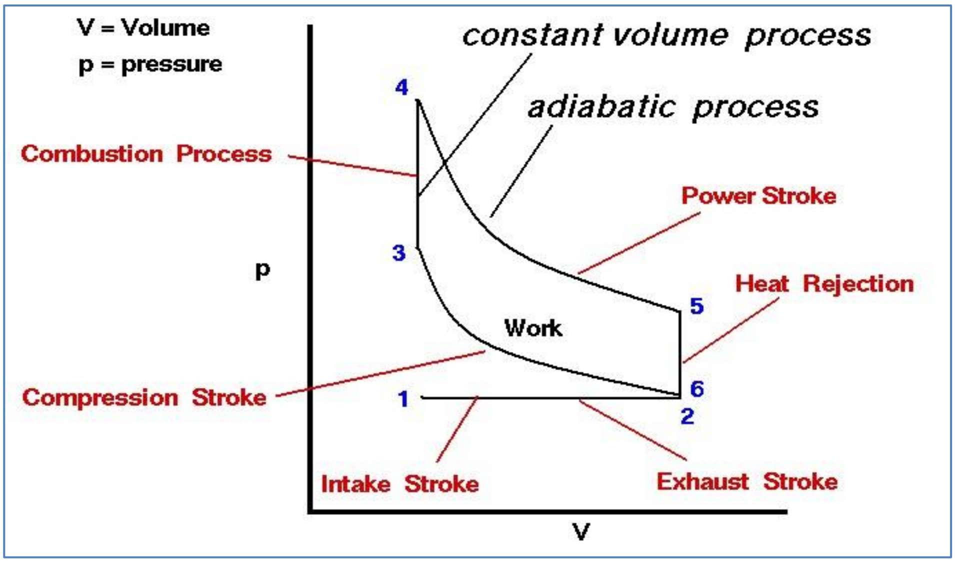

Figura 2. Ciclo presión-volumen de un motor gasolina. Fuente PSA Peugeot Citroën

3.1.1.2 Proceso de combustión de un vehículo de un motor diésel

El proceso es muy similar al funcionamiento de un motor de encendido provocado, si bien hay que añadir las siguientes diferencias [39]:

- Cuando se inicia un proceso de combustión, el fluido comprimido es aire y gases residuales que pueden quedar de ciclos anteriores. En consecuencia, el combustible se introduce al final de la fase de compresión iniciándose un proceso de autoencendido.

- La relación de comprensión de un motor de encendido por compresión (diésel) es mucho más elevada que la de un motor gasolina.

3.1.1.3 Sistema de control de un motor

El control de trenes de tracción se basa en un sistema encargado de transformar la voluntad del conductor en un punto de operación del tren de tracción acorde a las prestaciones de consumo, emisiones y seguridad establecidas para el motor en cuestión. El elemento clave de este sistema es la *ECU* motor, más comúnmente conocida como calculador motor, formada por *software* y *hardware*. A partir de la información recibida por los sensores a los que se conecta el calculador motor, éste decide cómo va a accionar los actuadores para el control del motor [39, 40].

El proceso de combustión del motor se puede describir de manera sencilla tal como se explica a continuación (Fig.3) [39, 40]. En un principio, el aire filtrado entra a través del turbo gracias al conducto de admisión. La función principal de este turbo no es otra que incrementar su densidad y mejorar, en consecuencia, la admisión en los cilindros. Como resultado, la temperatura del aire se ve incrementada, si bien no debe serlo en exceso para evitar procesos de detonación dentro de la cámara de combustión, fenómeno que daña el motor al ocasionar grandes gradientes de presión y temperatura. En consecuencia, existe un intercambiador de calor para enfriar el aire antes de entrar en la cámara de combustión. Dependiendo de las peticiones del conductor, se genera un mayor o menor par que influye en una mayor o menor admisión de aire. Para controlar la masa inyectada de aire existe una mariposa cuya posición se controla mediante la posición del pedal del acelerador. Una vez que se ha establecido la cantidad de aire a inyectar, comienza el proceso de mezcla de aire y combustible cuya homogeneidad dependerá del tipo de motor a controlar. Cuando se ha producido el proceso de combustión, los gases salen por el conducto de escape. Posteriormente se encuentra una turbina que tiene como principal función hacer operar correctamente al turbocompresor de entrada. El calculador motor establece la cantidad de gases que irán a través de la citada turbina para garantizar el punto de funcionamiento óptimo del motor. El resto de los gases son inyectados bien en la válvula denominada *Exhaust Gas Recirculation (EGR)* o bien al escape. La válvula *EGR* permite recircular los gases para optimizar la temperatura en los cilindros y, en consecuencia, disminuir la cantidad de óxidos de nitrógeno generados en un motor diésel.

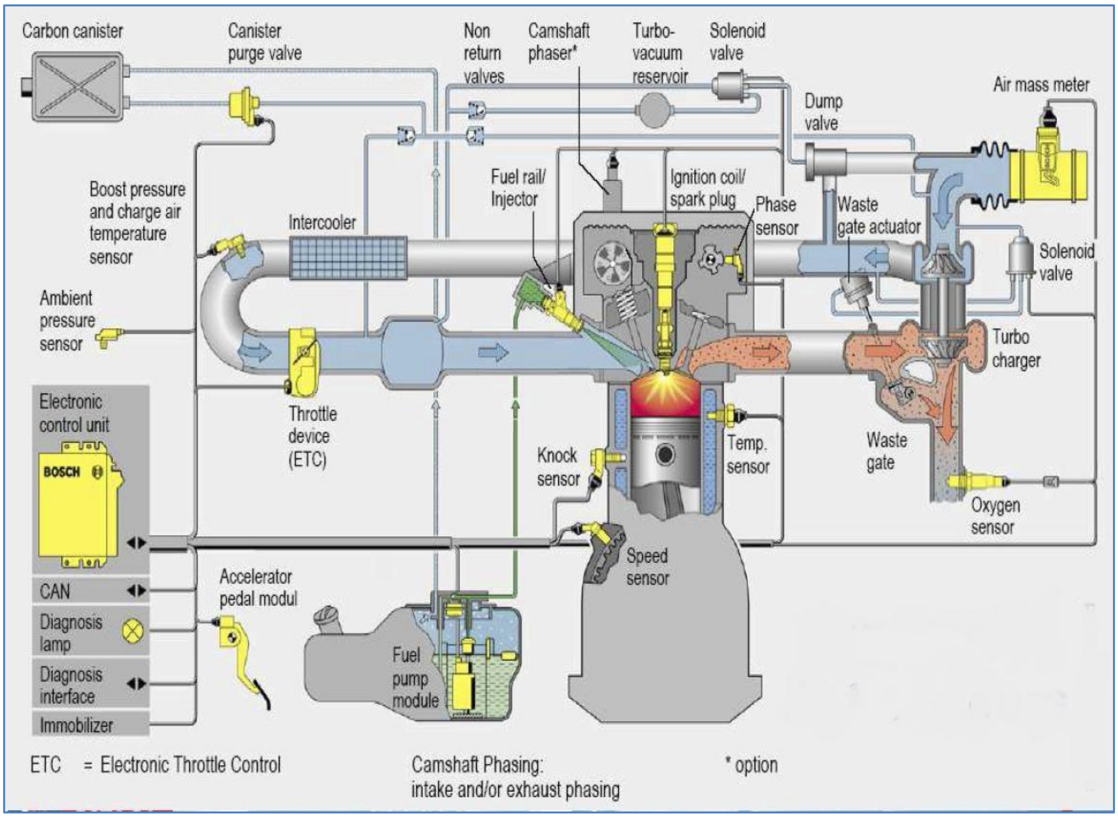

Figura 3. Funcionamiento general de un motor de combustión interna alternativo. Fuente PSA Peugeot Citroën

Es importante destacar que las funciones del calculador motor no quedan reducidas al control del proceso de combustión. Engloba aspectos más complejos como bien pueda ser el control de los gases de combustión y reducción de contaminantes (catalizadores, filtros antipartículas, inyección de urea), control de la bomba de combustible de baja presión, etc. [39, 40]. Teniendo en cuenta estos aspectos, la validación del *software* de un calculador motor es altamente compleja como se muestra a lo largo de esta tesis doctoral.

A la hora de generar el par motor el calculador motor debe elegir el par óptimo y decidir cuál es el par final que se va a aplicar. Existen múltiples módulos que pueden enviar una solicitud de par como es el caso de la función regulador de velocidad, limitador de velocidad, control adaptativo, limitación de la caja de cambios, etc. tal como se muestra en la Fig.4 que muestra la conocida cadena de arbitraje de par [39, 40]. Es importante recalcar que el par a aplicar deberá ser físicamente realizable, no sólo desde las condiciones físicas del motor sino también debe garantizar que no se produzcan "tirones" en el proceso de conducción.

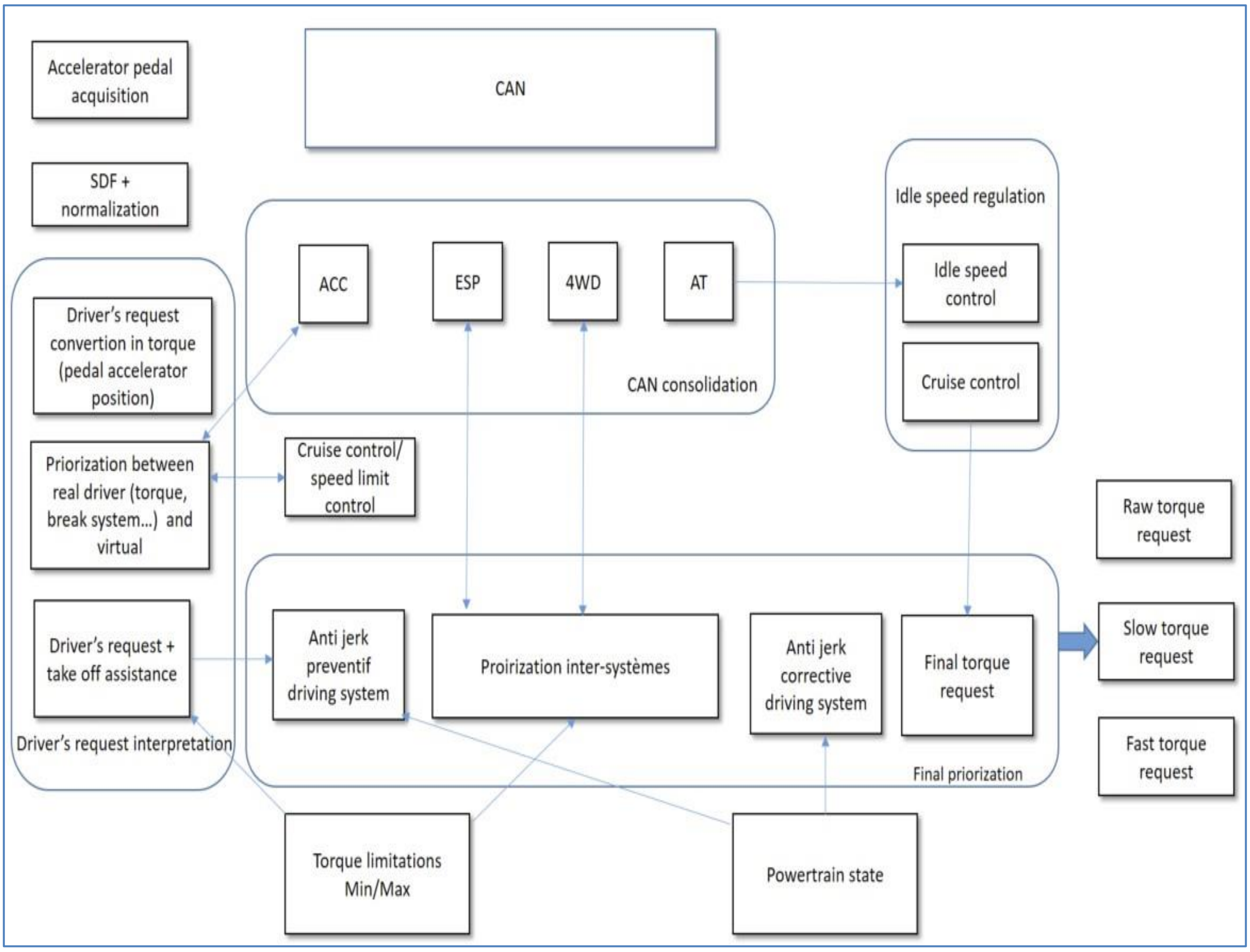

Figura 4. Cadena de arbitraje del par motor

3.1.1.4. Arquitectura electrónica de un vehículo

El número de *ECUs* presentes en los actuales vehículos se ha incrementado de manera sustancial en las últimas décadas, donde la electrónica se ha ido haciendo más y más presente [40, 41]. Ya en 2013, la Universidad de Stanford estimaba que los coches podían ir equipados hasta con un total de 70 calculadores [41]. Esta cifra, sin duda, puede verse incrementada debido a la llegada del vehículo autónomo donde son necesarios múltiples *ECUs*, así como *software* altamente complejo para implementar las prestaciones deseadas para el vehículo.

Cuando se diseña una arquitectura electrónica de un vehículo, se especifica cómo se van a interconectar las distintas *ECUs*, protocolos que van a utilizar, ciberseguridad necesaria para garantizar la integridad del vehículo y la seguridad de las personas, velocidad de transmisión, modo de acceso al medio, etc. (Fig.5) [42].

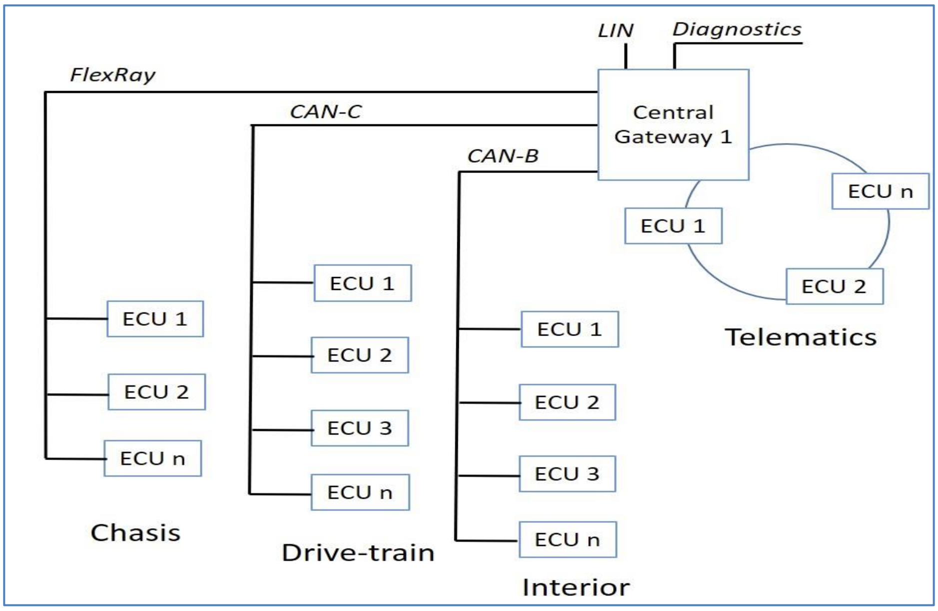

Figura 5. Ejemplo de arquitectura electrónica

A la hora de diseñar una arquitectura, se han de tener en cuenta una gran cantidad de parámetros. Como normal general, y de manera resumida, a continuación, se enumeran los principales factores a tener en cuenta [41, 42]:

- <u>Velocidad de transmisión.</u> Este factor está ligado a que no todos los elementos integrantes de la red necesitan transmitir información a la misma velocidad. A modo de ejemplo, las tramas emitidas por la *ECU ESP* emite las tramas más frecuentemente que la unidad encargada de controlar el aire acondicionado. Esto es debido a que la información transmitida por el *ESP* es más crítica al estar relacionada con el sistema de frenado. Esta velocidad de transmisión está íntimamente ligada al protocolo de comunicación usado en la red. Principalmente, en automoción se utilizan los protocolos *Controller Area Network (CAN)* y *Local Interconnect Network (LIN),* si bien algunos fabricantes integran ya aplicaciones ethernet.
- <u>Topología.</u> Mediante este término nos referimos a cómo están conectados las unidades de control entre ellas. Existen múltiples topologías como bien puedan ser en bus, en anillo, en estrella, etc. si bien las más utilizadas son las de estrella y lineal.
- <u>Acceso al medio.</u> Hace décadas, el cableado interno de los vehículos era altamente complejo, pues las conexiones, en muchos casos, eran hilo a hilo. La multiplexación fue

un gran avance en la automoción, pues permitía usar un único cable para la transmisión de múltiples informaciones. De hecho, dicho cable era compartido por múltiples elementos conectados a la red electrónica del coche. Como consecuencia, la reducción de costes en la fabricación fue sustancial. Sin embargo, esta compartición del medio (cable) resultaba compleja, pues si dos elementos conectados a la red accedían simultáneamente, la información se veía corrompida y alterada. Como resultado, debían existir mecanismos de control de acceso al medio que, como es lógico, dependen del protocolo que se esté utilizando (*CAN*, *LIN*, etc.). A modo de ejemplo, en el caso del bus *LIN*, el acceso al medio es simple, pues es una comunicación maestro esclavo. En cuanto al *CAN*, utiliza el concepto de bits recesivos y dominantes para establecer la prioridad de acceso al medio [40, 43].

- <u>Prestaciones en tiempo real</u>. La información transmitida por el bus en un vehículo se hace en tiempo real. La consecuencia principal es que debe ser recibida dentro de unos límites establecidos y los calculadores deben saber en cualquier momento como actuar en el caso de no recibir una trama o bien si ésta contiene errores. Tal como se deduce, las redes electrónicas de los vehículos constituyen sistemas de tiempo real [40, 6].
- <u>Inmunidad frente a interferencias</u>. En general, cuando se diseña un calculador, un factor clave en el diseño es la compatibilidad electromagnética tanto en emisión como en inmunidad. En cuanto a emisión, la *ECU* no debe producir perturbaciones a su alrededor por encima de unos límites establecidos por la normativa europea tanto en emisión como en radiación. En lo referente a la inmunidad, cuando una *ECU* se encuentra funcionando en un entorno debe ser capaz de no verse influencia por campos magnéticos presentes a su alrededor dentro de los límites establecidos por la norma. Si bien tratar este punto en detalle excede el objeto de esta tesis, es importante remarcar que algunos protocolos como el *CAN* tratar de minimizar el efecto de las perturbaciones. Para reducir el impacto de los campos magnéticos exteriores, el bus *CAN* está compuesto por dos cables trenzados denominados *CAN_H* y *CAN_L* tal como se muestra en la Fig.6 [40, 44].

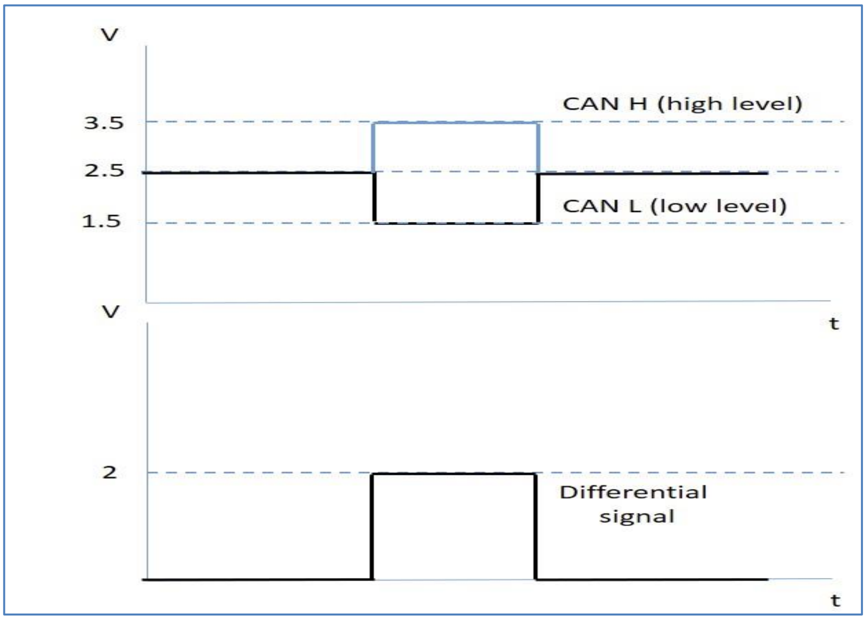

Figura 6. CAN_H y CAN_L

- Gateways o pasarelas. Estos elementos tienen una función muy importante en la red, y requieren un estudio cuidadoso. Una de sus primeras funciones es la de transformar señales codificadas en un determinado protocolo en otra señal codificada en un protocolo diferente. A modo de ejemplo, una *gateway* puede transformar una trama *CAN C* (1 Mbit/s) en una trama *CAN b* (125 kbits/s). Quizá la función más importante que están empezando a realizar ahora relacionada con la ciberseguridad es el filtrado de tramas. En otras palabras, la *gateway* se puede colocar en la cabecera de la red electrónica y no deja acceder a la información de las diferentes *ECUs* siquiera para ver la referencia de la calibración o versión del *software* de un determinado calculador. La única manera de hacerlo es mediante un proceso de intercambio de claves estando obligatoriamente conectado a la red informática del fabricante bien sea porque el ingeniero o persona que va a realizar la manipulación se encuentre en las instalaciones del fabricante o bien porque disponga de un elemento *USB (Universal Serial Bus)* que le permita conectarse a la red [40].

3.1.2 Sistemas de diagnosis

Conviene realizar una descripción rápida del proceso de sistema de diagnosis de un vehículo para entender correctamente las particularidades del *software* del calculador motor, pues es un factor importante en el proceso de validación *software* desarrollado en esta tesis. Debido a la complejidad de las arquitecturas electrónicas presentes en los vehículos, existe un sistema de diagnosis en tiempo real. La Fig.7 muestra el ciclo seguido hasta considerar que un defecto está permanentemente presente en un vehículo [40]. De forma general, el diseñador de la función establece cuanto tiempo ha de detectarse el defecto hasta que se considera como permanente. Es importante destacar que, si por alguna circunstancia el defecto deja de estar presente durante un cierto tiempo establecido por el diseñador, se deja de considerar como presente y se denomina defecto fugitivo, si bien esta terminología depende del constructor en cuestión.

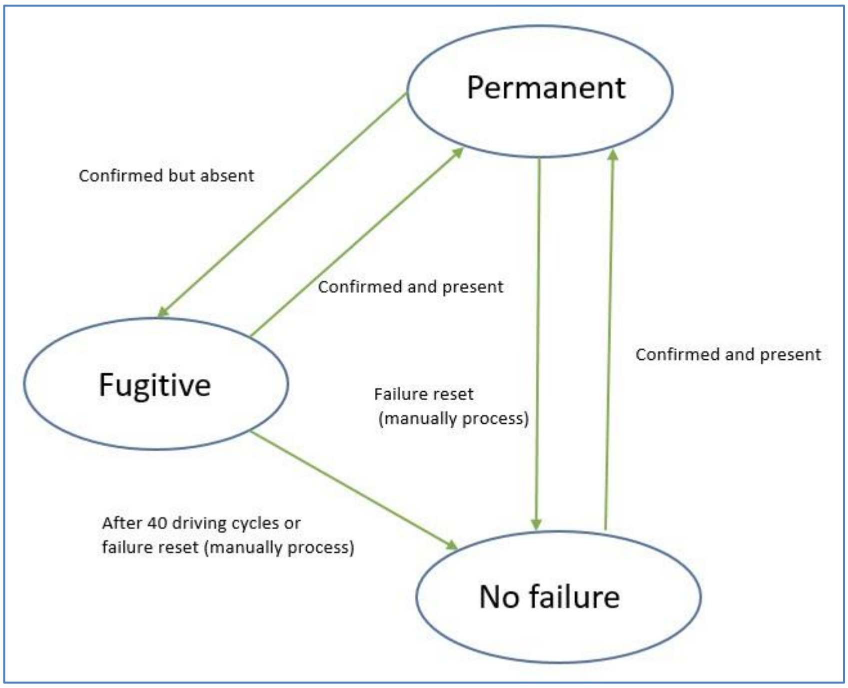

Figura 7. Ciclo de detección y desaparición de defectos

3.2 Cadenas de tracción eléctricas

3.2.1 Visión global de un EV

El objetivo de este capítulo es mostrar los detalles fundamentales del funcionamiento de un *EV* para una mejor comprensión del método, resultados y conclusiones de esta tesis doctoral. En la Fig.8 se muestran los elementos básicos de un *EV* [45, 46].

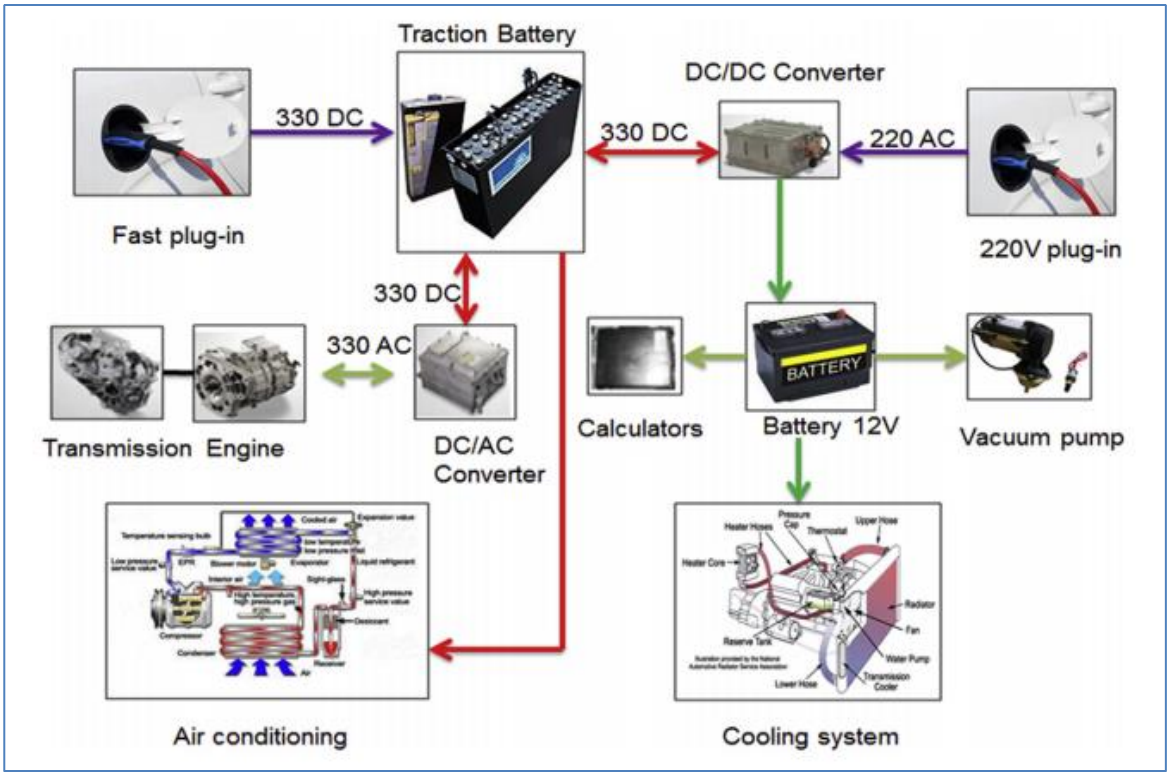

Figura 8. Elementos de un EV

Uno de los elementos clave de un vehículo de estas características es el motor eléctrico que, según el tipo del que se trate, el proceso de control será distinto. En cuanto a su disposición, pueden existir un motor por rueda motriz o cuatro (uno por cada rueda). En cualquier caso, se puede optar por motores de corriente continua o alterna [45, 46]. El siguiente elemento clave de todo *EV* es la batería, componente crítico en este tipo de vehículos pues dependiendo de su tecnología y características permite obtener una mayor o menor autonomía. El voltaje de la batería debe ser adaptado para todos los elementos del *EV* que necesiten alimentación. Esto se consigue mediante los convertidores DC/DC o también denominados reguladores de tensión, cuya salida es una tensión regulada y, en algunos casos, con limitación de corriente. En este punto conviene destacar que la frecuencia de conmutación usada para realizar la regulación tiende a ser elevada para disminuir la capacidad de los condensadores. Esto repercute en una consiguiente disminución del volumen, peso y coste [45, 46]. Sin embargo, el hecho de utilizar frecuencias elevadas de conmutación conlleva necesariamente la generación de ruido electromagnético tanto por su línea de entrada como por radiación. En consecuencia, es un aspecto importante a la hora de cumplir con requerimientos de compatibilidad electromagnética [44]. En algunos casos, resulta necesario transformar esa corriente continua en corriente alterna, especialmente si el motor controlado es de corriente alterna. El inversor es el dispositivo que permite transformar la corriente continua en corriente alterna con la magnitud de frecuencia y magnitud que estime el diseñador. En lo referente a los sistemas de transmisión, resulta importante destacar que los *EVs* no se encuentran equipados con cajas de cambios. Existen muchas razones que justifican este hecho, si bien la principal es una cuestión puramente económica, pues técnicamente este tipo de trenes de tracción proporciona el par máximo prácticamente desde la salida, estando, en consecuencia, la potencia máxima disponible muy pronto. Todo ello repercute en que la ganancia en términos de eficiencia es prácticamente nula. Ahora bien, a pesar de lo expuesto, no quiere decir que no sea posible encontrar en el mercado vehículos con cajas de cambios. El único inconveniente es que serán siempre vehículos de alta gama con precios bastante elevados.

3.2.2. Papel del *EV*

En esta tesis doctoral se ha considerado necesario estudiar la influencia en el ecodiseño por parte del *EV*. En los últimos años se llevan realizando políticas que buscan aumentar la presencia de estos vehículos en el parque automovilístico como: exención del impuesto de matriculación, reducción en el pago de impuestos municipales que pueden ir entre un 50% y un 75%, aparcamiento gratuito en zonas céntricas de ciudades o incluso reducción de los peajes. Actualmente, se puede encontrar el Plan Moves que consiste en un programa de incentivos enmarcado en favorecer la movilidad eficiente y sostenible [47]. Este proyecto está dotado de un presupuesto de 100 millones de euros y otorga, entre otras ventajas, ayudar directas que pueden alcanzar los 5.500 euros siempre y cuando el vehículo adquirido sea de cadena de tracción híbrida o eléctrica. Estos planes no sólo tienen un ámbito nacional, de tal manera que se pueden encontrar iniciativas tales como el *European Green Deal (EGD)* que se base en tres pilares fundamentales: reducción gradual de los gases de efecto invernadero hasta 2050, estimulación del crecimiento económico teniendo en cuenta la limitación de los recursos existentes y, finalmente, no olvidar a ningún actor o sector de la sociedad durante este proceso de transformación [48]. Para la realización de todo esto, se están tomando medidas en muchos ámbitos tales como mejora de la eficiencia energética de los edificios, mejorar la integración de las *REs* y conseguir una gran mejora en el transporte sostenible y gestión inteligente del tráfico. Como consecuencia, la potencial aportación del *EV* resulta fundamental y es en este punto donde se centra también la presente tesis doctoral.

3.3 Desarrollo del *softwar*e de automoción

3.3.1 Concepción del *software*. Introducción.

En el sector de la automoción existen diferentes metodologías para afrontar el desarrollo de un *software,* si bien la más extendida es el ciclo en V [49, 50]. El ciclo en V o modelo en V se muestra en la Fig.9, distinguiéndose dos partes fundamentales. La parte izquierda de la V muestra el análisis de las especificaciones y el diseño del sistema como la arquitectura del sistema. El resultado de esta primera parte del proceso es la codificación del *software* (vértice de la V). La parte derecha representa todas las actividades a la validación.

A grandes rasgos, en las primeras fases del modelo en V, se procede al análisis en detalle de los requerimientos solicitados por el cliente y a los que el producto debe responder cuando se haya diseñado. Esta fase es crítica, pues una mala interpretación de un requerimiento puede implicar modificaciones futuras importantes con su consiguiente coste. Una vez analizados los requerimientos, el resultado no es otro que las especificaciones funcionales que describirán el funcionamiento esperado. En toda esta fase se describe la arquitectura del sistema y de los componentes, se evalúa si existen *SMs* reutilizables de otros proyectos, etc. En caso de no existir, se deben diseñar, dando como resultado las especificaciones técnicas en Simulink® que el constructor automóvil envía al proveedor encargado de codificar el *software*. En este punto, se genera una versión de *software*, es decir, se alcanza el vértice inferior de la V (Fig.9). En este momento, se realiza una primera verificación del código consistente en comprobar que, para una serie de valores de datos de entrada, los modelos Simulink® responden de la misma manera que el código fuente generado. En este punto, es importante destacar que únicamente se detectan bugs asociados a errores de codificación, pero no de prestaciones del *software.* En otras palabras, en determinadas ocasiones el *software* puede estar bien codificado pero la prestación del motor no es la adecuada. Como consecuencia, el error deriva de un olvido o mala redacción de un requerimiento, y no de la codificación del *software*. Cuando finaliza la comparación entre el código y los modelos Simulink®, se procede a iniciar el proceso de verificación integrando el *software* y el *hardware* asi como el funcionamiento a nivel sistema. Posteriormente, se realiza la aceptación final del producto que queda avalada mediante rodajes de flotas de vehículos para comprobar la fiabilidad y calidad del *software* desarrollado durante el proyecto. Esta última fase es esencial para comprobar si se producen detecciones de defectos erróneas por mala calibración o implementación de una estrategia poco robusta de detección, respuesta del producto desde un punto de vista seguridad según la ISO 26262, etc. [48].

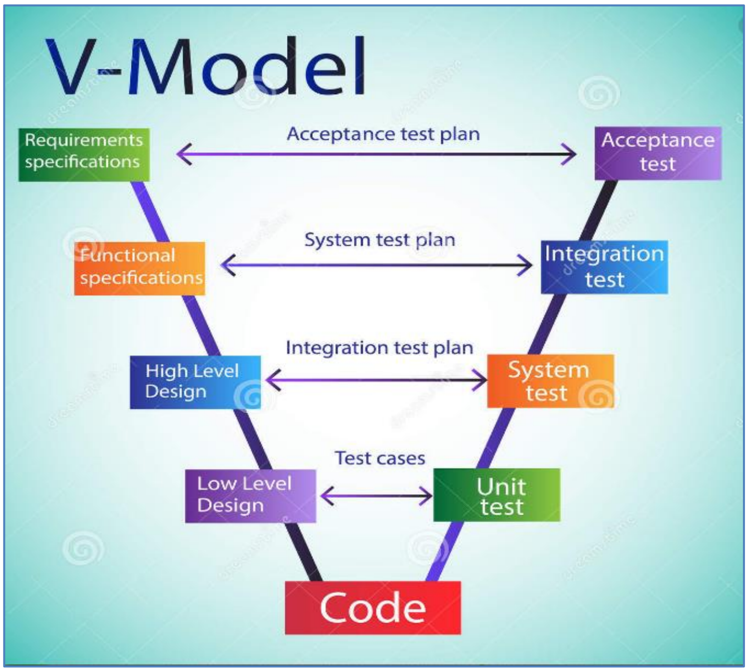

Figura 9. Ciclo en V. Fuente Renault

3.3.2 Características básicas de un *software* de un calculador motor

Como ya ha sido comentado con anterioridad, el *software* de un calculador motor asi como el de otras *ECU*s, es altamente complejo y presenta unas características que merece la pena reseñar para una mejor comprensión de esta tesis doctoral [42]:

- Arquitectura *hardware* y *software* compleja. Las *ECUs* poseen microcontroladores que integran diferentes funciones. Entre los eventos y periféricos que se han de manejar destacan las memorias de lectura cuyo contenido puede ser borrado por operaciones eléctricas, conocidas como *electrically erasable programmable read-only memory (EEPROM)*, contadores de eventos o temporizadores al igual que drivers de comunicación para conectarse a buses tales como el *CAN* y el *LIN* entre otros.
- Sistemas sensibles al tipo de dato utilizado y su precisión. Dentro del calculador motor existen funciones encargadas de realizar estimaciones de variables físicas. Errores en la

elección del tipo de dato o precisión incorrecta lleva a estimaciones erróneas con repercusiones diversas.

- Sistemas que deben ser extremadamente fiables y seguros. El calculador motor debe tener un sistema de diagnosis en tiempo real muy robusto. A su vez, este tipo de sistemas maneja características definidas como *Automotive Safety Integrity Level B* (ASIL) según la ISO 26262 [51]. En otras palabras, funciones con una repercusión clara en la seguridad de los pasajeros. Por tanto, en algunos casos, es posible encontrar redundancias en las implementaciones de funciones. Por ejemplo, es habitual encontrar diseños de nivel 1 y nivel 2 de una misma función, de tal manera que, en caso de diferencias de cálculo entre ambos niveles, el calculador se puede ver forzado a tomar decisiones drásticas, como, por ejemplo, realizar reset *software* o *hardware*. Además, también es habitual realizar aseguramiento de tramas *CAN* para comprobar, de nuevo, si existen diferencias entre los diseños de nivel 1 y 2.
- Operación en tiempo real. Los procesos que corren en el calculador motor deben ejecutarse dentro de los tiempos especificados. Para lograr esto, en otros factores, destaca asegurar una tasa de ocupación del microcontrolador máxima. Si bien este parámetro depende del fabricante, es habitual no exceder el 70%-75%. Por tanto, los algoritmos implementados deben destacar por su eficiencia.
- Eficiencia en la implementación. Los algoritmos implementados deben hacer uso de los recursos disponibles en el calculador el tiempo mínimo necesario. A su vez, hay que tener en cuenta que una falta de eficiencia en la implementación puede llevar a tallas de código importante y, en consecuencia, problemas importantes en la industrialización. Cabe recordar que cuando los vehículos están en una cadena de producción, el tiempo de carga del *software* y su parametrización debe estar comprendido entre un minuto y medio o dos minutos. Por tanto, tamaños grandes de *software* no permiten respetar esta exigencia.

3.3.3 Estandarización del *software*

El número de *ECUs*, así como la complejidad de vehículos se ha visto incrementada en la última década. Este hecho lleva unos costes muy importantes en la generación del *software* y *hardware*. Para solucionar este problema, surgió la iniciativa denominada *AUTOSAR (AUTomotive Open Systems ARchitecture)* con vistas a conseguir arquitecturas electrónicas abiertas para estandarizar las funciones claves asociadas al funcionamiento de un *software* de una *ECU*, así como los interfaces asociados [52]. El resultado principal es que las soluciones monomarca desparecen y, al estandarizarse los *SMs*, se produce una mejora en fiabilidad y calidad del *software* de los calculadores. Lógicamente, *AUTOSAR* propone el uso de múltiples módulos tal como se muestra en la Fig.10, si bien cada fabricante en función del tipo de calculador que vaya a implementar elegirá las partes que desea codificar en su *software*. Un punto importante es que no sólo el *software* debe responder a los requerimientos *AUTOSAR* sino también los microcontroladores o elementos *hardware* que formen parte del sistema.

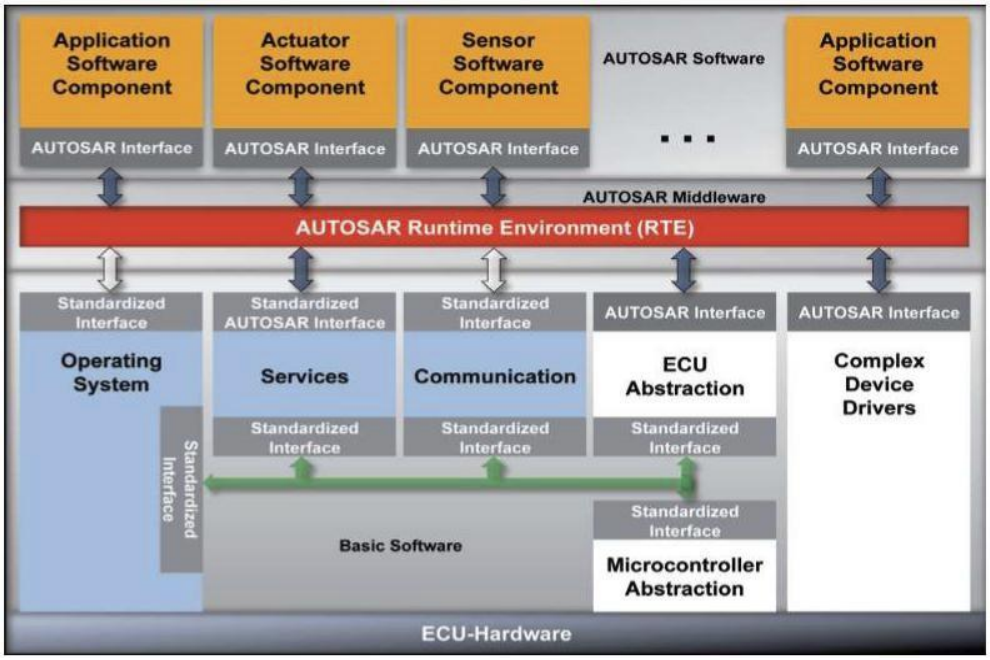

Figura 10. Arquitectura AUTOSAR. Fuente PSA Peugeot Citroën

3.3.4 Medios utilizados para la validación del *software*

Resulta fundamental para entender esta tesis doctoral las formas en que se valida el *software* de un calculador motor u otras *ECU*s. El objetivo fundamental del equipo proyecto encargado del diseño y desarrollo del *software* de un calculador motor es generar un código que responda a lo indicado en las especificaciones técnicas y respete las normativas existentes asociadas a diferentes aspectos como las emisiones. Durante la fase de proyecto se generan múltiples versiones de código que, poco a poco van ganando en madurez. Además de la complejidad asociada a este *software*, es importante remarcar que se trata de un *software* altamente configurable. De hecho, esta configuración o parametrización la realizan los equipos de puesta a punto para garantizar las prestaciones del motor. En un principio, el lector puede pensar que lo más lógico sería realizar los procesos de validación *software* sobre vehículos prototipo. La realidad es que éstos son extremadamente caros de fabricar y, además, determinados puntos de funcionamiento que hay que testear cuando se valida el *software* son muy complicados de alcanzar sobre un vehículo real. Consecuentemente, la validación se realiza bien sobre vehículo bien sobre simuladores *HIL* [53, 54].

3.3.5 Simulación *HIL*

Esta técnica de validación es ampliamente usada en el mundo de la automoción. Consiste en que el *software* embebido ejecutado sobre el *hardware* real del calculador motor interactúa con un modelo que simula el comportamiento dinámico del vehículo. El proceso de simulación no es complicado en cuanto a sus bases teóricas (Fig.11). En principio, existen tres elementos clave en una simulación de este tipo. En primer lugar, el calculador motor que tendrá en su interior el código fuente del *software* que vaya a ser objeto de validación. En segundo lugar, el banco *HIL* que modela el comportamiento dinámico del vehículo. Por último, el interfaz del modelo que permite realizar acciones tales como acelerar, modificar valores de una trama *CAN*, cambiar de marcha, etc. de tal manera que se producen cambios en las variables internas del calculador motor debido a que la dinámica del modelo (simulador *HIL*) cambia si, por ejemplo, aumentamos la temperatura del aceite fuertemente.

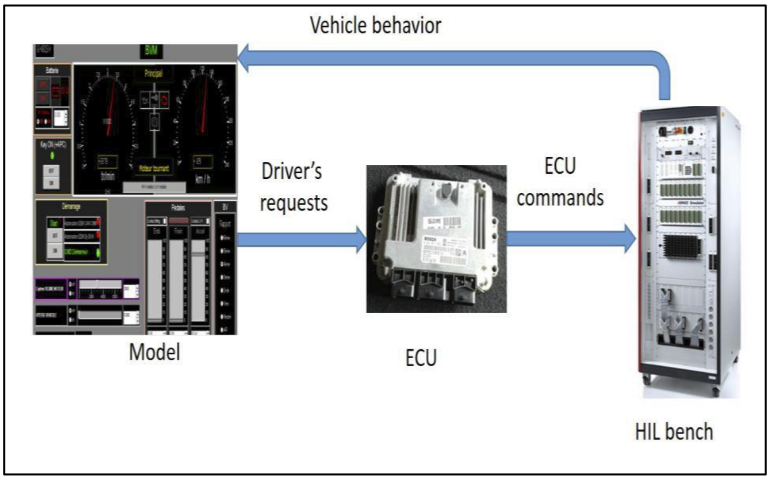

Figura 11. Proceso de simulación HIL

Durante todo el proceso de simulación se realizan adquisiciones de datos que, posteriormente, son analizadas para verificar si el comportamiento del *software* ha sido conforme a lo esperado. Para realizar estas adquisiciones se utilizan módulos de entrada/salida (Fig.12) y el *software* INCA® del fabricante ETAS® perteneciente a Robert Bosch [55].

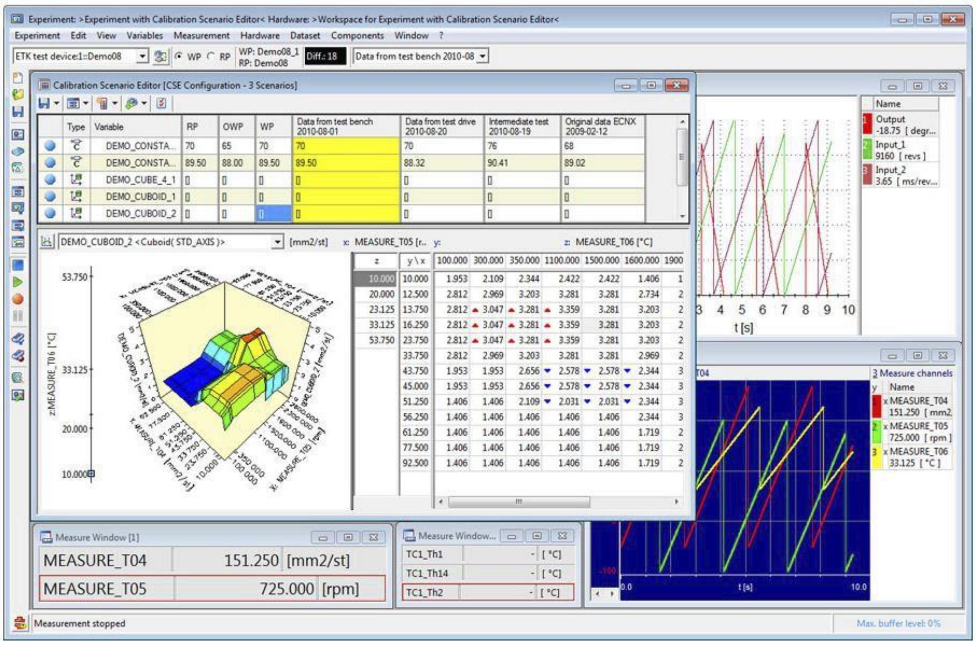

Figura 12. Módulo de entrada / salida de ETAS®. Fuente ETAS®

Las variables que quedan registradas en la adquisición de datos son las que el ingeniero de validación haya seleccionado previamente. En la nomenclatura del proveedor ETAS®, se habla de construir un experimento. Esta acción consiste en añadir sobre un interfaz las variables *software* que van a irse registrando durante la adquisición, su modo de visualización (en gráfico o bien mostrándose su valor en una casilla de texto, etc.) tal como se puede observar en la Fig.13.

Figura 13. Ejemplo de resultados mostrados por INCA® Fuente ETAS®

La dificultad principal del proceso de validación es que, en la mayoría de los casos, no es posible acceder a las variables internas del *software* del calculador motor y modificar su valor directamente, sino que se requiere que se realicen manipulaciones sobre el modelo (acelerar, cambiar el valor leído por un captador, etc.) hasta conseguir alcanzar los valores deseados para las variables de entrada. Sin embargo, este proceso es extremadamente complejo, y no se consiguen alcanzar esos valores exactos debido a las interacciones de los *SMs* presentes en el código fuente. Esta tesis doctoral propone soluciones para mejorar el proceso de automatización y ejecución de *TCs* mediante simulaciones *HIL*. En algunos casos, se pueden modificar las variables internas del *software* mediante el uso de variables de calibración, si bien, hay que recalcar que son casos contados en comparación con las variables a las que no se puede acceder en modificación. Por último, para hacerse una idea de la complejidad de este *software*, existen un total de 40.000 variables a controlar.

3.3.6 Aplicación generalizada de las técnicas de validación

Es importante dedicar un apartado en esta tesis doctoral con el fin de explicar la posibilidad de aplicar de manera general una técnica de validación para testear un *software* de automoción. Como norma general, toda técnica de validación puede aplicarse a cualquier sistema con la particularidad de que pueden ser tediosas o poco efectivas cuando se aplican sobre *SMs* que tengan determinadas características. Así, por ejemplo, la técnica conocida como de hilo a hilo, consistente en verificar todas las conexiones entre modelos Simulink®, observando si para unas determinadas variables de entrada, el modelo Simulink® proporciona el valor esperado, resulta tediosa cuando se aplica a modelos muy complejos. Técnicas como la caja negra, o *black-box* en inglés, permite verificar si el sistema se comporta como se espera abstrayéndose el ingeniero de validación de cómo ha sido codificado el *software.* Tal como se muestra en esta tesis doctoral, la tasa de cobertura de validación del *software* no es alta cuando se emplea esta técnica. El estado del arte de la validación se mostrará en el apartado 5, pero en este punto es conveniente retener que es necesario encontrar técnicas de validación que puedan aplicarse a cualquier *ECU* y sin importar la complejidad de *SMs*. Tal como se detalla en esta tesis, la técnica propuesta basada en sistemas expertos (*EXs)* puede ser utilizada para cualquier complejidad y a su vez se puede aplicar sobre cualquier *ECU* siempre y cuando las especificaciones hayan sido confeccionadas en Simulink® (caso más habitual en las *ECUs* complejas).

4. OBJETIVOS DE LA TESIS DOCTORAL

Esta tesis doctoral se centra en los campos de la validación del *software* y de la proposición de modelos sostenibles. Antes de abarcar con más detalle estos objetivos, conviene detallar lo tratado en esta tesis referente a los modelos de transporte sostenible. Estos modelos pueden ser modelos de transporte sostenible por sí mismos al utilizar medios que permitan el desplazamiento sin producir emisiones (al menos locales) como es el caso de los *EVs*, autobuses eléctricos, tranvías, taxis eléctricos, etc. Sin embargo, un modelo puede ser sostenible si tiene aportaciones positivas a otros aspectos de la sostenibilidad, como bien pueda ser el ecodiseño, mejor integración de las *REs*, proposiciones y mejores sobre políticas medioambientales, etc. En esta tesis, además de proposiciones innovadoras para la validación del *software*, se ha propuesto un modelo de transporte sostenible y sus contribuciones paralelas al ecodiseño, al *EGD* y a la tecnología *V2B* basándose en conceptos tales como el *ER*, *EC* y el *EDR*.

Dicho esto, esta tesis tiene como objetivos:

a. <u>Proposición de técnicas innovadoras en la validación del *software*</u>. En esta tesis se propondrán técnicas de validación novedosas que traten de solventar los problemas existentes en el sector de la automoción. Estarán basadas en *Dlls* y *EXs*. Para evaluar las prestaciones de las técnicas propuestas en esta tesis doctoral, se efectuarán comparaciones con técnicas ampliamente usadas en el sector de la automoción.

b. Mediante la combinación del *software* validado y existente en las *ECUs* de los *EVs*, <u>se han evaluado las contribuciones al ecodiseño de los *EVs*</u>, elemento fundamental en cualquier modelo de transporte sostenible. La presente tesis busca la disminución del impacto ambiental durante el proceso de diseño. Para ello, se propondrá soluciones basadas en movilidad eléctrica asi como un algoritmo basado en los conceptos de *ER*, *EC*, *EDR* y redes neuronales.

c. <u>Proposición de ejes de mejora en las actuales políticas medioambientales basándose en modelos de transporte sostenible</u>. Esta tesis propone ejes de mejoras que se pueden incorporar a actuaciones actuales como el *EGD*. La solución aportada en esta tesis se basa en la movilidad eléctrica y algoritmos de *EC*, *ER* y *EDR* asi como redes neuronales.

d. Evaluación del impacto de los modelos de transporte sostenible y de los algoritmos de eficiencia energética en *EVs* basados en los conceptos de *ER*, *EC* y *EDR* sobre la tecnología *V2B*.

e. Proposición de un modelo de transporte sostenible. Esta tesis presenta un modelo de transporte sostenible basado en movilidad eléctrica, estudiando su viabilidad económica para todos los participantes en el mismo (propietarios de los *EVs*, empresas generadoras de electricidad y comercializadoras).

Para la consecución de estos objetivos, el proceso de investigación se ha estructurado de la siguiente manera:

1. Se establece un modelo de transporte sostenible basado en movilidad eléctrica. A partir de ahí, se estableció la hipótesis de la influencia que tiene el *software* de automoción en la sostenibilidad.
2. Se ha realizado un detallado estudio del estado del arte de la validación electrónica de vehículos. Teniendo en cuenta el amplio perímetro que engloba este concepto (*hardware* y *software*), se ha procedido a acotarlo, centrándose en la parte *software*. Dado que existen múltiples tipos de *software* según su campo de aplicación, la presente tesis está centrada en el sector de la automoción tanto en vehículos de tracción tradicionales como *EVs*.
3. A partir de los datos obtenidos anteriormente, se buscaron posibles soluciones innovadoras que introdujeran mejoras en la realización de la validación del *software*. Este proceso conllevo la aplicación de una nueva técnica basada en *EXs*. Para verificar las prestaciones de esta técnica, se establecieron una serie de métricas para poder realizar la comparación con otras técnicas ampliamente usadas en la actualidad.
4. A partir del proceso de validación *software*, introducir mejoras en el *software* que contribuyeran a los modelos de transporte sostenibles. En este caso, se optó por proponer algoritmos de *ER*, *EC* y *EDR*. El objetivo fundamental de este punto es proponer rutas a los conductores teniendo en cuenta su modo de conducción, las características propias de la ruta, así como proponer al conductor los momentos óptimos de carga teniendo según la contribución de las *REs*.

5. A su vez, se estudió la posibilidad de utilizar este algoritmo para la obtención de datos de rodaje de *EVs* que fueran de utilidad para los redactores de políticas ambientales europeas. Más concretamente, aportaciones al *EGD.*
6. Finalmente, se evalúo el impacto de los conceptos de *EDR, EC* y *ER* sobre la tecnología *V2B* y sobre el ecodiseño con vistas a evaluar el incremento de energía disponible para la citada tecnología gracias al uso de algoritmos de mejora de consumo energético en *EVs*.

4.1 Unidad temática de la tesis

De la unidad temática de la tesis, se desprende que se centra en dos ejes fundamentales:

a. Innovación de las técnicas de validación del *software*.
b. Contribución a los modelos de transporte sostenibles.

Según la estructura del proceso de investigación detallada anteriormente, estos dos ejes han sido tratados y acotados al sector de la automoción y a vehículos de tracción eléctrica, gasolina y diésel.

4.2 Modalidad de presentación de la tesis

La presente tesis doctoral se presenta bajo la modalidad de Tesis por compendio de publicaciones. Dicha modalidad se ampara en documento aprobado por el Comité de Dirección de la EIDUNED, en su reunión de 16 de enero de 2017, y por la Comisión de Investigación y Doctorado de la UNED, con fecha 21 de febrero de 2017.

Las tesis presentadas bajo esta modalidad deben respetar la siguiente estructura:

- *Introducción en la que se justifique la unidad temática de la tesis.*
- *Hipótesis y objetivos a alcanzar, indicando en que publicación o publicaciones se abordan.*
- *Marco teórico en el que se inscribe el tema de la tesis y herramientas metodológicas o remisión a las publicaciones.*
- *Copia completa de las publicaciones, ya sean publicadas o aceptadas para publicación, donde conste el nombre y adscripción de la autoría y coautoría, en su caso, así como la referencia completa de la revista o editorial en la que los trabajos hayan sido publicados o aceptados para su publicación, en cuyo caso se aportará justificante de la aceptación*

de la revista o editorial. En todos estos casos siempre deberá constar de forma explícita la filiación del doctorando o doctoranda a la UNED.

- *Conclusiones, indicando de qué publicación o publicaciones se desprenden.*
- *Resúmenes en español y en inglés o, en su defecto, en el idioma habitual para la comunicación científica en su campo de conocimiento científico, técnico o artístico.*
- *Otras aportaciones científicas derivadas directamente de la tesis doctoral.*
- *Informe con el factor de impacto y cuartil del Journal Citation Reports (SCI y/o SSCI), SCOPUS, Sello de Calidad FECYT o de toda base de datos selectiva y con factor de impacto de referencia del área en el que se encuentran las publicaciones presentadas.*
- *Fuentes y/o Bibliografía.*

Dentro del apartado 2.1, toda tesis puede ser presentada si existen "*un mínimo de 4 artículos (al menos, tres ya publicados y el cuarto aceptado) en revistas de índices de impacto en cualquiera de los cuartiles de la relación de revistas del ámbito del Programa en el que está inscrita dicha tesis y referenciadas en la última relación publicada por el Journal Citation Reports (SCI y/o SSCI), SCOPUS y del Sello de Calidad FECYT, o bases de datos relacionadas por la Comisión Nacional Evaluadora de la Actividad Investigadora para los campos científicos correspondientes a las área de conocimiento del Programa de Doctorado y, en su caso, a las específicas líneas de investigación de los mismos. El doctorando debe ser primer firmante o segundo, en este último caso, el primero debe ser el director de la tesis*".

4.3 Hipótesis y objetivos de las líneas de investigación de esta tesis doctoral

Las líneas de investigación anteriormente expuestas han dado como resultados un total de 5 publicaciones en las revistas: *Energy*, *Energies*, y *The Journal of Software: Evolution and* Process [56, 57, 58, 59, 60], cuyo factor de impacto será detallado en apartados posteriores. En este apartado se exponen, de manera resumida, las hipótesis iniciales que debían ser confirmadas durante la investigación, así como las principales líneas de trabajo.

4.3.1 Correlación entre las publicaciones derivadas del trabajo de investigación durante la tesis doctoral

La Fig.14 muestra la relación entre publicaciones, es decir, el hilo conductor entre las mismas. En un primer lugar, se realizó un proceso de investigación para la proposición de un modelo de transporte sostenible basado en movilidad eléctrica en la ciudad de León [57]. Posteriormente, se exploró las posibles contribuciones a los citados modelos y a la sostenibilidad del *software* de un calculador motor o bien de la *VCU* de un *EV*. Para ello, se realizaron proposiciones sobre cómo efectuar el proceso de validación del citado *software*, elemento clave del sistema electrónico de una *ECU,* además del *hardware*. Durante este trabajo, se obtuvo una publicación [60]. Finalmente, la última fase de esta tesis se centró en establecer la relación entre el s*oftware* de una *ECU* y la sostenibilidad. Para ello, se estimó que un modelo de transporte sostenible puede ser sostenible por sí mismo, al ofrecer medios de transporte limpios al no generar emisiones, o bien, por proponer innovaciones sobre políticas y aspectos importantes ligados a la sostenibilidad. En este punto, se realizaron tres publicaciones al mostrar el impacto de los modelos de transporte sostenibles sobre el ecodiseño, sobre el *V2B* y sobre el *EGD* [56, 58, 59]. Por tanto, durante esta tesis se ha mostrado la importancia del *software* de una *ECU* sobre la mejora de las prestaciones de los modelos de transporte sostenible, las políticas actualmente en vigor (ecodiseño y *V2B*) y otras actualmente en discusión y desarrollo como el *EGD* [56, 57, 58, 59, 60].

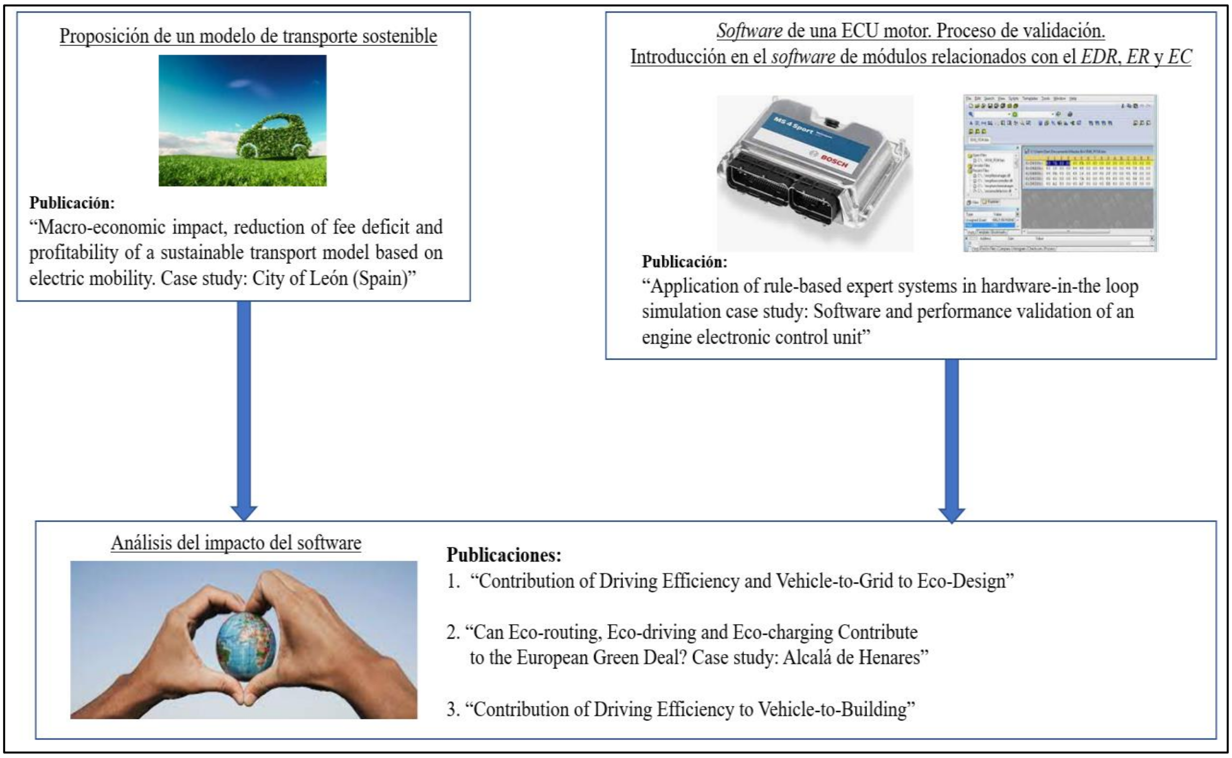

Figura 14. Relación entre publicaciones

4.3.2 Publicaciones obtenidas

a. <u>Modelos eléctricos de transporte sostenible</u>

En la actualidad, el sector del automóvil está sufriendo una transformación muy profunda en lo referente a los aspectos tecnológicos. En un primer lugar, la paulatina eliminación de los trenes de tracción tradicionales, como son los basados en gasolina y diésel, por otros más sostenibles como la tracción eléctrica. Dado que el paso de unos trenes de tracción a otros implica fuertes cambios tanto tecnológicos como sociales, los híbridos juegan un papel muy importante en esta fase de transición [61]. En segundo lugar, todo lo referente al vehículo autónomo en el que disciplinas como la inteligencia artificial, tecnología de sensores, cámaras, etc. juegan un papel esencial [62]. Centrándose en la sostenibilidad, ésta puede definirse como la satisfacción de las necesidades actuales sin comprometer la capacidad de las generaciones futuras de satisfacer las suyas, garantizando el equilibrio entre crecimiento económico, cuidado del medio ambiente y bienestar social. Sin lugar a duda, la reducción de las emisiones es un elemento fundamental para la sostenibilidad. Dado que el sector de transporte es uno de los que más energía consume y emisiones genera, los *EVs* combinados con una mejor integración de las *REs* serán vitales para garantizar la sostenibilidad en el transporte. Los modelos de transporte sostenible enmarcados dentro de la movilidad eléctrica se basan en el uso de medios de transporte eléctrico que, por definición, son cargas para el sistema eléctrico o bien incluso generadores. Referente a su capacidad de ser carga, hay que prestar atención a la capacidad del sistema eléctrico de soportar una gran demanda de carga en determinados momentos. En lo que se refiere a su capacidad de comportarse como generadores, los *EVs*, mediante la tecnología *V2G*, ceden la energía almacenada en sus baterías a la red eléctrica en los momentos del día de mayor consumo. Este tipo de modelos de transporte sostenible hace frente a problemas importantes [63, 64]:

a. El proceso de cesión de energía y posterior carga de los *EVs* conlleva una degradación de las baterías importante y no siempre aceptada por el propietario del vehículo.

b. El propietario del *EV* debe recibir un pago justo por ceder la energía a la red que sea capaz de compensar la degradación de la batería a la vez que obtiene un beneficio económico que le anime y empuje a participar en la cesión de energía a la red.

c. Las comercializadoras y actores en general del sistema eléctrico deben ser capaces de mantener su negocio. Este punto implica mantener un beneficio, pero también compensar al propietario del *EV* por ceder energía almacenada en la batería a la red.

d. El modelo de transporte sostenible propuesto no debe aumentar el déficit tarifario existente en España. Es más, si es posible, debe contribuir a su disminución.

La hipótesis principal de esta línea de investigación era proponer un modelo de transporte sostenible basado en movilidad eléctrica y comprobar si todos los actores involucrados obtenían un beneficio y, a su vez, se disminuía el déficit tarifario. La metodología se basó en proponer un modelo de transporte sostenible basado en vehículos, taxis y autobuses eléctricos para la ciudad de León. Dicha ciudad se escogió teniendo en cuenta su implicación con la sostenibilidad (plan de sostenibilidad ambicioso), sus particularidades en cuanto número de habitantes, tamaño y, sobre todo, decisiones y obras que en ese momento se estaban llevando a cabo, tales como la construcción de nuevas líneas de tranvías. Basándose en rodajes reales realizados con *EVs*, se pudo estimar consumos medios diarios y, en consecuencia, la cantidad de energía que podría estar disponible para su utilización en la tecnología *V2G*. Posteriormente, se realizó un estudio detallado de las líneas de transporte urbano de la ciudad de León, obteniendo mediante datos oficiales la cantidad de kilómetros recorridos y consumos de gasolina existentes. Finalmente, se procedió a un análisis económico de rentabilidad para todos los actores del modelo de transporte sostenible con vistas a analizar la rentabilidad de cada uno de ellos. En esta investigación se demostró que era posible disminuir el déficit tarifario y obtener una rentabilidad para todos los participantes en el modelo de transporte sostenible.

Energy: Macro-economic impact, reduction of fee deficit and profitability of a sustainable transport model based on electric mobility. Case study: City of León (Spain). Todos los detalles del fundamento teórico del artículo, así como los detalles de la revista se muestran en la tabla 1 del apartado 6.

b. Validación del *software*

Como se ha expuesto a lo largo de esta tesis doctoral, el *software* presente en una *ECU* debe ser validado exhaustivamente para asegurar que alcanza los requisitos de calidad y seguridad esperados. Conseguir este objetivo lleva implícito un coste económico nada despreciable para los constructores que deben emplear una gran cantidad de horas de validación. A su vez, y a pesar de esta inversión, en los vehículos comercializados siguen encontrándose fallos de *software* que requieren, en algunos casos, campañas de recuperación de vehículos ya comercializados. Esto impone unos costes y un desgaste de imagen al constructor muy significativo [3]. A partir de esto, la hipótesis principal era la de proponer técnicas de validación que permitieran la reducción de costes y, a su vez, mejorar la capacidad de detección de fallos *software*. En este punto, las metodologías actuales se centran en la mejora de un indicador importante como es la tasa de cobertura [65, 66]. Sin embargo, es importante distinguir entre la tasa de cobertura *software* y la tasa de cobertura funcional [65]. La primera de ellas se basa en verificar la cantidad de líneas de código que son ejecutadas, y en consecuencia validadas, cuando se ejecuta un *TC*. Cuanto más alto sea esta tasa, más líneas de código se han verificado. En cuanto a la tasa de cobertura funcional, el ingeniero de validación se abstrae de las líneas de código y únicamente se centra en estados funcionales, sin importarle cómo se ha codificado el *software*. A modo de ejemplo, si el pedal del acelerador del vehículo queda bloqueado, se verifica que el vehículo acaba deteniéndose porque el *software* detecta esta incidencia, sin importar cómo ha sido programado internamente dicha función. La cuestión es que en muchos casos las técnicas actuales se centran en o bien mejorar la cobertura funcional o bien en mejorar la cobertura de *software*. El objetivo de esta parte de la investigación no era otra que proponer una metodología que permitiera mejorar ambos parámetros de manera simultánea. La hipótesis a demostrar es que dos *EXs* trabajando en cooperación permiten la mejora de los indicadores de tasa de cobertura funcional y de código simultáneamente. Para ser más específico, esta tesis doctoral busca probar que dos *EXs* trabajando en cooperación ofrecen mejores prestaciones que las técnicas tradicionales de validación cuando se procede a la validación del *software* de un calculador motor. A su vez, y tal como se expuesto en los conceptos teóricos fundamentales para entender esta tesis doctoral, resulta extremadamente complicados alcanzar los valores indicados en un *TC* debido a la interacción de *SMs*. El resultado es que la salida esperada indicada en el *TC* dejaría de ser válida si no se alcanzan los valores exactos indicados en el mismo[8]. En consecuencia, resulta imposible saber para el validador si el *software* se ha comportado correctamente o no. En esta parte de la

[8] Recordar que en un *TC* se indica el valor que las variables *software* de entrada deben alcanzar, las acciones que hay que realizar sobre el vehículo para obtener dichos valores, así como el valor de las variables *software* de salida para dichos valores de las de entrada

investigación, se propuso una segunda hipótesis: el uso de las *Dlls* permite saber el valor esperado del *software* independientemente de que no se hayan alcanzado los valores exactos indicados en el *TC*. Como ha sido comentado en la introducción de esta tesis doctoral, el *software* de un calculador motor se hace a partir de modelos Simulink®. Pues bien, la conversión de los citados modelos en *Dlls* permite que en cualquier momento se les pueda llamar mediante código Python y obtener, en consecuencia, los valores esperados del *software* para unas entradas dadas. Además de lo expuesto, también se busca demostrar que se pueden detectar fallos *software* que otras técnicas no son capaces. Esto es así debido a que determinadas funciones realizan principalmente cálculos y a no ser que se produzca un gran error en los mismos que impliquen fallos funcionales del vehículo, el ingeniero de validación nunca los detectará. Mediante las *Dlls* es posible hacerlo.

La metodología empleada para la realización de esta línea de investigación se basó en la validación de *SMs* presentes en un calculador motor mediante diferentes técnicas tales como las técnicas de causa-efecto o la basada en modelos funcionales, ampliamente utilizada en el sector de la automoción. Posteriormente, dichos *SMs* se validaron mediante la técnica propuesta en esta tesis doctoral basada en *EXs*. Entre los parámetros usados para evaluar las prestaciones de esta técnica frente a las demás fueron la tasa de cobertura tanto *software* como funcional, fallos *software* encontrados y tiempo necesario para la implementación de cada una de las técnicas de validación empleadas en la investigación con vistas a verificar si existía una ganancia en tiempo (productividad).

The Journal of Software: Evolution and Process: Application of rule-based expert systems in hardware-in-the loop simulation case study: Software and performance validation of an engine electronic control unit. Todos los detalles del artículo relativos a su fundamento teórico, así como los datos de la revista se muestran en la tabla 2 del apartado 6.

c. Modelos de transporte y sostenibilidad

c.1 Ecodiseño

Como ya se ha indicado a lo largo de esta tesis, los modelos de transporte pueden ser sostenibles per se, y, además, realizar también aportaciones que hagan sobre otros campos como puedan ser los aspectos sociales y medioambientales. En este caso, el simple uso de *EVs* es un modelo de transporte sostenible muy básico pero que puede tener un fuerte impacto sobre otras áreas como es el caso del ecodiseño [67]. Por tanto, al hablar de modelos de transporte sostenible no hay que imaginar la electrificación de todo medio de transporte. Simplemente con una electrificación de una pequeña parte, se pueden conseguir mejoras en la sostenibilidad muy importantes.

Uno de los puntos más candentes en la actualidad en lo referente al desarrollo de productos no es otro que el ecodiseño. Mediante este concepto, las empresas centran gran parte de sus esfuerzos en conseguir el diseño de productos sostenibles y con el menor impacto medioambiental posible. Múltiples factores relacionados con el ecodiseño han sido identificados en diversas investigaciones [68, 69, 70]. Entre ellos, se pueden encontrar fabricar productos sin producir desechos peligrosos, usar tecnologías limpias, usar componentes reciclados y de fácil reciclaje, diseñar productos fácilmente desmontables y, finalmente, productos que puedan ser reciclados de manera sencilla [71]. Se han realizado diferentes propuestas para introducir mejoras en estos aspectos. Morgan y Liker invitan en su estudio a implantar y utilizar las metodologías *lean* de fabricación en las fases de diseño de productos [72]. Tal como detallan Rosen y Kishawy, este uso permitiría elegir entre diferentes alternativas relacionadas con el ecodiseño, de tal manera que se podrían evaluar de una manera sencilla los costes y los beneficios de hacer productos más respetuosos con el medio ambiente [73]. En lo referente a la eficiencia energética, las investigaciones actuales están más centradas en dos conceptos principales como son producto final y en la fabricación que en los aspectos desarrollados con el proceso de diseño. El primero de ellos está focalizado en la utilización de etiquetas informativas acerca de la eficiencia energética del producto [74]. El segundo de ellos se centra en cómo reducir los consumos energéticos durante el proceso de fabricación. Ka-Leung-Moon et al. proponen una serie de recomendaciones y directivas para el diseño y producción de productos de moda sostenibles y de bajo consumo de energía [75]. La integración de las *REs* juega un papel muy importante en el ecodiseño. Como detallan Crul, Diehl y Ryan, teniendo en cuenta que el número de productos que necesitan energía eléctrica para funcionar aumenta rápidamente, es vital analizar la integración de las *REs* en el proceso de diseño. En su estudio proponen guías para integrarlas en el producto final [76]. Por último, los desechos generados en un proceso de fabricación es un elemento importante a tener en cuenta. A modo de ejemplo, la ciberseguridad implica una cantidad de rechazos y desechos como se detalla en párrafos posteriores. Tecchio et al. analizaron en detalle la importancia de la eficiencia en el uso de materiales para reducir la cantidad de rechazos y desechos en la concepción de productos, así como para favorecer la reutilización de materiales [77]. Además de los procesos de fabricación, existen muchas actividades que generan contaminantes durante la fase de diseño de un producto. Entre ellos, se pueden encontrar: validación del *software* del producto, fabricación de prototipos para probar el producto, así como la eficiencia energética de edificios [78, 79]. Se podría detallar una lista más amplia que los tres factores anteriormente mencionados que impactan el ecodiseño durante las fases de desarrollo, como son las emisiones generadas durante los desplazamientos al centro de diseño de los ingenieros involucrados en un proyecto. Como se muestra en detalle en esta tesis doctoral, el número de ingenieros, su localización con respecto al centro de estudios entre otros factores impacta el ecodiseño.

Otro punto importante a tener en cuenta antes de enunciar el objetivo de línea de investigación son los conceptos de *ER*, *EC* y *EDR*. En esta tesis doctoral se muestra como el *EC*, el *EDR* y el *ER* tienen un impacto positivo, convenientemente utilizado, en el ecodiseño. El *EDR* incluye todos los hábitos de conducción que permiten reducir las emisiones asi como el consumo de energía. Actualmente, una gran cantidad de modelos de vehículos ya comercializados incorporan sistemas que informan al conductor sobre la eficiencia de su modo de conducción. Qi et al. investigaron en detalle sobre las contribuciones al ahorro de energía por parte del *EDR* mediante el uso de *EVs* [80]. Sabrina et al. propusieron un trabajo similar basados en retroalimentaciones continuas al conductor relativas al modo de conducción [81]. Chen, Si and Chen et al. realizaron un estudio englobado dentro del concepto de *EDR* con vistas a investigar sobre las prestaciones e importancia de los sistemas de monitorización de baterías en los *EVs* [82].

El *ER* ayuda al conductor a encontrar la ruta entre dos puntos A y B más eficientes considerando múltiples parámetros tales como las condiciones en tiempo real del tráfico, tipos de carretera y gradiente de pendientes, peso del vehículo y ocupantes entre otros. Nunzio, Thibault y Sciaretta implementaron un nuevo modelo basado en las fluctuaciones de velocidad y la infraestructura existente de carreteras para establecer la mejor ruta [83]. La Universidad de California ha trabajado en sistemas capaces de recoger informaciones en tiempo real relativas al consumo en condiciones reales de conducción con vistas a realizar un posterior procesamiento para mejorar las rutas propuestas al conductor [84]. En cuanto al concepto de *ER*, éste se refiere a cuál es el momento óptimo para poder realizar el proceso de carga. En la presente tesis doctoral, el *ER* mide la contribución de las *REs* en cada momento de tal manera que el conductor será informado sobre los momentos óptimos para realizar la carga. Como consecuencia, dicho proceso será más verde y, además, permite integrar las *REs* de una mejor manera en el sistema y al uso del *EV*.

En este punto, la presente tesis se centra en el consumo energético durante la fase de concepción de un producto en los centros de diseño. El objetivo de esta parte de la línea de investigación es evitar la paradoja de diseñar un producto sostenible para la sociedad habiendo sido poco sostenible su fase de diseño. En este punto, se plantea la pregunta de cómo se puede hacer más sostenible la fase de diseño más allá de las técnicas lean de diseño. En esta tesis doctoral se pretende demostrar que un modelo de transporte sostenible basado en *EVs* permite reducir las emisiones durante la fase de diseño de un producto. El segundo objetivo es proponer un algoritmo que permita mejorar la eficiencia energética de los *EVs* de tal manera que se demuestre que conceptos tales como el *EDR*, *EC* y *ER* se encuentran fuertemente ligados al concepto de ecodiseño.

La metodología seguida en esta línea de investigación fue diseñar un algoritmo de navegación basado en redes neuronales, *ER*, *EC* y *EDR* implementado mediante el interfaz de programación Here® y el lenguaje de programación Python. A partir de este algoritmo y mediante el uso del *EV* por parte de ingenieros pertenecientes a un centro de estudios en la ciudad de Toulouse (Francia), se pudo determinar las reducciones de consumos energéticos en los edificios del citado centro.

Energies: <u>Contribution of Driving Efficiency and Vehicle-to-Grid to Eco-Design</u>. Todos los detalles del fundamento teórico del artículo, así como los detalles de la revista se muestran en la tabla 3 del apartado 6.

<u>c.2 Aportaciones a la tecnología *V2B*</u>

V2B es una técnica actualmente bajo investigación por su potencial para disminuir emisiones ligadas a edificaciones. Un sistema *V2B* se compone principalmente de *EVs*, generadores de energía distribuida localmente, cargas críticas, un sistema de control a cargo de la gestión de energía del edificio (*BEMS*) y almacenamiento estático. El objetivo del *BEMS* es ejecutar algoritmos para obtener ingresos económicos como la reducción de picos [85]. Tal como detalla Odkhuu et al., *V2B* permite el uso de cargadores bidireccionales asi como la integración de recursos energéticos renovables a pequeña escala, como sistemas fotovoltaicos y turbinas [86]. En consecuencia, es posible extraer y transferir energía desde / hacia edificios dependiendo del estado de la batería de los *EVs*. Además de esto, la tecnología *V2B* ofrece importantes servicios para reducir la carga pico del consumo de energía del edificio a través de la reducción de picos, el cambio de carga, el llenado de los valles de consumo, una mejor integración de *REs* y respaldo en caso de escasez de electricidad [86]. Algunas investigaciones muestran que se obtiene una reducción importante de la electricidad fósil debido a la contribución de *REs* gracias a la transferencia de la energía de las baterías del *EV* al edificio según detalla Buonomano et al. [87]. Zhou et al. describen en su investigación las principales ventajas de la integración de los *EVs* con las *REs*, como la reducción del consumo de energía de los edificios, la reducción de la presión de importación / exportación en la red eléctrica y el cambio de las cargas pico a períodos sub o no pico [88]. Actualmente existen problemas técnicos relacionados con la tecnología *V2B*, como la característica estocástica del horario de conducción de los *EVs* [87,88], en los que se centra esta tesis doctoral. Otros temas están relacionados con la infraestructura y la vida útil de las baterías de los *EVs* [89]. Ghaderi demostró en su investigación que *V2B* ofrece ganancias significativas incluso considerando la degradación de la batería en base a un escenario compuesto por 6 *EVs* y un sistema *V2B* [90]. Gagne et al demostraron en su investigación que *V2B* es económicamente viable en mercados regulados [91]. En la bibliografía se pueden encontrar estudios similares relacionados con la viabilidad económica de tecnologías similares como *V2G* [57].

En esta parte de la investigación se ha investigado la contribución de las técnicas *ER*, *EDR* y *EC* sobre la disminución de las emisiones de edificios situados en dos zonas climáticas diferentes (Jaén y Alcala de Henares). Para tener en cuenta el uso estocástico del *EV*, se han tomado muestras de diferentes grupos sociales (autónomos, trabajadores locales y trabajadores que ejercen su actividad fuera de su ciudad de residencia). A partir de las medidas de consumo gracias al uso de *ER*, *EDR* y *EC*, se ha podido determinar las ganancias introducidas por la eficiencia en la conducción en la reducción de consumo de un edificio.

Energies: *Contribution of Driving Efficiency to Vehicle-to-Building.* Todos los detalles del fundamento teórico del artículo, así como los detalles de la revista se muestran en la tabla 4 del apartado 6.

c.3 Aportaciones de los modelos sostenibles a las políticas europeas.

En los últimos años se llevan realizando políticas que buscan aumentar la presencia de *EVs* en el parque automovilístico como: exención del impuesto de matriculación, reducción en el pago de impuestos municipales que pueden ir entre un 50 y un 75%, aparcamiento gratuito en zonas céntricas de ciudades o incluso reducción de los peajes. Actualmente, se puede encontrar el Plan Moves que consiste en un programa de incentivos enmarcado en favorecer la movilidad eficiente y sostenible. Este proyecto está dotado de un presupuesto de 100 millones de euros y otorga, entre otras ventajas, ayudar directas que pueden alcanzar los 5.500 euros siempre y cuando el vehículo adquirido sea de cadena de tracción híbrida o eléctrica. Estos planes sólo tienen un ámbito nacional. A nivel internacional, se pueden encontrar iniciativas tales como el *EGD* fundamentado en tres pilares fundamentales: reducción gradual de los gases de efecto invernadero hasta 2050, estimulación del crecimiento económico teniendo en cuenta la limitación de los recursos existentes y, finalmente, no olvidar a ningún actor o sector de la sociedad durante este proceso de transformación [48]. Para la realización de todo esto, se están tomando medidas en muchos ámbitos tales como mejora de la eficiencia energética de los edificios, mejorar la integración de las *REs* y conseguir una gran mejora en el transporte sostenible y gestión inteligente del tráfico. Como consecuencia, la potencial aportación del *EV* resulta fundamental, y es en este punto donde se centra también la presente tesis doctoral.

Un punto importante en la mejora de eficiencia energética es la eficiencia en la conducción. Consecuentemente, los conceptos de *EDR, ER y EC* pueden tener una influencia importante sobre las políticas ambientales actualmente en desarrollo en el seno de la Unión Europea, como es el caso del *EGD*. En este punto, esta línea de investigación se plantean varias hipótesis que resultarán en los objetivos fundamentales de la tesis doctoral:

a. ¿Deben ser las políticas de implantación del *EV* deben ser generalistas o bien centrarse teniendo en cuenta las particularidades de los sectores sociales que integran la población activa? Parece lógico pensar que el uso del *EV* no será el mismo entre un autónomo, un trabajador que trabaje fuera o dentro de la ciudad.

b. ¿Cuál es el impacto de la eficiencia en la conducción en tecnologías actualmente en fuerte estudio como *V2G*?
c. ¿Permiten las políticas actuales compatibilizar técnicas como *V2G* y *V2H*?

Teniendo en cuenta todo esto, los objetivos fundamentales de esta tesis se centran en responder a las anteriores preguntas. Para ello se ha seguido la metodología expuesta en la Fig.15, en la que se pueden observar los factores clave a tener en cuenta en esta línea de investigación. El primero de ellos se centra en el análisis de la población activa de la ciudad sujeta a este estudio, clasificándola en diferentes sectores sociales tales como autónomos, trabajadores que ejercen su actividad fuera de la ciudad o trabajadores que la ejercen en la ciudad sujeta a este estudio. Este punto es un elemento clave pues el uso del *EV* es diferente. Las adquisiciones de datos obtenidas en los desplazamientos de los conductores participantes en la investigación servirán para establecer un perfil de utilización del *EV* diferente como se expone a lo largo de esta tesis. Es importante recalcar que los desplazamientos son aleatorios (no planificados) como consecuencia de la actividad profesional de cada conductor. El segundo punto esencial a tener en cuenta es el algoritmo empleado para el cálculo de consumos de los *EVs* para cada sector de la población. El citado algoritmo será descrito en el siguiente apartado, así como en las publicaciones surgidas de esta tesis.

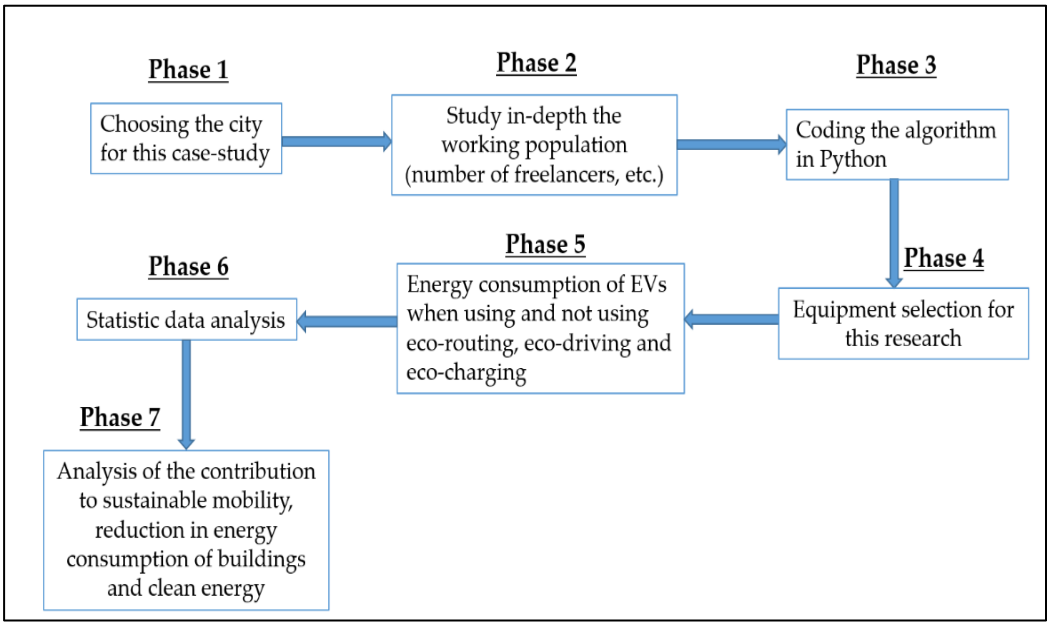

Figura 15. Método seguido en esta investigación

Esta parte de la investigación fue efectuada en la ciudad de Alcalá de Henares, localizada en la Comunidad de Madrid, a aproximadamente 32 km de la capital de España. Según los datos publicados por el Instituto Nacional de Estadística, en 2018, esta ciudad contaba con 198.750 habitantes. En cuanto al tráfico, éste es monitoreado con un total de 17 cámaras distribuidas en la ciudad, principalmente en el centro.

Energy: Can Eco-routing, Eco-driving and Eco-charging Contribute to the European Green Deal? Todos los detalles del fundamento teórico del artículo, así como los detalles de la revista se muestran en la tabla 5 del apartado 6.

5. MARCO TEÓRICO DE LA PRESENTE TESIS. REMISÓN A PUBLICACIONES

Tal y como se ha expuesto a lo largo de esta tesis, las líneas de investigación se han centrado en la introducción de técnicas de validación de *software* innovadoras, así como la contribución del *software* en sí mismo en la introducción de modelos de transporte sostenible. Para garantizar la validez de los resultados de esta tesis en sus distintas líneas de investigación, se han planteado metodologías robustas basadas en:

- En lo que se refiere a la validación *software*, se han llevado a cabo medidas reales obtenidas de la validación del *software* usando simuladores *HIL* disponibles en las instalaciones del constructor en el que el doctorando ha realizado su actividad laboral. A su vez, para una mayor representatividad de los datos, el *software* empleado se encontraba en desarrollo e iba a ser destinado a vehículos cuya comercialización estaba prevista a finales del 2017. Por tanto, se pudo comprobar de manera fehaciente las ventajas aportadas por las técnicas de validación propuestas en un proyecto real de automoción frente a otras utilizadas ampliamente en este sector.
- En el caso de la evaluación de las aportaciones del *EV* a la sostenibilidad, los datos de los rodajes se han obtenido de manera empírica mediante el uso del *software* Inca® del fabricante ETAS® [55] o bien mediante *data logger* (registrador de datos) principalmente. Todas estas medidas han sido analizadas mediante el uso del *software* MDA® de Etas® para la calibración de los modelos de consumo energético tal como se explicará posteriormente [92].
- En cuanto a la aplicación de un modelo de transporte sostenible, los datos expuestos en la investigación no son el resultado de una verificación empírica sino de un proceso de análisis de viabilidad económica riguroso. Gracias a ello, se han obtenido datos sobre la viabilidad de este tipo de modelos. Es de remarcar que los datos relativos a los consumos de autobuses y taxis eléctricos han sido obtenidos de experiencias en otros lugares de España y de sitios web oficiales. En cuanto a los rodajes de vehículos se han obtenido de manera empírica.

Tanto las metodologías como los resultados obtenidos han sido verificados mediante análisis de sensibilidad y el análisis de amenazas a la validez de la investigación. El resultado de todo esto ha sido que los artículos mencionados han pasado el proceso de *peer review* en las citadas revistas.

5.1 Relación entre publicaciones

La relación entre los papers está descrita y definida en la sección 4.3.1.

5.2 Publicación 1. "Macro-economic impact, reduction of fee deficit and profitability of a sustainable transport model based on electric mobility. Case study: City of León (Spain)"

Los modelos de transporte sostenibles son elementos fundamentales a la hora de favorecer la sostenibilidad teniendo en cuenta la evolución del número de habitantes de las ciudades y a las necesidades de movilidad. Por tanto, es vital la reducción de emisiones ligadas al transporte. Para ello, existen diferentes opciones, como bien puede ser electrificar el transporte con una correcta integración de las *REs* o bien promover otros modos de transporte tales como bicicletas etc. que permiten la movilidad sin generar emisiones. No cabe duda de que el futuro de la automoción pasa por la electrificación de los trenes de tracción y la paulatina desaparición de los vehículos diésel y gasolina. Esto conlleva importantes ventajas como implantar de una manera más amplia técnicas como la *V2G*, *V2H* y en general, V*ehicle-to-X* (vehículo conectado) [93]. A la hora de proponer un modelo de transporte sostenible, los investigadores se encuentran con diferentes dificultades entre las que destacan la fuerte inversión necesaria por parte de todos los actores involucrados en el modelo, como son los usuarios de los *EVs*, las comercializadoras y las compañías eléctricas. Consecuentemente, en este artículo se ha realizado un estudio detallado de la viabilidad del modelo de transporte propuesto basado en movilidad eléctrica, estudiando los siguientes indicadores económicos [94]:

- Valor actual neto. Se trata de un parámetro considerado para estudiar la viabilidad de una inversión. Se puede definir como un criterio consistente en actualizar los cobros y pagos de un proyecto para determinar las posibles ganancias y pérdidas de esa citada inversión. Se calcula mediante la ecuación (1).

$$VAN = -I_O + \sum_{t=1}^{n} \frac{F_t}{(1+TIR)^t} = -I_o + \frac{F_1}{(1+TIR)} + \frac{F_2}{(1+TIR)^2} + \frac{F_3}{(1+TIR)^3} + .. + \frac{F_n}{(1+TIR)^n} \quad (1)$$

donde I_0 es la inversión inicial, F_t son los flujos de caja y n es el periodo de tiempo considerado.

Una vez obtenido el Valor Actual Neto *(VAN)*, se pueden encontrar tres posibles situaciones:

1. *VAN*>0. Los valores actualizados de cobro y pagos actualizados tienen un valor positivo y, por tanto, la inversión generará beneficios. Lógicamente, a mayor valor del *VAN*, mayores beneficios.
2. *VAN* =0. Se trata del caso en que un proyecto no genera ni valores positivos ni negativos. En estos casos, no quiere decir que el proyecto deba ser rechazo pues quizá puedan existir otras razones que empujen a la empresa en cuestión a la realización del proyecto.
3. *VAN*<0. En estos casos, se habla de un proyecto que genera pérdidas y, salvo que puedan existir otras razones fuera del plano económico para la realización del citado proyecto, debe ser rechazado.

- Tasa interna de retorno *(TIR).* Se puede definir como la tasa de interés o rendimiento que tiene una determinada inversión. Se calcula según lo indicado en la ecuación (2).

$$-I_O + \sum_{t=1}^{n} \frac{F_t}{(1+TIR)^t} = -I_o + \frac{F_1}{(1+TIR)} + \frac{F_2}{(1+TIR)^2} + \frac{F_3}{(1+TIR)^3} + .. + \frac{F_n}{(1+TIR)^n} = 0 \quad (2)$$

donde I_0 es la inversión inicial, F_t son los flujos de caja y n es el periodo de tiempo considerado.

El valor de la *TIR* es fundamental para considerar si una inversión debe realizarse o no. Así se distinguen tres casos en función del parámetro k que no es otra cosa que la tasa de descuento de flujos elegida para el *VAN*.

1. *TIR*>*k*, el proyecto será aceptado.
2. *TIR*=*k*. situación similar a la del *VAN* es cero. En este caso, la inversión sólo puede realizarse si mejora la competitividad de la empresa.
3. *TIR*<*k*. El proyecto debe ser rechazado por su falta de rentabilidad.

- *Payback* (amortización). Se trata de un método sencillo para verificar el momento en el que se recupera la inversión realizada para un determinado proyecto. Las ventajas principales de este indicador es su simplicidad de cálculo, además de ofrecer una idea sobre la liquidez del negocio y del nivel de riesgo entre otros. Sin embargo, presenta inconvenientes tales como no tener en cuenta el momento en el que se reciben los flujos netos de caja. Se puede calcular mediante la ecuación (3):

$$Payback = a + \frac{I_o - b}{F_t} \quad (3)$$

donde *a* es el número del periodo inmediatamente anterior hasta recuperar el desembolso inicial, I_o es la inversión inicial del proyecto, *b* es la suma de los flujos hasta el final del periodo a, y F_t es el valor del flujo de caja del año en que se recupera la inversión.

El *payback* favorece elegir aquella inversión en la que su plazo de recuperación será menor.

Los pasos elegidos para realizar el cálculo de estos indicadores fueron:

- Estimaciones de ventas de *EVs* asi como taxis y autobuses eléctricos operando en la ciudad elegida para este estudio.
- Costes de carga para los usuarios de *EVs*.
- Costes asociados a los peajes eléctricos.
- Consumos equivalentes en diésel y gasolina para realizar el cálculo de disminución de emisiones.
- Cálculo de las pérdidas de impuesto de valor añadido por no ingresos del estado por la disminución del consumo de combustibles.
- Ingresos por las ventas de emisiones según el protocolo de Kyoto.
- Ingresos por participación en la técnica *V2G*.
- Etc.

La lista exhaustiva de todos de todos los parámetros está disponible en los datos suplementarios proporcionados a la revista Energy en el momento de su publicación.

5.3 Publicación 2. "Application of rule-based expert systems in hardware-in-the loop simulation case study: Software and performance validation of an engine electronic control unit"

El *software* de un calculador motor (trenes de tracción de gasolina o diésel) se desarrolla a partir de modelos Simulink® encargados de controlar las distintas funciones del motor térmico (control de emisiones de NO_x, cantidad de gasolina o diésel a inyectar en los cilindros, etc) [39]. En esta investigación el fundamente teórico se basa en la utilización de dos *EXs* basados en reglas que no son otra cosa que sistemas que trabajan mediante reglas, comparación de resultados y aplicación de nuevas reglas [95]. El funcionamiento teórico del sistema se describe en la Fig.16. En primer lugar, existen dos *EXs* que trabajan en cooperación. El primer de ellos genera reglas *software* mientras que el segundo genera reglas de prestación *software* [96]. Dicho con otras palabras, el primer verifica que una parte del código se ejecuta correctamente (ejecución a bajo nivel) en tanto que el segundo verifica que el sistema ha funcionado correctamente, abstrayéndose sobre cómo se ha codificado el *software* [97]. Por tanto, el *EX software* va generando reglas aleatorias *software*, expresadas mediante un *TC*, y comienza la simulación *HIL*. Transcurrido un tiempo, el sistema *software* comunica el estado alcanzado en la simulación pues, como ya se ha expuesto, en determinadas ocasiones no se alcanzan los valores exactos previstos en el *TC* debido a las interacciones entre *SMs*. Finalmente, el *EX* de prestación determina cuál debería ser el estado funcional del vehículo para esa regla *software*. En este punto es importante remarcar que, en el caso de que tras la simulación *HIL* no se alcance el valor exacto de la regla *software*, es decir, en el *TC*, el *EX software* llamará a una *Dll* que encapsula los modelos Simulink® bajo validación, para que proporcione los valores teóricos de las variables que el *software* debería proporcionar para la situación actual del sistema [98].

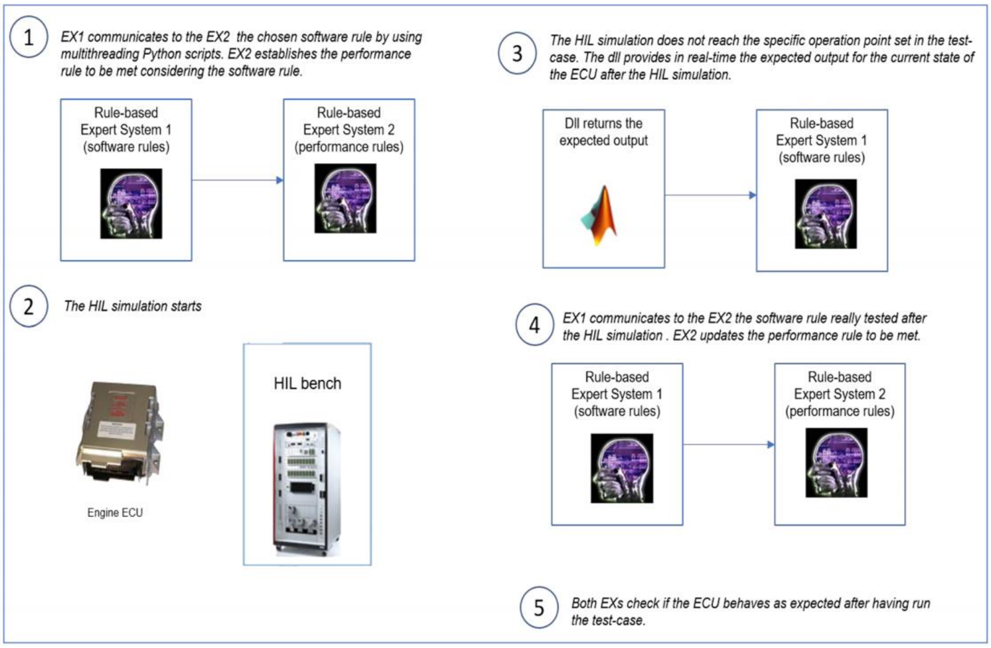

Figura 16. Funcionamiento de los sistemas expertos basados en reglas en esta investigación

Los modelos de inferencia implementados para el *EX software* han sido realizados mediante modelos confeccionados a partir de las especificaciones Simulink® (Fig.17). En el caso del *EX* basado en prestaciones, el sistema de inferencia se hizo mediante modelos funcionales (Fig.18). Por último, mencionar que la comunicación entre *EXs* se hizo mediante hilos mediante Python, existiendo un hilo principal encargado de ejecutar todo el código relacionado con la automatización del proceso: manipulación del modelo Simulink®, interfaz de Inca®, etc. [99]

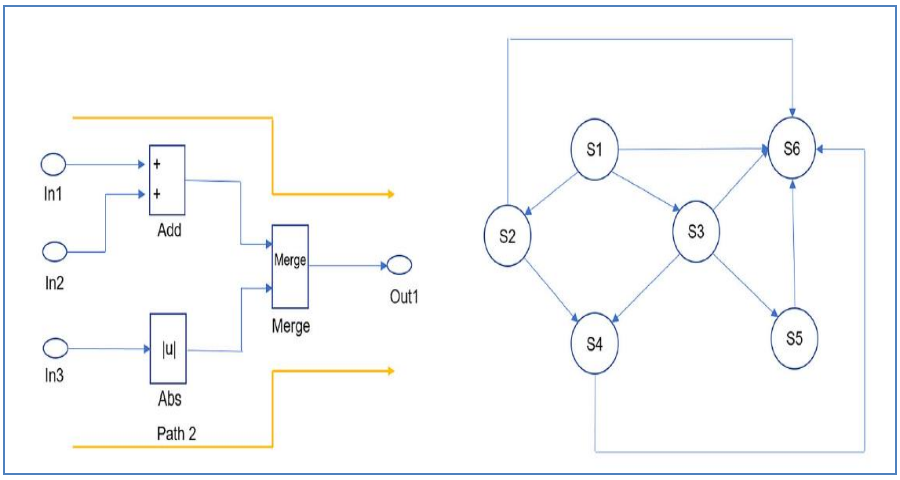

Figura 17. Sistema experto software realizado a partir de especificaciones Simulink®

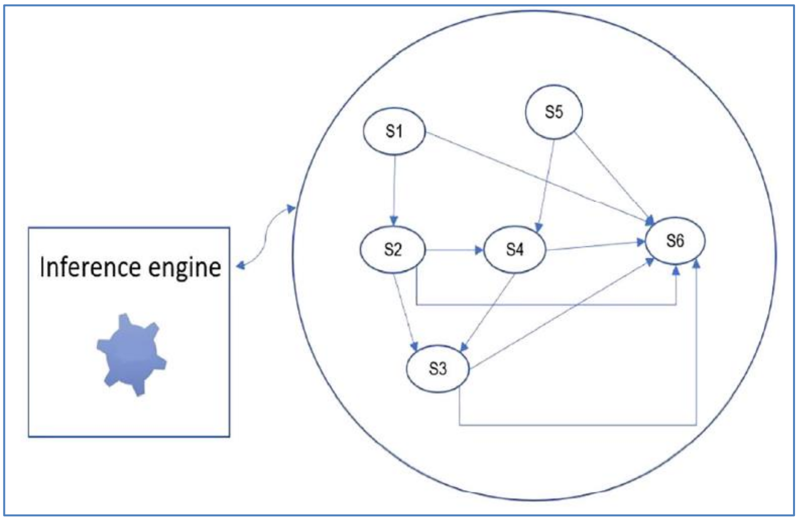

Figura 18. Sistema experto de prestación realizado a partir de modelos funcionales

Tras la ejecución de los *TCs* previstos mediante esta técnica y las técnicas ampliamente usadas en el sector de la automoción (causa-efecto y validación basada en modelos), se realizaron una serie de cálculos para obtener su prestación. Entre ellos destacan [100, 101, 102, 103]:

a) Tasa de cobertura funcional.
   Esta tasa se puede definir como el número total de requerimientos testeados frente al total de requerimientos funcionales.
b) Tasa de cobertura de código.
   Teóricamente hablamos de la cantidad de líneas de código verificadas frente al número total de líneas presentes. Sin embargo, para hacer más viable el cálculo de este indicador, se consideró la relación entre el número de bloques Simulink® testeados por una determinada técnica frente al número total de bloques existentes en el *SM* objeto de validación.
c) Fallos *software* detectados por cada técnica.
d) Tiempo necesario para la implementación de cada técnica.

Cabe reseñar que esta investigación se realizaron validaciones de *SMs* de la *VCU* para confirmar la posibilidad de aplicar esta metodología de validación sobre otras cadenas de tracción con resultados positivos. Por tanto, esta técnica va en línea y contribuye a las nuevas normativas y tendencias medioambientales de la Unión Europea como la prohibición de los vehículos de combustión asi como el *EGD.*

5.4 Publicación 3. "Contribution of Driving Efficiency and Vehicle-to-Grid to Eco-Design"

A la hora de hablar de modelos de transportes sostenibles se pueden distinguir diferentes situaciones [104]. La primera de ellas es que el modelo sea sostenible por sí mismo al generar cero emisiones locales a la vez que novedoso. La segunda es emplear un modelo de transporte sostenible existente pero que tenga una incidencia muy importante sobre otras actividades de la sociedad, mejorando la sostenibilidad. En esta línea de investigación la tesis se centra sobre esta segunda opción. La idea principal de este artículo ya ha sido expuesta en el apartado 3 de esta tesis. No obstante, como recordatorio se dirá que este artículo busca establecer propuestas para la reducción de emisiones durante el proceso de diseño de un producto. Para ello, se implementó un algoritmo basado en el interfaz de programación de Here® y en los conceptos de *ER*, *EC* y *EDR* [104, 105]. A partir de un grupo de ingenieros que participaban en el desarrollo de un producto en un centro de estudios, se verificó que, gracias al algoritmo propuesto, se conseguían mejoras en cuanto a la eficiencia en la conducción que repercutían en una disminución de las emisiones asociadas y de los gastos energéticos de los edificios que integraban el centro de estudios. En este apartado se describe el fundamento teórico detrás del algoritmo propuesto. Su implementación se basa en el uso de Here® y de redes neuronales.

a) Aplicación Here®

Here® es una empresa dedicada a los servicios de navegación, siendo una de las más importantes junto a TomTom® en la actualidad [105]. Here® ofrece un interfaz de programación que puede ser utilizado por desarrolladores para generar aplicaciones en diversos lenguajes de programación, entre ellos Python. En esta tesis, se optó por dicho lenguaje. Gracias a las funciones implementadas por Here® y añadiendo un código Python suplementario, es posible hacer aplicaciones robustas de navegación como es el caso de la presente tesis doctoral. En párrafos posteriores de este apartado se describirá el funcionamiento del algoritmo mediante Here® y las redes neuronales.

b) Redes neuronales

Las redes neuronales son ampliamente utilizadas en la actualidad para múltiples aplicaciones, como son sistemas de reconocimiento de voz, clasificación de patrones, predicciones e incluso sistemas de control [106]. Para su implementación se requiere un estudio en profundidad de los datos, pues haciendo esto, se consiguen grandes prestaciones de la red y se reducen problemas típicos tales como el *overfitting* (sobreajuste) [106]. Este problema es clásico en redes sobreajustadas, de tal manera que presentan una gran prestación para el conjunto de datos usados para su implementación y validación, pero no son capaces de generalizar. Otro punto importante a la hora de su diseño es el número de capas, número de neuronas por capa, así como la estructura en definitiva que se vaya a usar. Estos factores son determinantes para obtener buenas prestaciones de la red [106].

Una vez descritos los dos elementos fundamentales del algoritmo, se procede a explicar el fundamento teórico de su implementación (Fig.19). El funcionamiento del algoritmo se puede dividir en 9 fases. En la primera de ellas, los modelos de consumo de Here® son parametrizados. Here® es capaz de predecir el consumo energético del *EV* si se les indican los parámetros relativos a las pérdidas energéticas debido a aceleraciones, velocidad, elementos auxiliares, etc. Mediante el uso de los sistemas de adquisición descritos en el artículo, es posible determinar dichas pérdidas y parametrizar los citados modelos. En la segunda fase y haciendo uso de un interfaz web, el conductor indica a la aplicación diversos parámetros para el correcto funcionamiento de la misma, como el destino. En la fase 3, Here® hace el cálculo de las rutas óptimas (más corte, más rápida o la ruta equilibrada) teniendo en cuenta la parametrización de los modelos energéticos. Gracias a esto, los conceptos de *ER* y *EDR* son tenidos en cuenta. Para el procesamiento de todo lo anteriormente expuesto, (parametrización de modelos, llamadas Here® para el cálculo de la ruta, recogida de la información retornada por Here®, etc.) se ha codificado una aplicación en Python. Es importante resaltar también que Here® tiene en cuenta la situación del tráfico actual para la determinación de las rutas óptimas y de los consumos energéticos. En la fase 4, Here® retorna las rutas óptimas. En la fase 5, la aplicación codificada en Python establece el consumo, la capacidad de la batería al final del trayecto, si son necesarias cargas, tiempo de llegada estimada y los puntos de carga durante el trayecto. En la fase 6, elige si la ruta óptima, en cuanto a consumo energético, es la más corta, la más rápida o la equilibrada. En la fase 7, se ejecuta un bloque denominado *EC* cuya misión es la de informar al conductor en qué momento la carga es más respetuosa con el medio ambiente. Para ello, se emplean redes neuronales tal como se explicará posteriormente. En la fase 8, el conductor puede activar, si así lo desea el botón *EDR* del vehículo. Finalmente, el conductor conduce al lugar de destino.

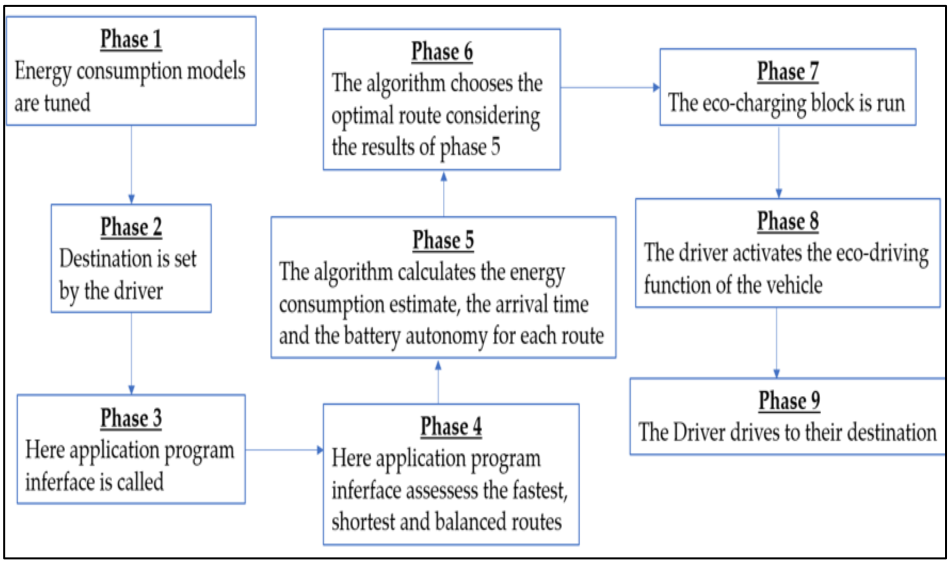

Figura 19. Método seguido en esta publicación

Los vehículos en la actualidad cuentan con sistemas para evaluar si la conducción de una determinada persona es respetuosa con el medio ambiente. Sin embargo, en el caso de los *EVs* de nada sirve realizar una conducción respetuosa si luego se efectúa la carga de la batería en momentos en los que la contribución de las *REs* es baja. En esta tesis se ha introducido el concepto de *EC,* que sirve para informar al conductor cuando es el momento óptimo para realizar el proceso de carga. Para ello se emplea la ecuación (4):

$$Eco - charging = \frac{RE_{c,t}}{RE_{max,d}} \quad (4)$$

donde $RE_{c,t}$ es la contribución de la *RE* en el total de la energía eléctrica demandada en MW y $RE_{max,d}$ es la contribución máxima de *RE* en MW para el día considerado por el algoritmo, es decir, día en que la carga pudiera tener lugar. Estos parámetros se calculan a partir de la ecuación (5):

$$RE_c = \frac{RE}{RE + NRE} \quad (5)$$

donde RE_c es la contribución de *REs* en %, *RE* es el total de electricidad generada a partir de *RE*s en MW y *NRE* es el total de energía eléctrica generada por fuentes no renovable como el carbón en MW.

A la hora de realizar la predicción, se ha realizado mediante redes neuronales *long short-term memory (LSTM)* y *nonlinear autoregressive (NAR)* [107, 108, 109 ,110]. Las primeras han servido para calcular la predicción relativa a la contribución de *REs* frente a la demanda total (ecuación 1 y 2), mientras que la segunda permite calcular la estructura de generación tal como se indica en la Fig.20.

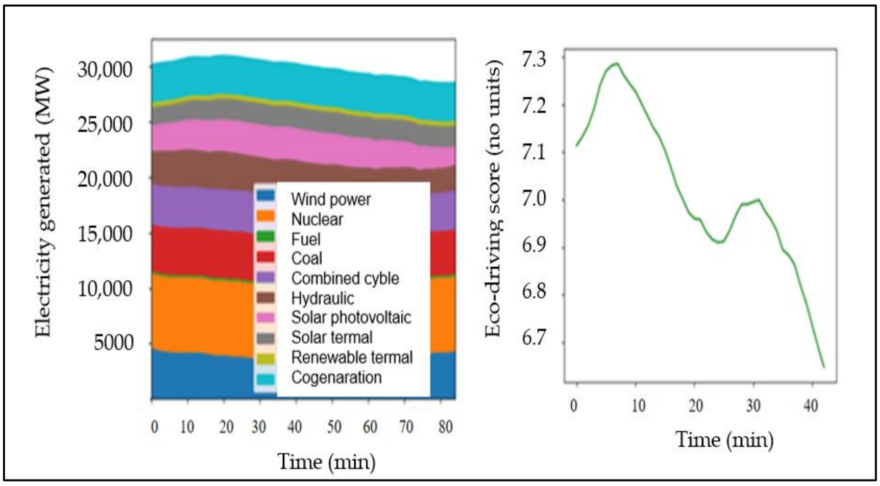

Figura 20. Estructura de generación

El detalle relativo a la estructura interna de las redes neuronales, algoritmos de aprendizaje y prestación de las redes puede encontrarse en la publicación. Es importante destacar que las redes *NAR* tratan de dar una información al conductor si bien no son elementos que proporcionen una exactitud para todos los momentos debido a condiciones súbitas que pueda haber en la generación de *RE* debido a cambios meteorológicos. En consecuencia, la exactitud en los cálculos reside sobre la red *LSTM* y no sobre la red *NAR*.

Los indicadores medidos para verificar las aportaciones de esta investigación fueron:

a) Disminución del consumo energético del *EV* gracias a la utilización del algoritmo.
b) Disminución del consumo energético del centro de estudios. Por tanto, reducción del consumo energético durante el diseño de un producto y, en consecuencia, mejoras sustanciales en cuanto al ecodiseño.
c) Estudio de la aportación del bloque *EC* para verificar si las cargas de los *EVs* se realizaron cuando dicho bloque lo recomendaba o no.

5.5 Publicación 4. "Contribution of Driving Efficiency to Vehicle-to-Building"

El fundamento teórico de la presente investigación se basa en lo expuesto en la publicación 3 (apartado 5.4). Mediante el uso de redes neuronales y conceptos como el *ER*, *EC* y *EDR* es posible obtener mejoras en el consumo energético de los *EVs* y, consecuentemente, se puede evaluar su aportación a la técnica *V2B*. Sin embargo, resulta de vital importancia tener en cuenta los grupos sociales (autónomos, trabajadores locales y trabajadores que ejercen su actividad profesional fuera de su ciudad de residencia) con el fin de tener en cuenta el uso estocástico de los *EVs*. El método utilizado para la realización de esta investigación se muestra en la Fig.21. En primer lugar, se eligieron dos ciudades que pertenecieran a diferente zona climática para evaluar el impacto de la temperatura sobre el consumo del *EV*. En segundo lugar, se hizo un estudio cuidadoso de edificios para elegir aquellos que fueran óptimos para el estudio. Posteriormente, se eligió a los participantes del estudio para asegurar un correcto mix entre los diferentes grupos sociales mencionados en el párrafo anterior. Finalmente, se realizaron las mediciones oportunas de consumos del edificio, de los *EVs* conducidos por los participantes en el estudio para poder obtener las mejoras que el *EDR*, *EC* y *ER* ofrecen para la reducción de los consumos energéticos de los edificios.

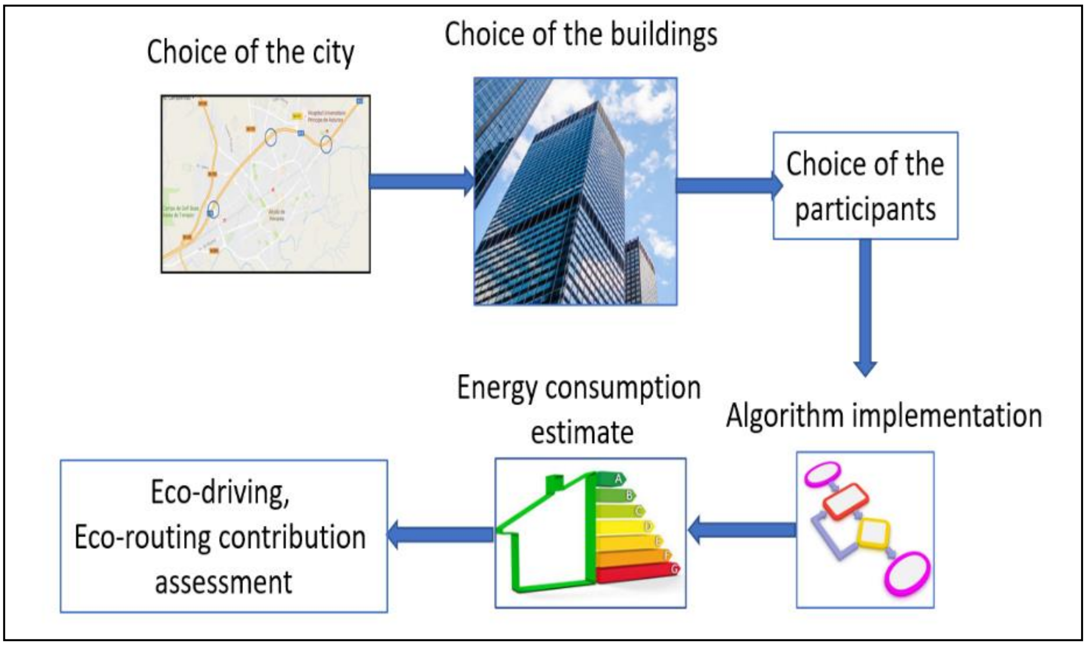

Figura 21. Método seguido en la investigación

5.6 Publicación 5. Can Eco-routing, Eco-driving and Eco-charging Contribute to the European Green Deal?

Los modelos de transporte sostenible deben empujar a promover el debate sobre la sostenibilidad. Consecuentemente, son un elemento esencial para promover nuevos debates relativos a la evolución de políticas medioambientales a nivel mundial, y en el caso de esta tesis doctoral, a nivel europeo. La idea principal de este artículo no es otra que probar que el uso estocástico del *EV* está ligado, entre otros factores, a la propia estructura de la población activa tales como los autónomos, trabajadores fuera de su propia ciudad y trabajadores urbanos. Por tanto, el fundamente teórico de esta línea de investigación fue el procesamiento estadístico de rodajes de diferentes grupos dentro de la población activa para obtener su potencial contribución a técnicas fuertemente en auge como son *V2G* y *V2H* [111, 112,113]. Además, los citados rodajes se realizaron sin y usando el algoritmo implementado en la anterior publicación. Gracias a esto, se observó la mejora en disminución de consumo por sector social.

Los factores estudiados para verificar la aportación de este estudio fueron:

a) Disminución del consumo energético del *EV* para cada sector de la población activa gracias a la utilización del algoritmo.
b) Mejoras en la contribución a la técnica *V2G* gracias a dicho algoritmo.
c) Mejoras en la generación de *RE*, estudiando la compatibilidad de las políticas *V2G* and *V2H* por sector de la población activa.

Para una generalización de los resultados, se procedió a confirmarlos mediante estudios muestrales de la población activa tal como se detalla en la publicación [114, 115, 116]. Este estudio se basó en confirmar el porcentaje de autónomos y de trabajadores dentro y fuera de la ciudad que se habían supuesto para medir las diferentes aportaciones. Mediante el uso de distribuciones binomiales se confirmó la hipótesis nula (ecuaciones 6 y 7) y los resultados indicados en la publicación.

$$H_o \text{ is accepted if} \quad \frac{|\hat{p} - p_0|}{\sqrt{\frac{p_0(1-p_0)}{n}}} \leq z_{\frac{\alpha}{2}} \qquad (6)$$

H_o is rejected if $$\frac{|\hat{p} - p_0|}{\sqrt{\frac{p_0(1-p_0)}{n}}} > z_{\frac{\alpha}{2}} \qquad (7)$$

donde *n* es la talla de la muestra, $\boldsymbol{\hat{p}}$ es la probabilidad de éxito en la muestra estudiada, $\boldsymbol{p_o}$ es la probabilidad que debe ser confirmada (hipótesis) y α es el intervalo de confianza.

6. TRABAJOS PUBLICADOS

Las publicaciones presentadas una tesis doctoral deben cumplir una serie de requisitos y condiciones establecidos en el documento aprobado por el Comité de Dirección de la Escuela Internacional de Doctorado de la Universidad Nacional de Educación a Distancia (EIUNED) asi como por la Comisión de Investigación y Doctorado de la UNED. Dichos requisitos y condiciones son:

1. El compendio de publicaciones estará formado por un mínimo de 3 artículos. Al menos dos de ellos deben estar publicados y el tercero aceptado. En el caso de publicaciones del tercer y cuarto cuartil, se han de publicar 4 artículos. En este caso, se presentan dos artículos situados en el primer cuartil y 3 en el tercer cuartil.

2. Los artículos han de ser publicados en revistas de índices de impacto en los dos primeros cuartiles de la relación de revistas del ámbito de la especialidad del Programa en el que está inscrita dicha tesis y referenciadas en la última relación publicada por el *Journal Citation Reports* (SCI y/o SSCI) y de *SCOPUS*. Todos los artículos se publicados o aceptados en revistas de los tres primeros cuartiles.

3. Todos los artículos deben estar publicados con fecha posterior a la primera matrícula de tutela académica en la EIDUNED. En este caso la primera matrícula se produjo en el curso académico 2013/2014 (octubre 2013) y los artículos se han publicado entre febrero de 2014 y mayo 2021.

4. El doctorando debe ser primer firmante o segundo, en este último caso, el primero debe ser el director o directora de la tesis. En todas las publicaciones que integran la tesis doctoral, el doctorando figura como primer autor o bien detrás del director y/o codirector de la tesis (D. Antonio Colmenar Santos y D. David Borge Diez).

Los datos de las publicaciones se muestran en las tablas 1, 2, 3, 4 y 5.

Tabla 1. Datos de la revista Energy. Publicación Macro-economic impact, reduction of fee deficit and profitability of a sustainable transport model based on electric mobility. Case study: City of León (Spain)

Datos sobre la publicación del artículo		
Título de la publicación	*Macro-economic impact, reduction of fee deficit and profitability of a sustainable transport model based on electric mobility. Case study: City of León (Spain)*	
Autores	1. Antonio Colmenar Santos (Director) 2. David Borge Diez (Codirector) 3. Pedro Miguel Ortega Cabezas 4. Vicente Miguez Camiña	
Afiliación de los autores	Departamento de Ingeniería Eléctrica, Electrónica y Control de la Escuela Técnica Superior de Ingenieros Industriales de la UNED. Departamento de Ingeniería Eléctrica y de Sistemas y Automática. Área de Ingeniería Eléctrica.	
Revista	*Energy*	
Estado de la publicación	Publicado el 1 de febrero de 2014 en el volumen 65	
DOI	https://doi.org/10.1016/j.energy.2013.11.077	
Índices de impacto *Journal Citation Reports* de la revista en el año 2020		
Categoría	*Thermodynamics*	*Energy&Fuels* *Engineering, Chemical*
Índice de impacto	7.147	
Quartil	Q1	
Índices de impacto *Scopus* de la revista en el año 2020		
CiteScore 2020 All publication types	11.5	
SCImago Journal Rank (SJR)	1.96	
CiteScore rank and Percentile per category	***CiteScore rank***	***Percentile***
Modeling and Simulation	4/290	98
Building and Construction	4/185	98

Civil and Structural Engineering	7/318	97
Management, Monitoring, Policy and Law	8/355	97
Mechanical Engineering	22/596	96
Industrial and Manufacturing Engineering	13/336	96
Energy Engineering and Power Technology	10/224	95
Fuel Technology	5/100	95
General Energy	4/65	94

En los anexos I y II se incluyen los siguientes documentos relativos a la publicación del segundo trabajo científico publicado:

• Anexo I: Copia de la publicación.

• Anexo II Informes relativos con los índices de impacto.

Tabla 2 Datos de la revista The Journal of Software: Evolution and process. Publicación Application of rule-based expert systems in hardware-in-the loop simulation case study: Software and performance validation of an engine electronic control unit

Datos sobre la publicación del artículo	
Título de la publicación	*Application of rule-based expert systems in hardware-in-the loop simulation case study: Software and performance validation of an engine electronic control unit*
Autores	1. Pedro Miguel Ortega Cabezas 2. Antonio Colmenar Santos (Director) 3. David Borge Diez (Codirector) 4. Jorge Juan Blanes Peiró
Afiliación de los autores	Departamento de Ingeniería Eléctrica, Electrónica y Control de la Escuela Técnica Superior de Ingenieros Industriales de la UNED. Departamento de Ingeniería Eléctrica y de Sistemas y Automática. Área de Ingeniería Eléctrica.
Revista	*The Journal of Software Evolution and process*
Estado de la publicación	Publicado el 31 de Julio de 2019
DOI	https://doi.org/10.1002/smr.2223
Índices de impacto *Journal Citation Reports* de la revista en el año 2020	
Categoría	*Software*
Índice de impacto	1.972
Quartil	Q3

Índices de impacto *Scopus* de la revista en el año 2020		
CiteScore 2020 All publication types	4.5	
SCImago Journal Rank (SJR)	0.37	
CiteScore rank and Percentile per category	***CiteScore rank***	***Percentile***
Software	151/389	61

En los anexos III y IV se incluyen los siguientes documentos relativos a la publicación del primer trabajo científico publicado:

• Anexo III: Copia de la publicación.

• Anexo IV: Informes relativos con los índices de impacto.

Tabla 3 Datos de la revista Energies. Contribution of Driving Efficiency and Vehicle-to-Grid to Eco-Design

Datos sobre la publicación del artículo		
Título de la publicación	*Contribution of Driving Efficiency and Vehicle-to-Grid to Eco-Design*	
Autores	1. David Borge Diez (Codirector) 2. Pedro Miguel Ortega Cabezas 3. Antonio Colmenar Santos (Director) 4. Jorge Juan Blanes Peiró	
Afiliación de los autores	Departamento de Ingeniería Eléctrica, Electrónica y Control de la Escuela Técnica Superior de Ingenieros Industriales de la UNED. Departamento de Ingeniería Eléctrica y de Sistemas y Automática. Área de Ingeniería Eléctrica.	
Revista	*Energies*	
Estado de la publicación	Publicado el 3 de agosto de 2020	
DOI	doi:10.3390/en13153997	
Índices de impacto *Journal Citation Reports* de la revista en el año 2020		
Categoría	*Energy & Fuels*	
Índice de impacto	3.004	
Quartil	Q3	
Índices de impacto *Scopus* de la revista en el año 2020		
CiteScore 2020 All publication types	4.7	
SCImago Journal Rank (SJR)	0.6	
CiteScore rank and Percentile per category	***CiteScore rank***	***Percentile***
Control and optimization	17/111	85

Energy (miscellaneous)	13/77	83
Electrical and electronic engineering	183/693	73
Energy Engineering and power technology	62/224	72
Fuel Technology	33/100	67
Renewable energy, sustainability and the environment	69/195	64

En los anexos V y VI se incluyen los siguientes documentos relativos a la publicación del tercer trabajo científico publicado:

• Anexo V: Copia de la publicación.

• Anexo VI: Informes relativos con los índices de impacto.

Tabla 4 Datos de la revista Energies. Contribution of Driving Efficiency to Vehicle-to-Building

Datos sobre la publicación del artículo		
Título de la publicación	*Contribution of Driving Efficiency to Vehicle-to-Building*	
Autores	1. David Borge Diez (Codirector) 2. Pedro Miguel Ortega Cabezas 3. Antonio Colmenar Santos (Director) 4. Jorge Juan Blanes Peiró	
Afiliación de los autores	Departamento de Ingeniería Eléctrica, Electrónica y Control de la Escuela Técnica Superior de Ingenieros Industriales de la UNED. Departamento de Ingeniería Eléctrica y de Sistemas y Automática. Área de Ingeniería Eléctrica.	
Revista	*Energies*	
Estado de la publicación	Publicado el 11 de junio de 2021	
DOI	doi:10.3390/en13153997	
Índices de impacto *Journal Citation Reports* de la revista en el año 2020		
Categoría	*Energy & Fuels*	
Índice de impacto	3.004	
Quartil	Q3	
Índices de impacto *Scopus* de la revista en el año 2020		
CiteScore 2020 All publication types	4.7	
SCImago Journal Rank (SJR)	0.6	
CiteScore rank and Percentile per category	***CiteScore rank***	***Percentile***
Control and optimization	17/111	85

Energy (miscellaneous)	13/77	83
Electrical and electronic engineering	183/693	73
Energy Engineering and power technology	62/224	72
Fuel Technology	33/100	67
Renewable energy, sustainability and the environment	69/195	64

En los anexos VI y VII se incluyen los siguientes documentos relativos a la publicación del cuarto trabajo científico publicado:

• Anexo VI: Informes relativos con los índices de impacto.

• Anexo VII: Copia de la publicación.

Tabla 5 Datos de la revista Energy. Publicación Can Eco-routing, Eco-driving and Eco-charging Contribute to the European Green Deal?

Datos sobre la publicación del artículo			
Título de la publicación	*Can Eco-routing, Eco-driving and Eco-charging Contribute to the European Green Deal? Case study: Alcalá de Henares (Spain)*		
Autores	1. Antonio Colmenar Santos (Director) 2. David Borge Diez (Codirector) 3. Pedro Miguel Ortega Cabezas 4. Vicente Miguez Camiña		
Afiliación de los autores	Departamento de Ingeniería Eléctrica, Electrónica y Control de la Escuela Técnica Superior de Ingenieros Industriales de la UNED. Departamento de Ingeniería Eléctrica y de Sistemas y Automática. Área de Ingeniería Eléctrica.		
Revista	*Energy*		
Estado de la publicación	Publicado el 1 de febrero de 2014 en el volumen 65		
DOI	https://doi.org/10.1016/j.energy.2013.11.077		
Índices de impacto *Journal Citation Reports* de la revista en el año 2020			
Categoría	*Thermodynamics*	*Energy&Fuels* *Engineering, Chemical*	
Índice de impacto	7.147		
Quartil	Q1		
Índices de impacto *Scopus* de la revista en el año 2019			
CiteScore 2020 All publication types	11.5		
SCImago Journal Rank (SJR)	1.96		
CiteScore rank and Percentile per category	***CiteScore rank***	***Percentile***	
Modeling and Simulation	4/290	98	

Building and Construction	4/185	98
Civil and Structural Engineering	7/318	97
Management, Monitoring, Policy and Law	8/355	97
Mechanical Engineering	22/596	96
Industrial and Manufacturing Engineering	13/336	96
Energy Engineering and Power Technology	10/224	95
Fuel Technology	5/100	95
General Energy	4/65	94

En los anexos II y VIII se incluyen los siguientes documentos relativos a la publicación del quinto trabajo científico publicado:

• Anexo II: Informes relativos con los índices de impacto.

• Anexo VIII: Copia de la publicación.

6.1 Publicación 1. "Macro-economic impact, reduction of fee deficit and profitability of a sustainable transport model based on electric mobility. Case study: City of León (Spain)"

6.1.1 Resumen de la publicación

<u>Resumen en español[9]:</u>

La economía española se enfrenta a dos cuestiones clave. La primera de ellas es la importante dependencia de las energías no renovables, que alcanzó el 76,4% y se situó 22 puntos por encima de la media de la Unión Europea. La segunda es la amenaza que representa el déficit tarifario para la sostenibilidad de la Red Eléctrica Nacional. Este hecho está obligando al Gobierno Español a implementar medidas enfocadas a la subida de impuestos. Sin embargo, estas decisiones no han conseguido contener la situación. Esta investigación propone el uso de modelos de transporte sostenibles basados en la movilidad eléctrica, redes inteligentes,

[9] Al ser una transcripción del artículo publicado, en este caso se han seguido las abreviaturas de la citada publicación y no las indicadas en el apartado nomenclatura de la presente tesis doctoral. Esto será de aplicación para los apartados 6 y 7.

autobuses, taxis y vehículos eléctricos, en la ciudad de León, España (135.059 habitantes) como un medio importante para controlar y reducir el déficit tarifario. A través de un análisis exhaustivo de la penetración del vehículo eléctrico en el mercado en comparación con las previsiones gubernamentales actuales, se ha realizado un riguroso estudio de rentabilidad para el período 2020-2030 (cuando estarán listas las redes inteligentes). Al introducir modificaciones en las políticas, la tasa interna de rendimiento y el valor real neto justifican la implementación del citado modelo de transporte. Así, el déficit de tarifas de León podría reducirse hasta en un 43%. Finalmente, se ha realizado un análisis de impactos macroeconómicos, como mejoras competitividad de la economía e impacto ambiental.

<u>Resumen en inglés</u>

The Spanish economy faces two key issues. The first of these is the significant reliance on non-renewable energy, which reached 76.4% and was 22 points over the European Union average. Secondly, the threat that the fee deficit poses to the sustainability of the National Grid. This fact is forcing the Spanish Government to implement measures focused on tax increases. However, these decisions have done little to contain the situation. This paper proposes the use of sustainable transport models based on electric mobility: smart grids, buses, taxis and electric vehicles, in the city of León, Spain (135,059 inhabitants) as an important means for controlling and reducing the fee deficit. Through exhaustive analysis of EV (electric vehicle) market penetration against current Government forecasts, a rigorous profitability study has been conducted for the period 2020–2030 (when smart grids will be ready). By introducing policy modifications, the Net Actual Value internal rate of return and payback figures justify its implementation. Thus, the fee deficit of León could be reduced by up to 43%. Finally, an analysis of macroeconomic impacts, such as competitive improvements in the economy, and environmental impact is conducted

6.1.2 Conclusiones

España se ve afectada por dos problemas clave: una alta dependencia energética y un importante déficit tarifario, ambos en niveles preocupantes. En esta investigación se propone la aplicación de una solución basada en un modelo de transporte sostenible compuesto por coches, autobuses y taxis eléctricos, redes eléctricas inteligentes y tecnologías de vehículo a red para la solución de ambos problemas. Su implementación se enfrenta a diversas dificultades, siendo una de ellas la opinión generalizada de que la reducción del consumo de gasolina reducirá los ingresos del Gobierno. Asimismo, la inversión para realizar este tipo de proyectos es considerable. Como resultado, existen dudas sobre su rentabilidad. Esta investigación, que toma en consideración el escenario propuesto por el Gobierno Español y las previsiones realizadas por el operador de sistema español, muestra que es posible rentabilizar este modelo de transporte sostenible para los usuarios de vehículos electricos, el Gobierno, comercializadoras y empresas eléctricas, mediante el uso de políticas regulatorias adecuadas. Como resultado, se recuperarían las pérdidas por impuestos sobre la gasolina.

Por otro lado, el déficit tarifario generado en los últimos 10 años como consecuencia de los desequilibrios entre los ingresos y los costes de las actividades reguladas, alcanzó los 26.062 M € en mayo de 2013. Esta investigación muestra que el déficit tarifario de León se puede reducir en un 43,5% - 47,1%. Además, la implementación del modelo conduce a una reducción de la demanda de gasolina y, por tanto, a una posible reducción del precio. Además, este beneficio podría utilizarse para reactivar la ayuda financiera para instalaciones de energía renovable. Este hecho mejora la competitividad de las empresas españolas y disminuye los costes operativos de los vehículos eléctricos. Como resultado, la economía española disfrutará de una mayor protección frente a las fluctuaciones del precio de la gasolina. La tasa interna de rendimiento, el valor actual neto, tasa de recuperación y rentabilidad obtenidos en este estudio son suficientes para asegurar la rentabilidad del modelo, además de proporcionar los medios para reducir el déficit tarifario. Los autores están trabajando en la preparación de futuros estudios centrados en la implantación de estos modelos en ciudades más grandes como Madrid y Barcelona.

6.2 Publicación 2: "Application of rule-based expert systems in hardware-in-the loop simulation case study: Software and performance validation of an engine electronic control unit"

6.2.1 Resumen de la publicación

<u>Resumen en español:</u>

Se necesitan técnicas innovadoras para validar el *software* a fin de reducir los costes y aumentar la calidad del *software*. Esta investigación tiene como objetivo verificar si dos sistemas expertos basados en reglas *(EXs)* combinados con bibliotecas dinámicas de datos *(Dlls)* funcionan mejor que otras técnicas ampliamente usadas en el sector de la automoción a la hora de validar el *software* de la unidad de control motor (*ECU*) mediante el uso de simulación *hardware- in-the-loop* (*HIL*).

Para realizar esta investigación, se eligieron quince módulos *software (SMs)* de diferente complejidad para ser validados mediante simulaciones *HIL* usando diferentes técnicas como la ejecución manual, *tester-in-the-loop (*testador en bucle), *model-based testing* (validación basada en modelos), un *EX* basado en reglas y la combinación de dos *EXs*, con vistas a evaluar la tasa de cobertura de código y funcional, la ganancia de productividad, la cantidad de fallos *software* encontrados, las limitaciones potenciales de cada técnica y la tasa de éxito de la simulación *HIL*. Los *test-cases* (casos de tests) utilizados se describen en profundidad en la sección de método.

La mejora que ofrecen las D*lls* y los *EXs* depende del número de estados del modelo funcional utilizado en los *EXs* y del número de subintervalos en los que se pueden dividir las variables de entradas de los *SMs*. Se puede detectar un rango entre 6 y 16 errores más cuando se utilizan dos *EXs*. La mejora de *HIL* puede alcanzar el 6%, 16,8% y 18% dependiendo de la complejidad de los *SMs*.

Resumen en inglés:

Innovative techniques to validate software are needed to reduce cost and increase software quality.

This research aims to check if two rule-based expert systems (EXs) combined with dynamic-link libraries (dlls) perform better than other techniques widely employed in the automotive sector when validating the engine control unit (ECU) software by using a hardware-in-the-loop simulation (HIL).

To perform this research fifteen software modules (SM) of different complexity were chosen to be validated in an HIL simulation by using different techniques such as the manual execution, the tester-in-the-loop, the model-based testing, a rule-based EX and the combination of two EXs to establish the code and functional coverage, the productivity gain, the number of bugs found, potential limitations of each technique and the success rate of the HIL simulation. The test-cases used are described in-depth in the method section.

The enhancement, that dlls and EXs offer, depends on the number of states in the functional model used in the EXs and the number of subintervals in which the SM inputs can be

divided. A range between 6 and 16 more bugs can be detected when using two EXs. The HIL enhancement can reach 6%, 16.8% and 18% depending on the SM complexity

6.2.2 Conclusiones

Existen varios problemas a los que se debe enfrentar el sector de la automoción a la hora de validar el *software* de la unidad de control electrónico motor (*ECU*) como son el diseño de *test-cases* representativos, cómo automatizar adecuadamente la simulación de *hardware-in-the-loop* (*HIL*) debido a la interacción de módulos *software* (*SMs*), y cómo poder encontrar errores de codificación y prestaciones *software* al ejecutar un *test-case.*

Esta investigación, realizada en el segundo fabricante de automóviles europeo más importante, se centra en la validación de *software* de un *ECU* motor mediante el uso de bibliotecas dinámicas de datos (D*lls*) y dos sistemas expertos basados en reglas (*EXs*), uno encargado de detectar errores de prestación *software* y el otro responsable de encontrar errores de código. Esta combinación permite detectar errores de prestación *software* y errores de codificación. En este estudio, los resultados alcanzados por el uso de D*lls* y dos *EXs* fueron comparados con otras técnicas ampliamente utilizadas en el sector de la automoción como *tester-in-the-loop*, la automatización mediante el uso de scripts de Python, un *EX* de prestación s*oftware* combinado con la automatización mediante scripts Python, y finalmente, la automatización mediante el uso de scripts Python sin uso de *EXs*. Los resultados obtenidos muestran que las D*lls* y dos *EXs* son capaces de detectar 6 errores más que el uso de D*lls* y un *EX* de prestación *software*, 14 errores más que el *tester-in-the-loop,* 16 errores más que la automatización usando Python, 15 errores más que una ejecución manual y 14 errores más que las pruebas basadas en modelos. El hecho de emplear *Dlls* y *EX*s trabajando en cooperación mejora la cobertura del código con respecto a las otras técnicas. Esta mejora depende del número de estados en el modelo funcional utilizado en los *EXs* y del número de subintervalos en los que las entradas de los *SMs* se puedan dividir como se muestra en esta investigación.

Los scripts Python y las *Dlls* se pueden usar combinados con diferentes técnicas, como el uso de un *EX* o dos *EXs*. Los resultados obtenidos muestran que la metodología propuesta en esta investigación mejora la tasa de éxito de las simulaciones *HIL* en comparación con la técnica *tester-in-the-loop* hasta en un 6% para *SMs* de complejidad baja, en un 16,8% para *SMs* de complejidad media y en un 18% para *SMs* muy complejos a pesar de las interacciones entre *SMs.*

Cuando se trata de automatización sin usar D*lls*, la metodología propuesta en esta investigación mejora la tasa de éxito de *HIL* hasta un 14,4% para las *SMs* de baja complejidad, un 27,4% para los *SMs* de complejidad media y un 47% para las *SM*s muy complejos a pesar de las interacciones entre *SMs*.

A pesar de que los *EXs* y D*lls* requieren más tiempo para implementarse para funciones muy complejas y simples, se cumplió con el plazo del proyecto. Cuando se trata de funciones de complejidad media, existe una ganancia de productividad considerando la cantidad de *SMs* que se testean en un proyecto *software* de *ECU* motor en comparación con el *tester-in-the-loop* y la ejecución manual. Además, el tiempo necesario para implementar la técnica basada en modelos es similar al necesario para dos *EXs*. Debe recordarse que los *SM*s de complejidad media son la mayoría en el *software* de un *ECU* motor.

6.3. Publicación 3: “Contribution of Driving Efficiency and Vehicle-to-Grid to Eco-Design”

6.3.1 Resumen de la publicación

Resumen en español:

El diseño de productos ecológicos implica mejoras en la eficiencia energética. Los productos ecológicos deben considerar no sólo las materias primas y los procesos de fabricación para mejorar la eficiencia energética, sino también la energía necesaria al diseñarlos. Esta investigación muestra cómo la navegación ecológica (*ER*), la carga ecológica (*EC*), la conducción ecológica (*EDR*), el vehículo a la red (*V2G*) y los vehículos eléctricos (*EVs*) pueden contribuir a la reducción del consumo de energía durante el diseño del producto. Para ello, se eligió a un grupo de 44 ingenieros asignados al proyecto para evaluar la energía total disponible para *V2G* al conducir *EVs* desde sus hogares hasta el centro de diseño utilizando un algoritmo codificado por los autores basado en los conceptos de *ER*, *EDR* y *EC*. La energía almacenada en los *EVs* se utilizó para cuantificar la reducción del consumo energético de los edificios presentes en el centro de diseño. Los resultados muestran que el ahorro de energía oscila entre el 2,89% y el 6,9% por día, es decir, 93 kWh por día durante el proceso de diseño. Además, el hecho de hacer más ecológico el proceso de diseño implica que las energías renovables (*REs*) se integren mejor durante el proceso de diseño. Al ejecutar el algoritmo, se informa a los conductores sobre el mix de *RE* cuando se lleva a cabo el proceso de carga. Finalmente, esta investigación muestra que las políticas actuales hacen que *V2G* y las técnicas de vehículo a casa no son compatibles.

Resumen en inglés:

Designing eco-friendly products involves energy efficiency improvements. Eco-friendly products must consider not only raw materials and manufacturing processes to improve energy efficiency but also energy needed when designing them. This research shows how eco-routing (ER), eco-charging (EC), EDR (EDR), vehicle-to-grid (V2G) and electric vehicles (EVs) can contribute to the reduction of energy consumption during product design. To do this, a group of 44 engineers assigned to the project was chosen to assess the total energy available for V2G when driving EVs from their homes to the design center by using ER, ED and EC by running an application coded by the authors. The energy stored in EVs was used to quantify the reduction in energy consumption of the buildings present in the design center. The results show that the energy saving ranges from 2.89% to 6.9% per day—in other words, 93 kWh per day during the design process. In addition, the fact of making the design process greener implies that renewable energies (REs) are integrated better during the design process. By running the application, drivers are informed about the RE mix when the charging process takes place. Finally, this research shows that current policies make V2G and vehicle-to-home techniques not compatible.

6.3.2 Conclusiones

El ecodiseño trata varios temas como materiales de bajo impacto, eficiencia energética, diseño para reutilización y reciclaje, estándares de diseño sustentable y energías renovables, entre otros. Sin embargo, la eficiencia energética no solo debe ocuparse de la fabricación sino también de la fase de diseño del producto. Esta investigación se centra en cómo los vehículos eléctricos (*EVs*), el vehículo conectado a la red (*V2G*), la conducción ecológica, las rutas ecológicas y la carga ecológica pueden contribuir al ahorro de energía durante el diseño del producto. Por tanto, estos factores juegan un papel fundamental en el ecodiseño. Teniendo en cuenta el método y los resultados obtenidos en esta investigación, se extraen las siguientes conclusiones:

(a) Ahorro de energía

El algoritmo propuesto en esta investigación, que utiliza modelos de consumo de energía debidamente ajustados para la conducción ecológica (*EDR*), la navegación ecológica (*ER*) y la carga ecológica (*EC*), permite reducir el consumo de energía entre un 2,89% y un 6,9%. Además de esta reducción, las redes neuronales proporcionan a los conductores información útil sobre cuándo es el momento óptimo para cargar la batería, teniendo en cuenta el aporte de energía renovable.

(b) Ecodiseño

Este algoritmo contribuye al ecodiseño como:

(b.1) Permite reducir las emisiones entre 8,96 y 23,55 kg por día de CO_2 más que cuando los conductores de *EVs* no utilizan el algoritmo.

(b.2) Esta investigación muestra que no sólo la cantidad de *EVs* es importante para aumentar la energía disponible, sino también la forma de elegir las ubicaciones de los ingenieros. El algoritmo propuesto en este estudio permite establecer las ubicaciones óptimas. Por lo tanto, un centro de diseño podría obtener más energía utilizando un número específico de *EVs*

(b.3) La contribución de *V2G* a la demanda energética del edificio varía entre 0.5% y 1.3% cuando se utiliza el algoritmo propuesto en este estudio en un pequeño centro de diseño.

(c) Compatibilidad entre *V2G* y *V2H*. Aunque el rendimiento de la batería no se degrade debido a los procesos de carga y descarga, las políticas actuales evitan que el usuario participe en *V2G* y *V2H* al mismo tiempo. La tarifa de carga de los *EVs* es más alta que los beneficios económicos obtenidos al usar *V2H*. En consecuencia, *V2G* no es compatible con *V2H*. Sin embargo, las políticas no se pueden cambiar si no se aumenta la potencia de las energías renovables instaladas. Por lo tanto, el mix de energías renovables versus energía no renovable no es lo suficientemente alta. En consecuencia, las políticas para promover los *EVs* son tan importantes como aumentar la potencia de la energía renovable instalada.

(d) Ciberseguridad. Algunas políticas para asegurar que no se viole una unidad de control electrónico (*ECU*) implican que la unidad de control electrónico deba ser reemplazada. En el presente estudio, se generan anualmente 190 kg de residuos teniendo en cuenta las unidades de control electrónico desechadas como chatarra. En consecuencia, algunas técnicas utilizadas para la ciberseguridad de la *ECU* no son respetuosas con el medio ambiente, y se debe investigar más sobre este tema para integrar mejor la ciberseguridad y el diseño ecológico.

6.4 Publicación 4: "Contribution of Driving Efficiency to Vehicle-to-Building"

6.4.1 Resumen de la publicación

Resumen en español:

El consumo de energía en el sector del transporte y en los edificios es motivo de gran preocupación en la sociedad actual. Esta investigación tiene como objetivo cuantificar cómo las rutas ecológicas, la conducción ecológica y la carga ecológica pueden aumentar la cantidad de energía disponible para la técnica V*ehicle-to-Building (V2G)*. Para ello, se clasificó la población ocupada en grupos sociales (autónomos, trabajadores locales y trabajadores que ejercen su actividad fuera de su localidad de residencia) que residen en dos ciudades con diferentes zonas climáticas (Alcalá de Henares -España y Jaén- España) ya que la forma de utilizar el vehículo eléctrico (*EV)* es diferente. Se implementó un algoritmo basado en la interfaz del programa de aplicación Here® y redes neuronales para adquirir datos del uso estocástico de los *EVs* de cada grupo social. Finalmente, se evaluó la mejorar relativa a la cantidad de energía disponible para la tecnología *V2B* gracias al algoritmo propuesto por los autores. Los resultados por día fueron los siguientes. Gracias al algoritmo propuesto se obtuvo una reducción que oscilaba entre 0,6 kWh y 2,2 kWh en función de los grupos sociales. El algoritmo propuesto facilitó un aumento de la energía disponible para el *V2B* que oscila entre 13,2 kWh y 33,6 kWh dependiendo de los grupos sociales. Los resultados muestran que las políticas de tarificación actuales no son compatibles con todos los grupos sociales y no consideran la contribución de las energías renovables a la demanda total de electricidad.

Resumen en inglés:

Energy consumption in the transport sector and in buildings are of great concern. This research aims to quantify how eco-routing, eco-driving and eco-charging can increase the amount of energy available for vehicle-to-building. To do this, the working population was broken into social groups (freelancers, local workers and commuters) who reside in two cities with different climate zones (Alcalá de Henares -Spain and Jaén- Spain) as the way of using electric vehicle is

different. An algorithm based on the Here® application program interface and neural networks was implemented to acquire data of the stochastic usage of EVs of each social group. Finally, an increase in the amount of energy available for vehicle-to-building thanks to the algorithm was assessed. The results per day were as follows. Owing to the algorithm proposed a reduction ranging from 0.6 kWh to 2.2 kWh was obtained depending on social groups. The proposed algorithm facilitated an increase in energy available for vehicle-to-building ranging from 13.2 kWh to 33.6 kWh depending on social groups. The results display that current charging policies are not compatible with all social groups and do not consider the renewable energy contribution to the total electricity demand.

6.4.2 Conclusiones

Las emisiones vinculadas al sector del transporte y a los edificios son una gran preocupación en la actualidad. En consecuencia, se debe realizar una mejora en ambos campos. Esta investigación propuso un algoritmo basado en la interfaz de la aplicación Here® (uno de los proveedores de mapas digitales más importantes), redes neuronales, vehículos eléctricos, planificación de rutas ecológica, conceptos de eco-conducción y eco-carga. Mediante el uso de este algoritmo, se evaluó el aumento de energía disponible para ser utilizada en la tecnología de vehículo a edificio. Sin embargo, un aspecto fundamental a tener en cuenta a la hora de analizar la energía disponible para la técnica vehículo a edificio es el uso estocástico de los vehículos eléctricos. Para ser más específico, es fundamental clasificar a la población activa en grupos sociales como autónomos, trabajadores locales y trabajadores que ejercen su actividad profesional fuera de su lugar de residencia. Debido a esto, se recopilaron muchos datos en condiciones reales de conducción gracias a la participación de conductores que pertenecían a diferentes grupos sociales ya que su forma de conducir es diferente. Finalmente, todas estas adquisiciones de datos se realizaron en dos ciudades (Alcalá de Henares - Madrid- España y Jaén-España) que se encuentran ubicadas en diferentes zonas climáticas. Las principales conclusiones que se pueden extraer son:

a) Ahorro de energía

Este algoritmo permite una mejora en el consumo energético de los vehículos eléctricos. Como era de esperar, el consumo de energía es diferente según el grupo social. En consecuencia, la contribución a la tecnología del vehículo al edificio es diferente. En cuanto a

Alcalá de Henares, la eficiencia energética alcanza los 2,2 kWh para autónomos al día. En lo que respecta a los trabajadores que ejercen su actividad fuera de Alcalá de Henares, esta ganancia alcanza los 1,5 kWh diarios y, finalmente, los 0,6 kWh por día en el caso de los trabajadores locales. En cuanto a Jaén, el ahorro es similar. La eficiencia energética alcanza los 1,9 kWh para autónomos al día. En lo que respecta a los trabajadores que ejercen su trabajo fuera de la ciudad, esta ganancia es de 1 kWh por día y, finalmente, de 0,6 kWh día para los trabajadores locales.

b) Contribución a la construcción de vehículos

La técnica de vehículo a edificio se basa en el principio de que el propietario del *EV* participará e inyectará la energía almacenada en la batería del *EV* al edificio. Sin embargo, es fundamental determinar la energía disponible y, nuevamente, el hecho de tener en cuenta los grupos sociales influye en la energía disponible para ser utilizada en la técnica de vehículo a edificio. Respecto a Alcalá de Henares, la energía disponible oscila entre 112 kWh y 144 kWh diarios en función del mix de grupos sociales existente en el edificio. En cuanto a Jaén, la energía disponible oscila entre los 76kWh y los 152kWh diarios en función del mix de grupos sociales existentes en el edificio. Por último, también hay que tener en cuenta que el patrón de consumo energético puede cambiar en función de los grupos sociales a los que pertenezcan los ocupantes.

c) Coste de la carga

Para que el proceso de carga sea más ecológico, es necesario cargar los vehículos eléctricos cuando la contribución de energía renovable sea mayor. Con base en el análisis del consumo de edificios realizado en esta investigación, el patrón de consumo de energía puede diferir según el grupo social al que pertenece el ocupante de la vivienda. El algoritmo proporcionado en esta investigación puede determinar cuándo la contribución de la energía renovable es mayor. Debido a esto, cuando su contribución es mayor, el precio de carga es más caro. Este estudio propone posibles cambios de tarifas para hacer compatibles las técnicas vehículo a edificio y vehículo a la red. Para aplicar esta tarifa, el aumento de MW de energía renovable instalados es tan importante como el aumento del número de vehículos eléctricos.

6.5 Publicación 5: "Can Eco-routing, Eco-driving and Eco-charging Contribute to the European Green Deal? Case study Alcalá de Henares"

6.5.1 Resumen de la publicación

Resumen en español:

El Pacto Verde Europeo (*The European Green Deal*) tiene como objetivo hacer de Europa el primer continente climáticamente neutro y reducir las emisiones de gases de efecto invernadero para 2050.

Esta investigación ofrece propuestas para el Pacto Verde Europeo basadas en el transporte sostenible, las energías limpias y la reducción del consumo energético de los edificios. Se propone un algoritmo basado en la interfaz de programación de Here®, redes neuronales, datos del operador del sistema de transmisión español, ruta ecológica *(ER)*, conducción ecológica *(EDR)* y carga ecológica *(EC)*. Su contribución a la integración vehículo-hogar, energía renovable y compatibilidad vehículo-hogar y vehículo-red se analiza mediante adquisiciones de datos de los viajes realizados por conductores de diferentes grupos sociales.

El algoritmo permite un ahorro de energía diario de hasta 2,2 kWh para autónomos, 1,5 kWh para viajeros y 0,6 kWh para trabajadores locales. La contribución del vehículo al hogar aumenta de 18 MWh a 553 MWh por año. Finalmente, las redes neuronales permiten una mejor integración de las energías renovables.

Las contribuciones al Pacto Verde Europeo son las siguientes: la eficiencia energética mejora cuando las políticas se dirigen al sector social adecuado junto con el *EDR* y el *ER*; las redes neuronales permiten lograr una mejor integración de las energías renovables ya que pueden predecir cuándo su contribución es mayor; y se deben desarrollar políticas para hacer compatible el vehículo a la red y el vehículo al hogar con el fin de reducir las emisiones de gases contaminantes.

Resumen en inglés:

The European Green Deal aims to make Europe the first climate-neutral continent and reduce greenhouse gas emissions by 2050.

This research offers proposals for the European Green Deal based on sustainable transport, clean energy and reduction in the energy consumption of buildings. An algorithm

based on the Here® application programming interface, neural networks, data from the Spanish transmission system operator, eco-routing, eco-driving and eco-charging is proposed. Its contribution to vehicle-to-home, renewable energy integration, and vehicle-to-home and vehicle-to-grid compatibility is analysed by using data acquisitions of the trips made by drivers from different social groups.

The algorithm allows a daily energy saving of up to 2.2 kWh for freelancers, 1.5 kWh for commuters and 0.6 kWh for local workers. The vehicle-to-home contribution increases from 18 MWh to 553 MWh per year. Finally, neural networks allow better integration of renewable energy.

The contributions to the European Green Deal are as follows: energy efficiency improves when policies are addressed to the adequate social sector combined with eco-driving and eco-routing; neural networks allow for achieving a better integration of renewable energies as they can predict when its contribution is higher; and policies to make vehicle-to-grid and vehicle-to-home compatible with reduced emissions must be developed.

6.5.2 Conclusiones

Esta investigación se llevó a cabo en la ciudad de Alcalá de Henares (Madrid, España) con el objetivo de investigar los impactos de la conducción ecológica (*EDR*), ruta ecológica (*ER*) y carga ecológica (*EC*) sobre varios factores vinculados al Pacto Europeo Verde *(EGD).* Para ello se implementó un novedoso algoritmo en Python, basado en la interfaz de aplicación Here®, redes neuronales y datos publicados por el operador de sistema español con el fin de reducir el consumo de energía e identificar el momento óptimo de carga de la batería de los vehículos eléctricos (*EVs).* Los datos se obtuvieron en base a los perfiles de los conductores, teniendo en cuenta los grupos sociales más importantes de la población activa, como autónomos, trabajadores locales y trabajadores fuera de la ciudad. Los resultados mostraron que *EDR*, *ER* y *EC* pueden ahorrar cantidades significativas de energía en el futuro si se cambian las políticas en España. Más específicamente, los resultados muestran que la eficiencia energética por vehículo podría alcanzar 1,5 kWh por día para los trabajadores que ejercen su actividad fuera de la ciudad objeto de estudio, 0,6 kWh por día para los trabajadores locales y 2,2 kWh por día para los autónomos cuando se utiliza nuestro algoritmo.

Se pueden hacer varias contribuciones al *EGD*, de la siguiente manera:

a) Es vital que se desarrollen diferentes políticas para diferentes grupos sociales (autónomos, trabajadores que ejercen su actividad fuera de la ciudad objeto de estudio, etc.) ya que estos no contribuyen de la misma manera.

b) La eficiencia energética obtenida mediante el uso del algoritmo propuesto aumenta la energía disponible para la tecnología vehículo conectado a domicilio (*V2H)*. La cantidad de energía disponible para *V2H* aumenta entre 18 MWh y 553 MWh dependiendo del grupo social.

c) El bloque *EC* utilizado en esta investigación permite a los conductores cargar los *EVs* cuando la contribución de las energías renovables es alta. De esta manera, las *ER* pueden integrarse mejor para descarbonizar el sector eléctrico.

d) Es poco probable que los autónomos y los trabajadores que ejercen su actividad fuera de la ciudad objeto de estudio participen en *V2H* o en la tecnología vehículo conectado a red (*V2G)* debido al número de kilómetros cubiertos diariamente, a menos que se puedan desarrollar políticas para garantizar precios más bajos cuando la contribución de energías renovables es alta. En España, los precios son actualmente más altos cuando la contribución de las energías renovables es mayor.

e) Las políticas no pueden cambiar si no se aumenta la potencia actualmente disponible de energías renovables en España. Como se describe en c), parte de la demanda podría moverse cuando la contribución de energías renovables es alta, gracias al bloque *EC* implementado en este algoritmo.

f) Los resultados obtenidos muestran que las políticas actuales para fijar el coste de carga de los EVs en España no son compatibles con una alta contribución a *V2H* y *V2G* de los diferentes grupos de la sociedad

7. OTRAS APORTACIONES CIENTIFICAS DERIVADAS DE LA TESIS

De la presente tesis se han derivado otras aportaciones consistentes en la redacción de dos capítulos de los libros indicados en los siguientes apartados.

7.1 Libro *Alternative Energy Systems in Buildings*

Tabla 6. Datos de la putlicación en Alternative Energy Systems in Buildings

Título	Alternative Energy Systems in Buildings
Fecha de la publicación	Enero 2019
Editores	Antonio Colmenar-Santos Enrique Rosales-Asensio David Borge-Diez
Contribución	Chapter 4. Solar Thermal Systems for High Consumption Demand Buildings. (coautor) Coautor
Editorial	Nova editors
ISBN	978-1-53614-203-7

7.1.1 Resumen de la publicación

Chapter 4. Solar Thermal Systems for High Consumption Demand Buildings. (coautor)

La energía solar térmica se ha convertido en una solución de energía renovable para nuevos edificios durante los últimos años. Aunque este sistema se ha integrado fácilmente en edificios de poca altura, un desafío continuo es la integración de la energía solar térmica en soluciones arquitectónicas exigentes para edificios de gran altura. Este artículo se focaliza en instalaciones solares de agua en edificios de gran altura, centrándose en la integración de colectores solares en el edificio, instalación de distribución de agua caliente y propone una solución para minimizar el riesgo de exposición a Legionela. Como ejemplo de los requisitos de la energía solar térmica en los países en desarrollo, el artículo analiza la introducción de estándares de agua caliente solar en Brasil, donde si bien existe un borrador de documento para una norma federal, ciudades como Sao Paulo ya cuentan con requisitos de energía solar térmica para cualquier edificio nuevo de la ciudad. Para impulsar el desarrollo de la integración renovable, iniciativas como PROCEL certifican el desempeño energético de los edificios si cumplen con el objetivo de mejora, frente a los requisitos reglamentarios, de generar un mínimo del 60% de agua caliente mediante energía solar térmica. El caso de estudio presentado para un hotel de 5 estrellas justifica claramente la instalación de sistemas solares térmicos en edificios con una alta demanda de agua caliente.

7.2 Libro Technologies and Applications for Fuel Cell, Plug-in Hybrid, and Electric Vehicles

Tabla 7. Datos de la publicación Technologies and Applications for Fuel Cell, Plug-in Hybrid and Electric Vehicles

Título	Technologies and Applications for Fuel Cell, Plug-in Hybrid, and Electric Vehicles
Fecha de la publicación	Enero 2019
Editores	Antonio Colmenar-Santos Enrique Rosales-Asensio David Borge-Diez
Contribución	Chapter 3. Profitability of a sustainable transport model based on electric mobility Chapter 5. Hydrogen Refueling Stations (coautor)
Editorial	Nova editors
ISBN	ISBN: 978-1-53614-205-1

7.2.1 Resumen de la publicación

Chapter 3. Profitability of a sustainable transport model based on electric mobility

En este capítulo, se integró el artículo publicado por la revista Energy en 2014 titulado *Macro-economic impact, reduction of fee deficit and profitability of a sustainable transport model based on electric mobility. Case study: City of León (Spain)*

Chapter 5. Hydrogen Refueling Stations

Un cambio hacia combustibles bajos en carbono es necesario para lograr la descarbonización del sector del transporte, el cual es responsable del 14% de las emisiones mundiales de gases. A pesar de que los vehículos de pila de combustible son vehículos con cero emisiones de escape, su uso es actualmente residual. Una integración masiva de vehículos de pila de combustible se enfrenta al dilema “del huevo de gallina”. Por una parte, los vehículos necesitan una infraestructura de repostaje adecuada para proporcionar un suministro de hidrógeno seguro y continuo. Por otra, un despliegue viable de la infraestructura de repostaje necesita el apoyo de un mercado inicial de vehículos. En este capítulo, se propone una estrategia factible para superar el citado dilema, utilizando la flota local de taxis como un mercado estable de consumidores de hidrógeno para poner en marcha una infraestructura de suministro de hidrógeno minorista en ciudades de alta densidad de población. El diseño se basa en dos objetivos: asegurar el suministro de hidrógeno, tener en toda la ciudad una alternativa cercana para repostar y maximizar la tasa de utilización de la infraestructura. La estrategia aplicada a la ciudad de Madrid muestra que 415 millones de dólares de fondos públicos asignados a lo largo de 25 años proporcionarían en seis años una red de 112 estaciones de repostaje de hidrógeno, capaces de suplir las necesidades de hidrógeno de 15.000 nuevos taxis eléctricos de pila de combustible lo que reduciría las emisiones de 300 kt CO_2 anuales.

8. CONCLUSIONES

8.1 Validación del *software*

Tal como se ha expuesto a lo largo de esta tesis, la validación del *software* de las *ECUs* es un elemento clave tanto en el presente como en el futuro de la automoción teniendo en cuenta que su número no para de crecer a medida que se añaden nuevas funcionalidades a los vehículos. Por tanto, es primordial centrarse en la proposición de nuevas técnicas de validación que permitan disminuir el tiempo necesario para verificar un *software* produciendo una mejora de su fiabilidad y calidad. Referente a la disminución de los tiempos de validación, las conclusiones de esta tesis son:

a. El uso de dos *EXs*, uno centrado en las prestaciones del *software* (caja negra, *black-box*) y el otro encargado de la codificación de dicho *software* (caja blanca, *white-box*), ofrecen mejores resultados en detección de errores *software* que las técnicas tradicionales ampliamente utilizadas en automoción.
b. Su implementación requiere más tiempo que las técnicas tradicionales utilizadas en automoción para funciones simples o muy complejas. A pesar de esto, su diseño no puso en riesgo la planificación del proyecto en el que se realizó esta investigación. Para el caso de *SMs* de complejidad media, se obtuvo una mejora en cuanto a productividad.
c. El uso de estos *EXs* combinados con *Dlls* permite conseguir una mejora en la automatización de los *TCs* mediante simulación *HIL*.
d. Los parámetros de cobertura de código asi como funcional se ven mejorados gracias al uso de los *EXs,* si bien su valor depende del número de estados en el modelo funcional utilizado en los *EXs* y del número de subintervalos en los que las entradas *SM* se pueden dividir.
e. La técnica expuesta en esta tesis doctoral es aplicable a cualquier *ECU* de un vehículo, siempre y cuando las especificaciones del *software* hayan sido confeccionadas en Simulink® (caso más habitual en los *software* complejos de automoción). Este hecho es muy importante, teniendo en cuenta la prohibición de los vehículos de combustión a partir del 2035 en la Unión Europea.

8.2 Modelos de transporte sostenibles

En la presente tesis, se ha descrito un modelo de transporte sostenible basado en movilidad eléctrica. Es importante tener en cuenta que estos modelos siempre han sido puestos en duda desde un punto de vista económico, puesto que nunca se ha encontrado certeza en la posible rentabilidad para todos los participantes en el citado modelo, como son el Estado, las empresas eléctricas, comercializadoras y el usuario del *EV*. De lo expuesto en esta tesis, se pueden deducir las siguientes conclusiones:

a. España tiene una fuerte dependencia energética, así como un fuerte déficit tarifario que requiere tomar medidas rápidamente.
b. Siguiendo el modelo propuesto en la siguiente tesis, queda demostrado que el Estado no pierde dinero por el no ingreso por impuestos de hidrocarburos. Este estudio muestra que es posible rentabilizar este proyecto para los usuarios de *EVs*, el Gobierno, comercializadoras y empresas eléctricas, mediante el uso de políticas regulatorias adecuadas. Como resultado, se recuperarían las pérdidas por impuestos sobre la gasolina.
c. Esta investigación muestra que el déficit tarifario de León se puede reducir en un 43,5% - 47,1%, consiguiendo a su vez una reducción de la demanda de gasolina Este beneficio obtenido por el Estado gracias a la aplicación de este modelo, podría utilizarse para reactivar la ayuda financiera para instalaciones de *RE*. Este hecho mejora la competitividad de las empresas españolas y disminuye los costes operativos de los *EVs*. Como resultado, la economía española disfrutará de una mayor protección frente a las fluctuaciones del precio de la gasolina.

d. Esta investigación va en línea con las políticas actuales de la Unión Europea, como el *EGD* y la prohibición de vehículos de combustión, pues demuestra que la promoción del *EV* es económicamente viable.

8.3 Aportaciones de los modelos de transporte sostenible

Esta tesis no sólo se ha centrado en la proposición de modelos de transporte sostenible sino también en las aportaciones colaterales que los citados modelos tienen en la sociedad, así como en la proposición de mejoras a tener en cuenta en las políticas europeas actualmente en discusión.

1. *Aportaciones a las políticas europeas*

Las siguientes conclusiones se pueden extraer:

a. El *EDR*, el *ER* y el *EC* deben ser factores a considerar en el actual *EGD*, por su importante contribución a la disminución de consumo energético de vehículos, de edificios y mejora de la integración de las *REs*.

b. Necesidad de investigar y promover nuevos algoritmos, tal como el expuesto en esta tesis, que permiten mejorar los citados tres parámetros: *EDR*, *ER* y *EC.*

c. Tal como la lógica indica, es necesario promover el uso de *EVs* para la reducción de emisiones locales. La aportación de estos vehículos a técnicas como *V2G* o *V2H* está fuertemente influenciada por el uso estocástico del *EV*. Esta tesis demuestra la importancia de tener en cuenta los sectores sociales existentes en la población activa (autónomos, trabajadores que trabajan fuera de la ciudad o en la propia ciudad) puesto que el uso del *EV* es distinto.

d. Tal como se ha descrito en esta tesis, los ahorros energéticos de los diferentes sociales usando el algoritmo empleado en esta tesis difieren fuertemente. Los resultados muestran que la eficiencia energética por vehículo podría alcanzar 1,5 kWh por día para los trabajadores que ejercen su actividad fuera de la ciudad objeto de estudio, 0,6 kWh por día para los trabajadores locales y 2,2 kWh por día para los autónomos cuando se utiliza nuestro algoritmo.

e. El uso del algoritmo propuesto en esta tesis permite mejoras sustanciales en cuanto a energía disponible para ser usada para *V2H*. Esta energía ha sido calculada teniendo en cuenta los grupos sociales anteriormente mencionados.

f. Resulta esencial que el propietario del *EV* disponga de un elemento que le indique en qué momento del día es mejor que realice el proceso de carga teniendo en cuenta la contribución de las *REs*. El concepto de carga ecológica utilizado en esta investigación permite a los conductores cargar los *EVs* cuando la contribución de las *REs* es alta. De esta manera, las *REs* pueden integrarse mejor para descarbonizar el sector eléctrico.

g. Las políticas no pueden cambiar si no se aumenta la potencia actualmente disponible de energías renovables en España.

h. Las políticas actuales para fijar el coste de carga de los *EVs* en España no son compatibles con una alta contribución a *V2H* y *V2G* de los diferentes grupos de la sociedad tal como se ha demostrado en esta tesis.

i. Esta investigación va en línea con las políticas actuales de la Unión Europea, como el *EGD* y la prohibición de vehículos de combustión, pues demuestra que la promoción del *EV* implica aplicaciones novedosas que repercuten en la disminución de emisiones gracias al uso de *EDR*, *ER* y *EC*.

2. *Aportaciones al ecodiseño*

Tal como se ha analizado en esta tesis, las actuales normativas de ecodiseño no tienen en cuenta los aspectos de eficiencia energética durante el diseño del producto. En otras palabras, la eficiencia energética no solo debe ocuparse de la fabricación sino también de la fase de diseño del producto. Gracias al ahorro de eficiencia eléctrica del *EV* gracias al algoritmo propuesto en esta tesis basado en *ER*, *EC* y *EDR*, se consiguen contribuciones importantes al ecodiseño gracias a la reducción de consumos energéticos de los edificios donde se encuentra el equipo diseño de un producto considerado en esta parte de la investigación. Las conclusiones que se pueden extraer son:

a. Algoritmos basados en *ER*, *EC* y *EDR*, como el propuesto en esta tesis doctoral, permite reducir el consumo del *EV*. A su vez, las redes neuronales proporcionan a los conductores información útil sobre cuándo es el momento óptimo para cargar la batería, teniendo en cuenta el aporte de *RE*.

b. Este ahorro energético descrito en el apartado anterior permite reducir las emisiones de los edificios que integran el centro de estudio considerado en esta investigación. Gracias al algoritmo propuesto se pueden conseguir reducciones de emisiones de hasta 23.55 kg por día más que sin utilizar el citado algoritmo.

c. Un punto esencial demostrado en esta tesis es que no sólo es importante el uso de *EVs* durante el desarrollo de un producto para reducir emisiones durante el diseño del mismo, sino que es esencial elegir las ubicaciones de los ingenieros participantes en el desarrollo del producto.

d. La contribución de *V2G* a la demanda energética del edificio varía entre 0.5% y 1.3% cuando se utiliza el algoritmo propuesto en este estudio en un pequeño centro de diseño.

e. Esta investigación va en línea con las políticas actuales de la Unión Europea, como el *EGD* y la prohibición de vehículos de combustión, pues demuestra que la promoción del *EV* implica aplicaciones novedosas que repercuten en la disminución de emisiones gracias al uso de *EDR*, *ER* y *EC*.

3. *Aportaciones a la técnica V2B*

En este eje de la tesis doctoral y usando el mismo algoritmo descrito en el apartado anterior, se pueden deducir las siguientes conclusiones:

a. Los resultados muestran lo importante de tener en cuenta el uso estocástico del *EV* a la hora de evaluar la técnica *V2B* pues el rango puede variar entre 112 kWh y 144 kWh dependiendo del mix de ocupantes del edificio (autónomos, trabajadores locales o trabajadores de fuera de la ciudad objeto de estudio).
b. En el caso de España, a partir de las dos ciudades tenidas en cuenta en este estudio, no se observan diferencias significativas entre los consumos debido a los efectos de la temperatura.
c. Las políticas actuales relativas a la carga hacen del todo inviable la participación en las técnicas actualmente bajo estudio como son la *V2G*, *V2B* o *V2H*. Consecuentemente, se muestra en esta tesis doctoral posibles variaciones de la actual tarifa aplicada al *EV* a la hora de efectuar la carga de la batería.
d. Si bien las administraciones se están centrando actualmente en la promoción del *EV*, en esta tesis se muestra que igual o más importante es promover las instalaciones de *RE* para poder obtener una integración óptima de las técnicas *V2G*, *V2H* o *V2B*.
e. Esta investigación va en línea con las políticas actuales de la Unión Europea, como el *EGD* y la prohibición de vehículos de combustión, pues demuestra que la promoción del *EV* implica la disminución de las emisiones de edificios en un mayor grado cuando se combinan con *EDR*, *ER* y *EC*.

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2011- 2013 MÁSTER UNIVERSITARIO EN INVESTIGACIÓN en Ingeniería Eléctrica, Electrónica y de Control Industrial en la Universidad de Educación a Distancia (UNED) (2013).

2005- 2011 INGENIERO INDUSTRIAL en la Universidad Nacional de Educación a Distancia (UNED) en la especialidad de Electrónica y Automática

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Experiencia profesional

- Julio 2021 -Actualidad. Representante de la Dirección de Investigación y Desarrollo en Valeo Martos (Jaén) para el desarrollo de productos de iluminación interior.
- Noviembre 2020 – Julio 2021. Jefe de proyecto técnico en electrónica en Valeo Martos (Jaén) para el desarrollo de productos de iluminación interior.
- Noviembre 2019- Julio 2020. Jefe de proyecto técnico de desarrollo de software aplicativo para el control de motores térmicos en Altran Paris. Cliente Renault.
- Enero 2019- Noviembre 2019. Jefe de proyecto técnico para el diseño e industrialización de un calculador telemático en Actia Automotive (Toulouse).
- Septiembre 2017- Enero 2019. Jefe de proyecto técnico encargado de la validación y calibración de un software de un calculador motor en Assystem Paris. Cliente Renault.
- Mayo 2014- Julio 2017. Jefe de proyecto técnicos encargado de la validación y calibración de un software de un calculador motor en PSA Peugeot Citroën en su centro de La Garenne Colombes (Paris).
- Julio 2011 – Mayo 2014. Jefe de departamento de Animación de Sistemas de Calidad en la planta de PSA Peugeot Citroën en Madrid.
- Diciembre 2002 – Julio 2011. Auditor de procesos técnicos y responsable de la realización de ensayos de conformidad de producción en la planta de PSA Peugeot Citroën en Madrid.

Publicaciones

Colmenar-Santos, A.; Borge-Diez, D.; Ortega-Cabezas, P.M.; Míguez-Camiña, J.V. Macro economic impact, reduction of fee deficit and profitability of a sustainable transport model based on electric

mobility. Case study: City of León (Spain). *Energy* **2014**, 65: 303-318, https://doi.org/10.1016/j.energy.2013.11.077

Ortega-Cabezas P.M., Colmenar-Santos A.; Borge-Diez D., Blanes-Peiró J.J. Application of rule-based expert systems in hardware-in-the-loop simulation case study: Software and performance validation of an engine electronic control unit. *Journal of Software: Evolution and Process* 2020, https://doi.org/10.1002/smr.2223

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Ortega-Cabezas, P.M.; Colmenar-Santos, A.; Borge-Diez, D. ; Blanes-Peiró, J.J. Can eco-routing, eco-driving and eco-charging contribute to the European Green Deal? Case Study: The City of Alcalá de Henares (Madrid, Spain). *Energy* **2021**, 228, 120532, https://doi.org/10.1016/j.energy.2021.120532

Artículos en curso

Ortega-Cabezas P.M., Colmenar-Santos A.; Borge-Diez D., Blanes-Peiró J.J . Experience report on the application of genetic algorithms to reduce costs of the software validation process in the automotive sector during an engine control unit project. Software Quality Journal. Status: Accepted under minor revision.

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Macro economic impact, reduction of fee deficit and profitability of a sustainable transport model based on electric mobility. Case study: City of León (Spain)

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ABSTRACT

The Spanish economy faces two key issues. The first of these is the significant reliance on non-renewable energy, which reached 76.4% and was 22 points over the European Union average. Secondly, the threat that the fee deficit poses to the sustainability of the National Grid. This fact is forcing the Spanish Government to implement measures focused on tax increases. However, these decisions have done little to contain the situation. This paper proposes the use of sustainable transport models based on electric mobility: smart grids, buses, taxis and electric vehicles, in the city of León, Spain (135,059 inhabitants) as an important means for controlling and reducing the fee deficit. Through exhaustive analysis of EV (electric vehicle) market penetration against current Government forecasts, a rigorous profitability study has been conducted for the period 2020–2030 (when smart grids will be ready). By introducing policy modifications, the Net Actual Value internal rate of return and payback figures justify its implementation. Thus, the fee deficit of León could be reduced by up to 43%. Finally, an analysis of macroeconomic impacts, such as competitive improvements in the economy, and environmental impact is conducted.

1. Introduction

According to a Eurostat report published in February 2013, EU (European Union) energy dependency in 2011 – understood as the relationship between net imports and gross energy consumption – reached 54%. Between 2008 and 2011, consumption fell in 23 of the 27 member states of the EU. The most significant reductions took place in Lithuania (−24.5%), Ireland (−12.3%), Greece (−12.3%), Romania (−10.2%), Spain (−9.9%) and the United Kingdom (−9.9%). The Spanish energy dependency index is 76.4%; 22.6 points above the EU average [1].

The breakdown of final energy consumption by source shows the current energy dependency on non-renewable energies as well as forecasts for 2020, where oil products and derivatives will continue to play a predominant role in the economy (Fig. 1) [2].

The transport sector accounts for almost 40% of the total primary energy consumption. This figure can be broken down by transport mode as follows: 80% by road vehicle, 14% by air, 3% by train and 3% by sea. Thus, the sector consumes 65% of the total annual amount of petrol imported by Spain [2].

Considering the trend in terms of absolute variability of energy consumption, the tendency has been dissimilar. It followed the same pattern as GDP (gross domestic product) from 2005 until 2008, 2009 and 2010, when the energy intensity began to reduce owing to high energy prices and reduction in economic activity. The energy intensity in this area has had a downward tendency since 2004 as a result of lower activity levels in certain sectors and lower mobility of freight and passenger transport in all transport modes (Fig. 2) [2].

In Spain, 24% of greenhouse gases (namely CO_2) come from the transport sector. Therefore, significant efforts must be made to achieve the goals established in the various international agreements [2]. According to data published by the EU, the quantified emission limitation or reduction commitment as agreed in accordance with article 4(1) of the Kyoto Protocol for Spain is 115% (percentage of base year or period) [3].

León (42°35′59″N 5°34′18″O) is located in the region of Castilla y León (Spain). Its energy consumption pattern does not differ from the rest of Spain. This fact is demonstrated in the 2011 indicators

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Nomenclature

a	acceleration $[m/S^2]$
$A_{frontal}$	frontal area $[m^2]$
$c_{j,m}$	CO_2 emitted per vehicle
c_{drag}	drag coefficient
CEO	chief executive officer
CNE	National Energy Commission
d	number of EVs driven in the considered year
d_m	diameter [m]
DGT	traffic agency
EB	electric bus
E_{CO_2}	amount of CO_2/day generated by electric vehicles [t]
EREN	regional energy entity
ET	electric taxi
EU	European Union
EV	electric vehicle
f	factor of battery charge reduction after charging and discharging cycles [%]
g	gravity $[m/S^2]$
G	transmission gear ratio
GDP	gross domestic product
GPS	global position system
h	number of hours an EV joins the grid in V2G
IDAE	Institute for Diversification and Energy Saving
IMF	International Monetary Fund
INE	National Statistics Institute
IPC	consumer price index
IRPF	personal income tax
TIR	internal rate of return
$M_{Gt,veh}$	EV mass [kg]
MIET	Ministry for Industry, Energy and Tourism
MOVELE	electric mobility plan
NPV	net present value
n	number of working days/year
$n_{80\%}$	number of EVs with maximum battery charge of 80% of its nominal capacity
p	estimated energy for supply to Grid [MWh]
P	participation in V2G (85%)
P_{accel}	acceleration losses [W]
P_{aero}	aerodynamic losses [W]
P_{bat}	power battery [W]
P_m	motor's electric power [W]
P_{move}	power necessary to move the EV [W]
P_{res}	residual power [W]
P_{roll}	rolling losses [W]
P_u	effective power [W]
$p_{consumer}$	% benefit to EV user from V2G transaction
p_{pool}	MWh price in the pool during period of consideration [€/MWh]
p_{V2G}	user payment from V2G transactions [€]
RD	royal decree
RE	renewable energy
REE	spanish electricity grid
SEE	spanish electric system
SGs	smart grids
TSO	Transport system operator
VAT	value added tax
V2G	vehicle to grid

recently published by the EREN (Regional Energy Entity), of the Castilla y León Government, as depicted by Table 1 [4].

Due to the implementation of energy efficiency measures, combined with the slowing down of economic activity in the main Spanish sectors, a reduction in consumption took place in 2011. This is in line with the rest of the country.

Spain occupies a privileged position in the field of RE (renewable energy) and consequently if their use were encouraged, a significant reduction in Spanish energy dependency would occur. Castilla y León stands out when it comes to wind power and solar energy. Photovoltaic energy has increased from 13 MW installed in 1998 to 5,252 MW in 2010. Wind power in this region produces more than 20% of the total generated in Spain, with an installed power of 398 MW. This places Castilla y León in fourth position in relation to the other Spanish regions [5].

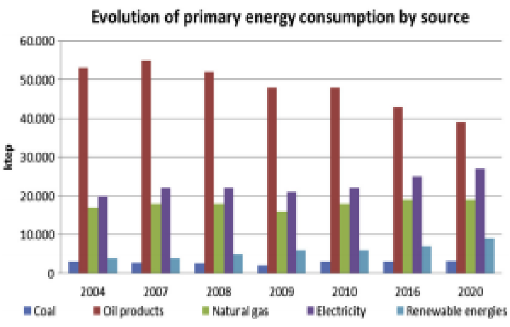

Fig. 1. Breakdown of primary energy consumption by source.
Source: IDAE (Institute for Diversification and Energy Saving).

When implementing and developing sustainable urban transport models, different types of factors should be considered; for example, technological, environmental, economic, social, etc. depending on the case-study city. As a result, a generalist model seems unlikely to be proposed, as shown in the conclusions of SUTRA (sustainable urban transportation) [6].

Among the technologies available to implement this model, one can currently find three options: hybrid vehicles, EVs (electric vehicles) and fuel cell vehicles [7–9].

- Hybrids are an intermediate case between the other two; they still generate greenhouse gases, but in smaller quantities [10].

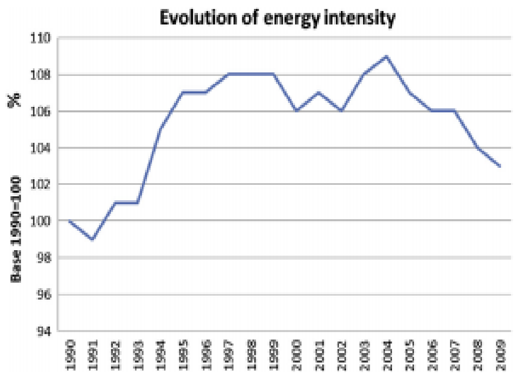

Fig. 2. Growth of energy intensity (2004–2010).
Source: Institute for Diversification and Energy Saving.

Table 1
Annual energy demand variation.

Conversion factors		tep	2008	2009	2010	2011
0.086	tep/MWh-PCI	Natural gas	1,646,104	1,621,927	1,782,444	1,763,711
0.086	tep/MWh	Electricity	1,121,980	1,091,957	1,083,169	1,062,349
1.13	tep/t	Liquefied petroleum gas	131,251	113,446	122,359	82,257
1.07	tep/t	Gasoline	417,268	403,026	381,568	349,921
1.035	tep/t	Diesel	3,382,600	3,209,617	3,268,997	3,039,979
0.96	tep/t	Fuel oil	149,156	101,872	68,963	67,520
		Coal	46,150	27,070	30,395	13,905
	Renewable Energy	Thermal solar	3611	3794	3932	3989
		Biomass	42,130	43,681	47,703	49,923
	Final	Geothermal	0	541	726	1016
		TOTAL	6,940,250	6,616,931	6,791,256	6,434,571
Annual variation				−4.66%	2.63%	−5.25%

Source: Government of Castilla y León.

- As for fuel cell vehicles, they are completely emission-free when operating. As proven by research from the National Renewable Energy Laboratory [11], their performance regarding autonomy and battery life is good. However, hydrogen generation is still a key issue facing problems such as production processes, economies of scale and technological development [12]. Even though this technology is still in development, the possibility of it playing an important role in the future must not be neglected [13,14].
- As for EVs, their main disadvantage is their low autonomy and the insecurity this causes for potential EV (electric vehicle) users [13]. However, this fact should not be considered a major setback for their potential expansion since one of the biggest battery manufacturers in Europe (Axeon) forecasts autonomies higher than 500 km by 2020 [15].

Both EVs and fuel cell vehicles generate well-to-wheel emissions that include the ones related to fuel production, processing, distribution and use. As a result, even though when driving, they are completely emission-free, other essential factors linked to their operation, such as electricity generation or fuel cell production, cause pollution.

Energy efficiency in the transport sector is a key issue in improving this factor, and many studies are being conducted on this subject. Some of these have aimed to predict energy consumption in this sector on a long-term basis [16,17]. In addition, some papers have assessed the influence of current European Union policies on private vehicles, especially on the subject of sustainability [18]. Others have focused on the use of electric transport to measure its impact on sustainability [19,20] as well as a better integration of RE [21,22]. Further research has centered strongly on the use of quantitative indicators [23].

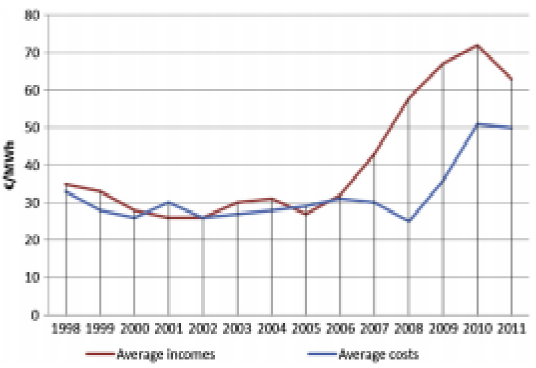

Fig. 3. Income and average cost evolution.

Source CNE.

Implementing these sustainable models brings significant costs as well as income loses for the Government. As a result, their profitability is in doubt.

Previous research [16,17,23] has not included specific case studies on sustainable models and their potential uses and economic profitability; instead, they have been limited to environmental aspects and energy dependency. This study has used a traditional model based on electric mobility: SGs (smart grids) [24,25], EVs (electric vehicles), EBs (electric buses) [26] and ETs (electric taxis). Through a reasoned proposal of adequate remuneration policies, it reconciles the interests of the Government, EV users and generation and distribution companies, for it is only if each of these parties is involved that the success of the proposed plan for a sustainable transport model will be assured. Furthermore, it will allow Spain to not only reduce its energy dependency and environmental impact, but also reduce the current tariff deficit (26,062 M€ in March 2013 [27]) without the need to impose high taxes, as has been the case in recent years.

2. Liberalization of the electricity market. Situation in Spain

All countries where a liberalization of the electricity market has taken place have dealt with imbalances between real costs and regulated fees. The United Kingdom and Eastern European countries have chosen to eliminate the latter, whilst others, such as the USA, have created an extra fee which is added to the regulated one, taking into account generation, transport, distribution and sales costs [28].

However, the Spanish electricity system has not restrained the growth of the fee deficit,[2] with a major increase in costs from 1998 to 2009. Until 2002 this increase was moderate, owing to lower financial costs and greater demand for electricity. Since 2003, the trend has strengthened due to renewable energy production and higher Brent prices [29]. Consequently, the Spanish market suffers from a structural income deficit on regulated activities. This is confirmed by the existing difference between average toll incomes and real system costs according to data published by the CNE (National Energy Commission) (Fig. 3) [30].

The Spanish Government has driven several legislative reforms to restrain the fee deficit since 2012. After the approval of RD 1/2012 of 27th January, financial aid to RE facilities for feeding

[2] The fee deficit is the difference between the total incomes coming from access tariffs and real costs. Whereas the former are regulated by the Government, the latter are made up by costs of transport, distribution, subsidies to renewable energies as well as other activities. In May 2013 the Spanish fee deficit reached 26.062 M€.

electricity into the grid was suspended. Law 15/2012 of 27th December was passed to impose a fiscal change in the electricity system by introducing three new taxes: one on electricity production value, one on nuclear fuel production and finally one on nuclear radioactive waste. In 2013, RD Law 9/2013 proceeded to suspend financial aid to all RE facilities, even those built before the approval of this RD. Finally, it must be pointed out that tolls have continued to increase in recent years (Table 2) [30].

If the current fee deficit were constrained at its current value, the only way to reduce it would be to increase taxes. As a result, Spanish competitiveness would be strongly affected. Spain currently has the third highest electricity price in the EU [31]. Therefore, this paper proposes a sustainable transport model for León by 2020 to contribute to reducing the fee deficit as well as achieving environmental targets, a reduction in petrol consumption and better integration of REs on a large scale.

3. Initiatives to encourage sustainable transport

Among the main actions taken to reduce energy dependency in Spain, one can find policies dedicated to encouraging the use of EVs as well as pilot schemes focused on public transport EBs and ETs, which are currently carried out in various Spanish and European cities.

EVs are essential to a sustainable transport model for reducing local CO_2 emissions, due to their performance (85%–90%) against traditional vehicles (90%) [32] and their potential for recharging with RE.

The MOVELE Plan(electric mobility plan) is outlined in the Integral Strategy as a means to promote EVs in Spain, between 2010 and 2014. A series of initiatives are being undertaken to stimulate penetration: financial aid for purchasing EVs, the introduction of Charging Manager roles (responsible for selling the necessary electricity to recharge EVs, pushing for the installation of new charge points in public spaces, car parks or shopping centers), and the introduction of the peak charge with a view to increasing overnight charging [33].

The final goal is achieving a total of 250,000 EVs in Spain by the end of 2014 [33]. This plan has been brought forward due to cooperation from Movistar [34], who will be in charge of communicating the charge point locations to EV owners through GPS (global position system) and Smartphone applications. As a result owners will always have information about the nearest charge point. This will help alleviate any concerns about the use of EVs, such as running out of energy mid-journey. Alongside this plan, the regional strategy strongly advocates EVs in Castilla y León, as led by the regional government. Its main target is achieving 15,000 EVs in Castilla y León [35].

EBs significantly reduce emissions from public transport. There are two factors impeding their widespread use: price and battery life. On the issue of battery life, different pilot schemes were conducted in 2011 and 2012, with significant results. In Madrid, from March 2012, an EB (electric bus) called FOTON was in operation, in order to test performance. The initial data obtained show a saving of 150 €/day/bus in petrol and maintenance [36]. Additionally, from January 2011, the first stage of the PILAVESA project started, in Pamplona (Navarra – Spain). The results obtained after 119 days of operation were: total energy consumption of 142,233 kWh and average daily consumption of 119 kWh. The second stage took place in April 2012; placing solar panels on the roof of the bus with the aim of increasing total battery life over 20–30 km [37]. In June 2012 an EB (model BYD K9), started operating in Barcelona (without passengers). The provisional results are acceptable considering the high traffic intensity in

Table 2
Toll evolution in the Spanish electricity system.

Toll	2004/ 2003	2005/ 2004	2006/ 2005	2007/ 2006	2008/ 2007	January 2009/ January 2008	July 2009/ January 2009	2009/ 2008	January2010/ July 2009	July 2010/ January 2010	Total 2010	January 2011/ July 2010	April 2011/ January 2011	October 2011/ April 2011	January 2012/ October 2011	Total 2003/ January 2012
Low voltage toll	**1.5%**	**1.7%**	**3.4%**	**0–9%**	**−11.4%**	**26.9%**	**15.0%**	**36.4%**	**11.9%**	**−2.2%**	**9.5%**	**0.0%**	**9.3%**	**−8.1%**	**10.6%**	**66.6%**
2.0A (Pc ≤10 kW)	1.5%	1.7%	4.2%	4.1%	−15.7%	34.2%	18.0%	46.3%	9.0%	−3.0%	5.7%	0.0%	10.8%	−11.5%	12.4%	74.1%
2.1A (10 < Pc≤15 kW)	−0.5%	1.7%	−0.5%	4.6%	−17.1%	36.9%	23.5%	33.0%	22.0%	0.0%	3.7%	0.0%	7.0%	0.0%	6.3%	108.8%
2.0 DHA (Pc≤10 kW)	6.8%	1.7%	6.8%	−12.6%	−18.0%	17.0%	27.3%	53.0%	9.6%	−5.3%	22.0%	0.0%	4.8%	−16.4%	21.2%	29.6%
2.1DHA (10 < Pc≤15 kW)	1.5%	1.7%	1.9%	−12.0%	−17.3%	16.6%	27.1%	32.5%	22-0%	0.0%	22.0%	0.0%	7.0%	0.0%	6.3%	57.5%
3.0A (Pc > 15 kW)	1.6%	1.7%	1.9%	−9.9%	2.9%	11.5%	2.5%	12.9%	17.6%	0.0%	17.6%	0.0%	7.0%	0.0%	6.3%	49.2%
High voltage toll	**1.6%**	**1.7%**	**2.6%**	**−18.6%**	**3.6%**	**24.5%**	**30.0%**	**55.2%**	**22.1%**	**0.0%**	**22.1%**	**0.0%**	**2.0%**	**0.0%**	**2.0%**	**83.7%**
3.1 A (1 kV a 36 kV)	1.6%	1.7%	2.8%	−0.9%	2.7%	34.9%	30.0%	55.2%	18.2%	0.0%	18.2%	0.0%	2.0%	0.0%	2.0%	133.4%
6.1 (1 kV a 36 kV)	1.6%	1.7%	2.8%	−13.0%	6.4%	23.2%	30.0%	41.7%	26.8%	0.0%	26.8%	0.0%	2.0%	0.0%	2.0%	107.8%
6.2 (36 kV a 72.5 kV)	1.6%	1.7%	1.9%	−39.3%	3.1%	13.1%	30.0%	30.0%	25.0%	0.0%	25.0%	0.0%	2.0%	0.0%	2.0%	25.9%
6.3 (72.5 kV a 145 kV)	1.6%	1.7%	1.9%	−40.7%	−1.4%	9.3%	30.0%	25.7%	24.1%	0.0%	24.1%	0.0%	2.0%	0.0%	2.0%	12.9%
6.4 (Greater than or equal to 145 kV)	1.6%	1.7%	1.9%	−48.7%	−8.0%	9.4%	30.0%	25.8%	0.0%	0.0%	0.0%	0.0%	2.0%	0.0%	2.0%	−26.5%
	1.5%	1.7%	3.2%	−5.1%	−8.4%	26.3%	18.4%	37.9%	14.5%	−1.6%	12.6%	0.0%	7.3%	0.0%	8.3%	70.7%

Source: CNE.

Barcelona. The EB was able to travel 210 km (compared to 250 km indicated by the manufacturer) [38].

Finally, the model considers ETs. In Spain, there is only one type (Nissan Leaf), registered in 2011. The most important results are: 47,600 km traveled, with a daily average of 140 km at 80% capacity, and a standard working day consumption of 13 kWh per 100 km [39].

4. Sustainable transport model profitability study. Case-study: city of León (Castilla y León–Spain)

When evaluating the profitability of a sustainable transport model, it is necessary to analyze a number of subjects such as the specifics of León, the model itself, the most realistic EV market penetration against Government forecasts, and future energy consumption to assess the share of V2G technology. Finally, a study is carried out on factors such as inflation, costs and energy consumption to establish the impact of this model from an economic, environmental and energy point of view.

4.1. *Specifics of León*

León is a city of 135,059 inhabitants located in the region of Castilla y León (Spain) where considerable investment is being made in the development of SGs. This involves the potential for use of this kind of network together with electric mobility and V2G technology. León is ideal for carrying out this case-study for several reasons.

When studying the current situation of León, it is essential to analyze the use of public and private transport. The first mode to consider is buses. The average age of the fleet is roughly 4 years and incorporates technologies such as Euro IV and biodiesel engines. When it comes to coverage, not all zones of the city are equally covered as not all areas are well connected by bus routes. Taxis are another significant element, with a total of 200 licenses (1.04 taxis/1000 inhabitants). In relation to private transport, it has been estimated using data published in León's urban mobility plan that 101,166 journeys a day are made, with an occupation rate per vehicle of 1.26 people, an average of 3.18 km/journey and an average speed of 11.62 km/h [40].

Tourist attractions and areas for eating out are located in the city center (Fig. 4). Because of this, several local by-laws prohibit traffic in certain zones. The rest of the zones are subject to restrictions for two reasons: improvements in inhabitants' quality of life and encouraging tourism. Downtown León has large parking areas which could be used to install charge points. Above all, the objective is to decrease the energy necessary for the operation of the city's transport.

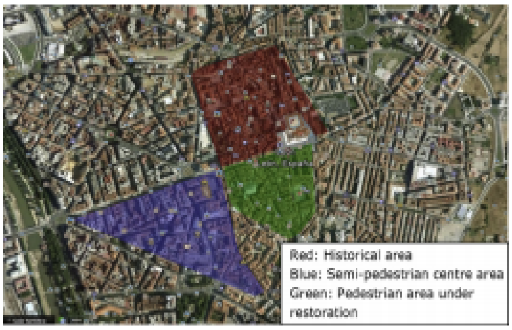

Fig. 4. Map: León city center.
Source: Google Maps and León Town Hall.

4.2. *Sustainable transport model*

In 2007, León had a total of 14 bus lines. Following approval in 2009 of the 'Integral Plan for sustainable mobility in León' this was reduced to 10, in order to reduce petrol. The number of buses necessary to operate public transport will remain constant in the years to come [40]. This study has allowed for 35 EBs to guarantee service.

Considering these figures, the average consumption was 41.5 l/100 km, with a total of 1,817,312 km/year [40].

The transport model described here consists of replacing the current conventional buses with an equivalent number of electric ones (BYD brand equipped with a 324 kWh battery) [41], at a cost of 400,000 €/unit [42]. Despite this, leasing has been chosen instead of buying, following Barcelona's example, with a total cost of 11,580 €/month/bus, maintenance included [43], with the option to buy for €125,750 each in the third year. Annual maintenance is estimated at 0.021 €/km/bus [44]. As a result, this concept will incur a cost of approximately 41,000 €/year, updated annually using the IPC (consumer price index).[3] This amount will be paid from the third year.

The model is completed by 200 ETs operating in the city by 2020. This number has been chosen by the authors since the number of licenses has changed slightly over the last few years and the mobility plan lacks a clear objective on this subject. A slow daily re-charge, overnight charge, and quick charge between 1 pm and 3 pm have been assumed in order to guarantee the battery life required for a full working day. The cost of ETs (Nissan Leaf), which goes up to 24,000 €/unit, has not been considered in the profitability study (Excel file enclosed with this paper). This is justified by the cost of its diesel counterpart (approximately 23,300 €/unit in Spain [45]), an assumed 10-year lifespan of 300,000 km, an average consumption of 8.5 l/100 km and a diesel price of 1.4 €/l. All these factors lead to a profit of 35,700 €, without considering income from taxi services, and so the slight original overprice of ETs will clearly be paid off. In addition, savings will be even higher as diesel prices will increase between 2020 and 2030.

Finally, the transport model will include 900 charge points at a cost of 2000 € each [46].

The use of this model implies benefits for all parties involved in the electricity sector as well as León's inhabitants:

a) Electricity companies and aggregators

Additional income and new business opportunities as a result of electricity sales from V2G, as well as electricity generation for the charging of EBs, ETs and EVs.

b) León inhabitants

León's inhabitants benefit from the sustainable transport model as the reduction of greenhouse gases such as NO_x, CO_2, and SO_x, will contribute to environmental and well-being improvements.

c) EV owners and the Government

EV users receive a reduction in maintenance and journey costs compared to traditional vehicle users, in addition to the payment received for joining the grid. However, the Government loses out through decreased income from hydrocarbon and VAT (value

[3] Index that measures the price development of gods and services consumed by families in a country.

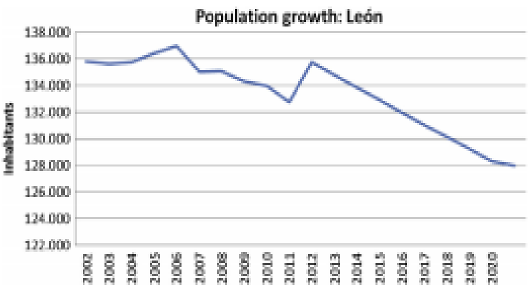

Fig. 5. Population growth: León. Estimate made using data from the Government of León.

added tax) taxes, which reduces the model's economic viability. Despite these considerations, after implementing this model together with retributive and tax policies, the Government is able to collect sufficient revenue to balance the aforementioned losses. As a result, energy dependency, as well as the fee deficit, is reduced, assuring the economic sustainability and competitiveness of the Spanish electricity sector. This paper presents a solution which assures profitability for all players involved in the electricity sector.

4.3. *Situation of smart grids in Castilla y León*

Currently, different initiatives are being conducted in Castilla y León to implement SGs based on smart counters and distribution networks. IBERDROLA is renewing its distribution network through development of the STAR project. The action plan consists of modernizing all the facilities by 2018, with an investment of 180 M€. This project starts in Salamanca, with an initial budget of 9 M€, replacing all traditional counters with smart ones and modifying a total of 315 power station buildings to adapt them to SGs. In the second stage, from 2013 to 2017, the project will continue in Burgos and León. Upon completion, IBERDROLA will reach a total of 1.6 million supply points with smart counters and 15,200 power station buildings will be adapted to SG technology [47].

4.4. *EV penetration forecast for León*

When estimating EV market penetration by 2020, an analysis of population and vehicle fleet growth in León is required. Regarding the former, the figures provided by the INE (National Statistics Institute) imply a decrease from 2006 to 2011. The average population during 2006–2011 was 135,236 inhabitants [48]. Despite the slight rise in 2012, the estimates from the Castilla y León Government for the period 2013–2020 show a population decrease, reaching −4.9% in 2020, as compared to 2012 [49]. Due to the lack of data for León, the authors have

Table 3
Spanish population growth.

Year	Population	Population variation	
		Absolute	Relative (%)
2012	46,196,278	–	
2022	45,058,581	−1,137,696	−2.46
2032	43,819,837	−1,238,745	−2.75
2042	42,771,150	−1,048,687	−2.39
2052	41,558,096	−1,213,053	−2.84

Source: INE.

Table 4
Forecasted population growth.

Year	2020	2021	2022	2023	2024	2025
Inhabitants	131,556	131,214	130,872	130,532	130,193	129,854
Year	2026	2027	2028	2029	2030	
Inhabitants	129,517	129,180	128,844	128,509	128,175	

Source: INE.

assumed the regional tendency. Thus, the average decrease will reach 0.7%/year (Fig. 5).

The population estimate for 2020–2030 is based on the demographic projections made for Spain by the INE [50], showing a progressive decline in inhabitants in the coming decades (Table 3).

Considering these figures, a decrease of 2.6% in the decade 2020–2030 has been assumed (Table 4).

In relation to the growth of León's vehicle fleet, the most recent data published in 2010 by the DGT (traffic agency) show an average growth of 2.46% [51]. Due to the lack of data from this date, the authors have assumed possible growth linked to demographic variability, owing to direct correlation between the use of vehicles and the population (Fig. 6).

Various departments and managers directly linked to the automotive sector disagree on the contribution of EVs to Spain's total vehicle fleet by 2020. On the one hand, the Government of the Basque Country estimates it to be 10% [52], whereas the CEO (chief executive officer) of Peugeot Spain sets the figure at 20% (EVs plus hybrids) [53]. In 2030, 2,500,000 EVs are predicted to be driven in Spain, based on a population of roughly 43 million inhabitants [54]. As a result, the ratio that links the number of vehicles to inhabitants is 0.582. Thus, León's contribution is close to 7,270 EVs, based on a population of 125,028 inhabitants [48].

The Spanish Government estimates a total of 600,000 EVs by 2020. Based on a figure of 131,556 inhabitants in León and approximately 45,000,000 in Spain, León should contribute 1754 EVs to this objective.

Only one EV was sold up until 2011 [55]. However, the Castilla y León Government predicts this number to reach 15,000 by 2015. Based on a population for Castilla y León of 2,518,683, and 132,913 for the city of León [48], the contribution of the latter should be 790 EVs, a huge increase on the current situation. Hence the authors have assumed, for the profitability calculation, that vehicle fleet penetration (Fig. 7) will be as follows: from current low values, penetration will increase progressively until it reaches 7,270. This figure corresponds to the Government's objective and will be achieved through technological maturity and new models on the market. These estimates are far from the current situation. This

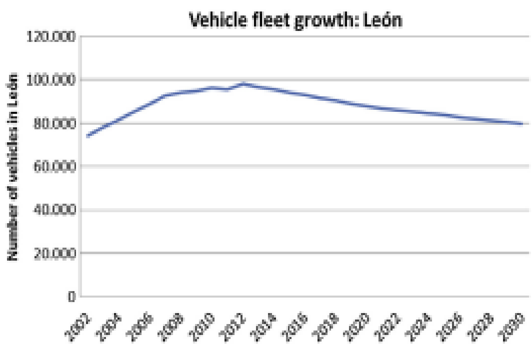

Fig. 6. Vehicle fleet growth: León. Estimate made using INE and DGT data.

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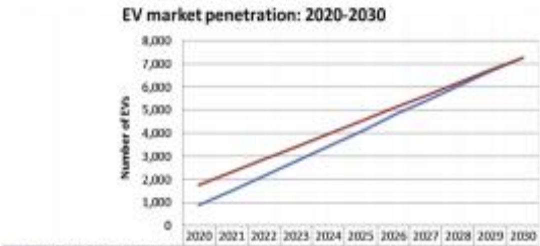

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of Evs in worst case scenario	877	1,518	2,159	2,800	3,441	4,082	4,763	5,404	6,045	6,686	7,270
Number of Evs in Government scenario	1,754	2,307	2,861	3,415	3,969	4,523	5,077	5,621	6,175	6,729	7,270

Fig. 7. EV market penetration: 2020–2030.

disparity of figures could lead this project to be loss-making in the early years and it is therefore necessary to set a worst-case scenario (Fig. 7). Despite this, profitability is assured as proven in the Results section.

4.5. Energy consumption for León in 2020–2030

The Spanish Government has set three scenarios linked to energy consumption: *low, reference and high* [56]:

a) Reference (or central) scenario

This is the most likely scenario as established by the Spanish Government and considers factors such as retaining current energy policies and associated programs for guaranteeing the security and sustainability of supply, a 2% growth in energy demand, the continuation of dependency on fossil fuels, and finally, an increase in the generation and consumption of electrical energy at a rate of 2.4% until 2030.

b) Low and high scenario

The forecasts for both scenarios are influenced by several factors such as international market growth, demographics, economic development and the environment. Electricity demand will increase at a rate of 3.4%/year (*high scenario*) and 1.5%/year (*low scenario*). The Spanish Government is still working with these scenarios. However, taking into account the economic situation and current energy consumption, the *low scenario* would be the most likely one.

An EV, equipped with a 24 kWh battery (Nissan Leaf [57]), drove a 32 km circuit in downtown León at rush hour, registering accelerations and speeds using a data logger. The aim of this exercise was to estimate the total amount of electricity for supply to the grid (Fig. 8). The distance reflects the average daily km driven according to data published by the MIET (Ministry for industry, energy and tourism).

Stops and accelerations due to traffic intensity increase the consumption of EVs in Wh/km. Hence the final battery capacity is reduced after completion of the journey. The available value was 19.1 kWh for supply to the grid, as shown in the detailed analysis in Appendix A.

The battery charging and discharging processes cause a decrease in battery capacity and, as a result, in potential energy for supply to the grid, as every 1,500 cycles cause a nominal capacity reduction of 20% [58]. Considering that an EV is expected to link to the grid for 220 days a year, after 6 years, the maximum available capacity will reach 80% of its nominal value. As the vehicle fleet gets older, the forecasted daily contribution to the V2G evolves as follows (1):

$$p_{V2G} = n_{80\%} \cdot f \cdot p + (d - n_{80\%}) \cdot p \qquad (1)$$

where $n_{80\%}$ represents the number of EVs with maximum battery capacity after recharging of 80% of its nominal value, n is the number of EVs in the considered year, f is the decreasing factor of the battery capacity due to discharging and charging cycles (20% considered) and p is the estimated energy to be fed into the grid (considered to be 0.0191 MWh).

The results are shown in Table 5.

In relation to ETs and EBs, no contribution will be made at any time. In fact, fast charges should be made to assure battery capacity lasts a working day.

The average daily consumption (MWh) estimated in 2020 for León would be 159 MWh. The Spanish TSO (transport system operator) does not provide data at a local level. Its minimum unit is

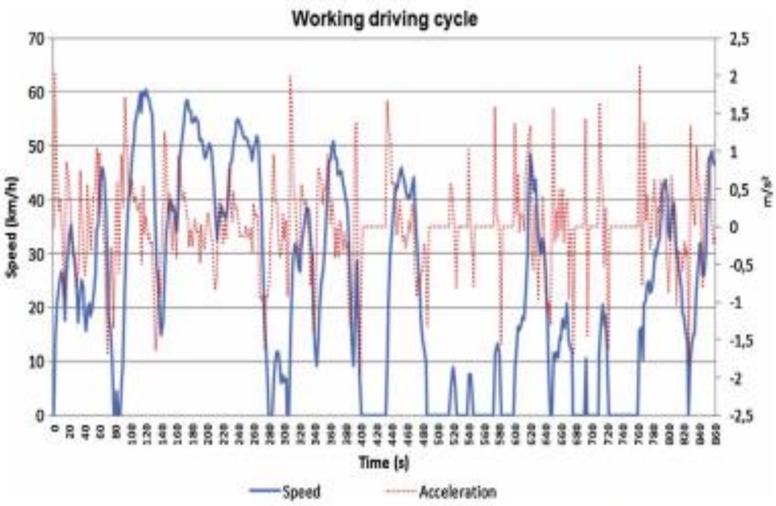

Fig. 8. Speeds and accelerations registered during working day. (Empirical data obtained using a data logger and an electric vehicle carrying out a 32 km journey in León. This number of km will not change for two reasons: Leon's population trend (analyzed in Section 4.4) and the fact that expansion of the city has already been completed. As a result, the size of León will remain the same)

Table 5
Worst case scenario and the Government's position on the contribution of EVs to V2G.[a]

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of EVs in worst-case scenario	877	1518	2159	2800	3441	4082	4763	5404	6045	6686	7270
Number of EVs in Government scenario	1754	2307	2861	3415	3969	4523	5077	5621	6175	6729	7270
Number of EVs in worst-case scenario (with reduced battery)	0[b]	0	0	0	0	0	877	1518	2159	2800	3441
Number of EVs in Government scenario (with reduced battery)	0	0	0	0	0	0	1754	2307	2861	3415	3969
% battery reduction	0	0	0	0	0	0	20%	20%	20%	20%	20%
Energy injected in the grid (MWh) in worst-case scenario	16.751	28.994	41.237	53.480	65.723	77.966	87.623	97.418	107.212	117.007	125.712
Energy injected in the grid (MWh) in Government scenario	33.501	44.064	54.645	65.227	75.808	86.389	90.270	98.548	107.013	115.479	123.695

[a] Government data have been analyzed and set out in Section 4.4.
[b] A residual presence of EVs is assumed in 2020. Thus the possible impact on the model due to charging and discharging processes is neglected.

regional. As a result, this figure was obtained by linking León's projected inhabitants in 2020 (131,556) [48,49] with those of Castilla y León (2,469,826) [48,49], to weight the data provided by the TSO.

4.6. *Income from the EV charging process. Losses for hydrocarbon tax*

The same circuit shown in Fig. 8 was conducted at rush hour, measuring consumption with a debimeter, in order to estimate losses due to hydrocarbon tax. The obtained result was 2.048 l. In relation to taxis, the previous result (2.048 l) was extrapolated. The result was 8.704 l, which takes into consideration 136 km/day from the data published by León Town Hall. León's conventional diesel buses consume 2065 l after driving 4978 km/day in 2020, once the reorganization of bus lines indicated in the Leon Mobility Plan [40] has been taken into account.

Estimating these consumptions in euros requires a prediction of the price of oil in 2020. From a euro/dollar parity of 1.2 $/€ and the worst-case scenario set by the IDAE (Institute for diversification and energy saving), the barrel price will reach 105.57 € in the reference scenario established by the US DOE (US Department of Energy) [59]. Because its price in May 2013 was 80.85 €/barrel, an increment of 5% a year is assumed from 2013 to 2020. Currently the cost of diesel is 1.348 €/l, and thus, in 2020, 1.82 €/l.

The Government will earn income from EV charging depending on the price of kWh in 2020–2030. Determining this date requires assessment of future inflation and the current forecast of the kWh price in 2020. IDAE assumptions forecast 0.0732 €/kWh [2]. Regarding inflation, the IMF (International Monetary Fund's) forecasts have been used [60]. Because this organization makes forecasts until 2017, the authors, considering the data published by the IMF until 2017, have established a possible growth between 2020 and 2030 as depicted by the profitability study (Excel file enclosed with this paper). However the Spanish Government has linked electricity with core inflation. This index connects the evolution of prices, removing the effect of energy products and raw commodities. In spite of the fact that there are no forecasts for its trend, its value has been lower than inflation so far [61], except in 2009 when the oil price changed exceptionally (Fig. 9). A decrease of 0.8% according to inflation is assumed for this profitability study. Regarding the EV recharging process, this study proposes the EV owner buys the energy at pool price.

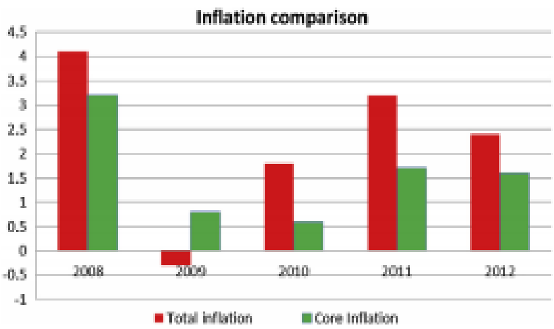

Fig. 9. Comparison between core inflation and inflation.
Source INE.

Losses due to hydrocarbon tax (42.8%) and its VAT (21%) are growing in line with current policies as EVs increase their penetration in the market. As a result fiscal modifications are necessary (Fig. 10).

4.7. *Pollution*

The diesel vehicle[4] used on the circuit (Fig. 8) emits 100 g CO_2/km. Therefore, private cars generate 32 g/km/day and taxis 136 g/km/day.

According to figures published in León's mobility plan, buses will cover 4,978 km/day in 2020 once the reorganization of bus lines has been taken into account [40]. The CO_2 emitted is 0.089 kg CO_2/passenger/km [62]. An average occupancy of 13 people and a 30-strong fleet are assumed in this paper.

The forecasted price in 2020 is 14 €/t of CO_2 [63], without any expected increase, unless annual CO_2 emissions are reduced. In this case the price could reach 32 €/t of CO_2. In this paper, a price of 17 €/t is assumed.

Table 6 depicts the results.

4.8. *Tax and retributory policies*

Modifications to tax and retributory policies are required to recover the losses of hydrocarbon taxes estimated in Section 4.6. This paper proposes:

a) Electricity tax

When implementing a sustainable transport model, all citizens benefit from environmental improvement, whether or not they own EVs. Therefore, a 0.25% increase on electricity tax is proposed, i.e. from the current value of 4.68%, to 4.93%. This charge is paid by all consumers (even companies). As a result the increment must be moderate.

[4] In this paper the vehicles which will be replaced by EVs are assumed to be diesel. This is supported by the fact that European legislation is increasingly overcharging more polluting vehicles.

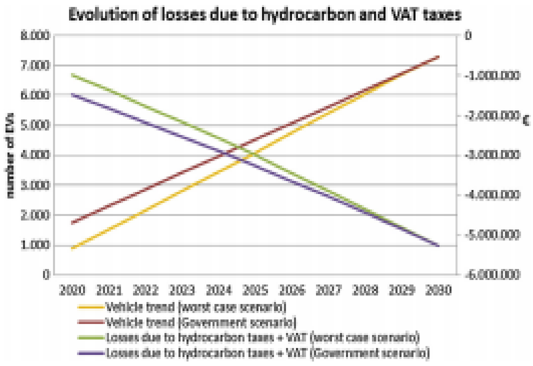

Fig. 10. Losses due to hydrocarbon and VAT taxes considering EV penetration.

b) V2G transaction tax

All incomes from V2G technology must be shared among the different players in the electricity system. When EV owners feed energy into the grid using their battery, they will get paid 67% of the price pool. Aggregators will receive 33% [64]. The incomes are shown in formula (2) [64]:

$$p_{V2G} = \frac{p_{pool}}{50} \cdot h \cdot p_{consumer} \qquad (2)$$

where p_{pool} is the price in € of MWh in the electricity pool, h (taken as 4 h) is the number of hours that users join the grid and $p_{consumer}$ (taken as 67%) is the consumers' benefit percentage. With such shares all parties in the system receive a return on their investment, as proven in the profitability study (Excel file enclosed with this paper).

Users' and aggregates' incomes must be subject to deductions by the Government. Aggregators and electricity companies take advantage of these models for several reasons: their business activities grow because of the charging process for V2G technology and their operational costs are reduced as energy is, in certain situations, obtained directly from EVs. This paper does not propose to change the current value of corporate incomes and generation taxes, 35% and 7% respectively, since an increase could affect consumers. For users, there are two options. Firstly, the V2G payment can be considered as an additional annual income with the corresponding IRPF (personal income tax) increase, along with the risk of not paying off the battery. Thus, participation in V2G would be viewed negatively. Another option considers incomes arising from V2G being subject to the IRPF but at the same time exempt (i.e. at 0%). This fact will help the Government gather sufficient information about the transactions. Therefore, this paper proposes to create a fee on users' annual incomes for joining the grid. Its value has been set at 5% to assure the Government's return without affecting the battery pay-off by the users.

c) Motor vehicle tax

In Spain, vehicles are levied with an annual tax. EVs, however, are exempt. Therefore, as their market penetration increases, Government losses also increase; and so a balance must be reached [65]. The level of taxation must take three factors into account: consumption-efficiency (kWh/km), power (kW) and size. The Government must establish the weighting of each parameter to guarantee the necessary revenues. An average increase of 10 €/vehicle against current incomes is assumed in this paper.

d) Registration tax

This tax is paid only once at the time of purchasing an EV. Its level is influenced by the same factors as mentioned previously. A slightly higher increase than that levied on traditional vehicles should be considered. In this paper, the increment is set at 50 €/vehicle.

Vehicle and registration taxes aim to finance the infrastructure necessary to implement this model, bearing in mind the potential profit for EV owners.

e) Tolls

An increment of 1% is considered to assure profitability.

5. Results

This model will be profitable as long as profitability is guaranteed for the Government, EV users, electricity companies and aggregators.

5.1. Government

This sustainable transport model based on electric mobility significantly reduces Government income from hydrocarbon tax and VAT (value added tax). Potential levies such as tolls, registration and motor vehicle taxes are supposed to balance the loss of income. However, the profitability associated with this model is achieved by assuring profits for EV owners from V2G and good EV market penetration. Regarding the former, as already exposed, the final owner's profit is close to 7,800 € after the battery is paid off. Inarguably these results encourage all EV owners to feed into the grid. Regarding the latter point, there is a key discrepancy

Table 6
Total emissions and associated taxes.

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CO_2 emissions per year (220 days considered) in worst-case scenario (t)	5862.70	6007.11	6151.51	6295.92	6440.32	6584.73	6738.14	6882.55	7026.95	7171.36	7302.92
Incomes from sales (17 €/t) in worst-case scenario	99,665.98	102,120.85	104,575.73	107,030.60	109,485.48	111,940.36	114,548.42	117,003.30	119,458.18	121,913.05	124,149.63
Emissions of CO_2 a year (220 days considered) in Government scenario (t)	6060.28	6184.85	6309.66	6434.47	6559.27	6684.08	6808.88	6931.43	7056.24	7181.04	7302.92
Incomes from sales (17 €/t) in Government scenario	103,024.68	105,142.53	107,264.22	109,385.91	111,507.59	113,629.28	115,750.97	117,834.36	119,956.04	122,077.73	124,149.63

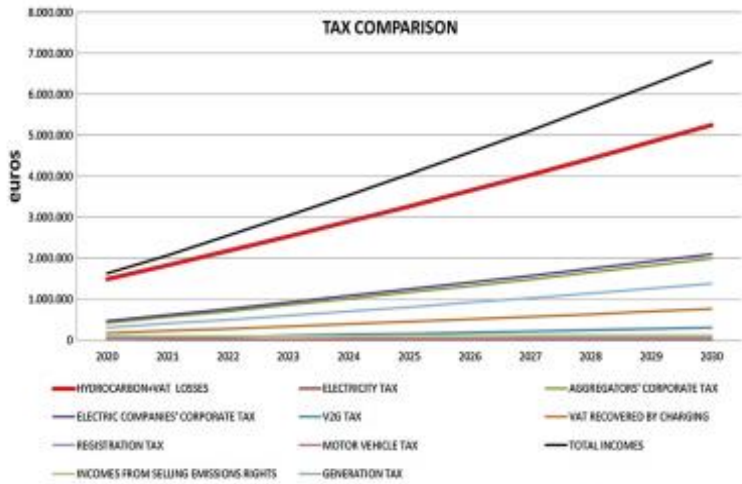

Fig. 11. Comparison: taxes against losses in hydrocarbon tax and associated VAT (Government scenario).

between the different Governments' forecasts. After analyzing the growth of León's vehicle fleet and its demographics, a comparison has been made between the situation described by the Government and a more pessimistic scenario, considering the number of EVs sold to date in Castilla y León. In both cases, profitability is assured. In the first scenario, payback is 6 years, TIR (internal rate of return) 20.14%, NPV (net present value) 34,252,068 € and net profits are close to 36,052,068 € between 2020 and 2030. In the second case, payback is 5 years, TIR 14.44%, NPV 31,490,628 € and net profits are close to 33,290,628 €. These figures could be used to decrease the fee deficit of 26,062 M€. Considering that the Spanish population will reach 44,836,892 by 2020 [50], León's fee deficit is 76,468,558 €. In the worst-case scenario, there is a 43.5% reduction compared to 47.1% in the Government scenario.

Profitability is ensured by two taxes:

a) Corporate Income Tax set at 35% of the aggregator and generator companies' profits.
b) 5% V2G Tax, proposed by the authors, on the total income earned by EV owners through the sale of energy to companies.

Increases in road, registration and electricity taxes are very low compared to previous levels and, consequently, their contribution to the final profitability is minor (Figs. 11 and 12).

Even though these results show significant profitability for the Government, they can fluctuate due to estimation errors regarding tolls, the MWh cost in 2020 and EV market penetration. In fact, tolls are a key issue. As depicted in Fig. 13, either they are increased or the model would turn out loss-making. Nonetheless, with increases of 1%, a 20.14% TIR would be obtained in the Government scenario.

MWh price is not a key issue for this model. From a 30% estimation error regarding the value established by the IDAE (73.2 MWh) this project becomes loss-making. This inaccuracy implies the electricity price will not increase in 8 years. This fact is unlikely considering the current fee deficit (Fig. 14).

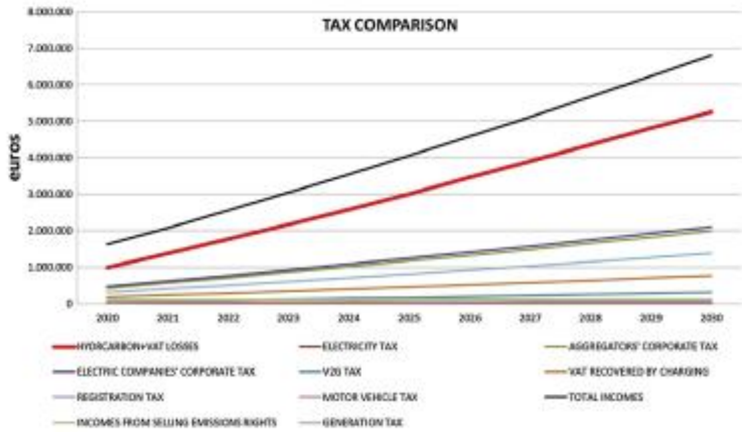

Fig. 12. Comparison: taxes against losses in hydrocarbon tax and associated VAT (worst-case scenario).

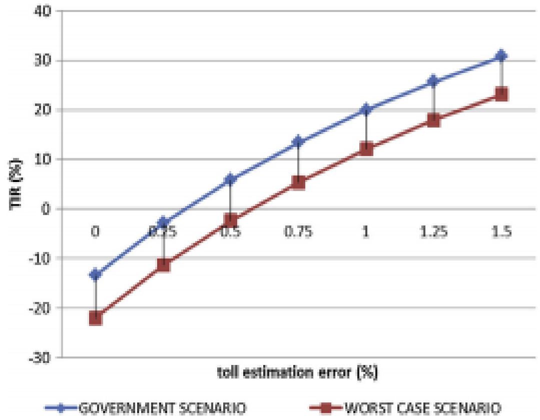

Fig. 13. TIR against tolls.

This model relies strongly on the level of EV market penetration. If this level is lower than the Government's forecast, the TIR declines (Fig. 15). However, even if it reaches 15% and a 5% V2G tax is applied, positive TIRs are still obtained. This estimation error can be put on the same level as V2G user participation.

It is important to point out that the Government's decision to carry out this type of project must also take social benefit into consideration, rather than focus solely on TIR, payback and NPV. In this case both views are positive.

This model does not affect the other taxes mentioned in this paper. However, it is important to increase them to implement and maintain new charging points. As examples, Figs. 16 and 17 show TIR evolution against V2G and motor vehicle taxes.

5.2. Aggregators and electricity companies

Aggregators will not incur any economic risks as their main function will be selling electricity coming from batteries in the pool and paying users for it.

As for electricity companies, taking into account the current overcapacity of the Spanish electricity system, they will not be forced to build new RE facilities (wind power or solar energy).

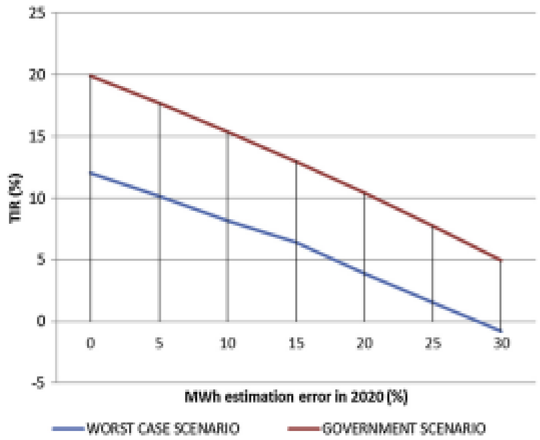

Fig. 14. TIR against MWh estimation error.

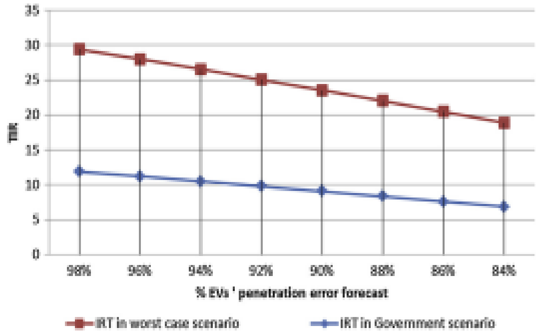

Fig. 15. TIR plotted according to the Government's forecast on EV penetration.

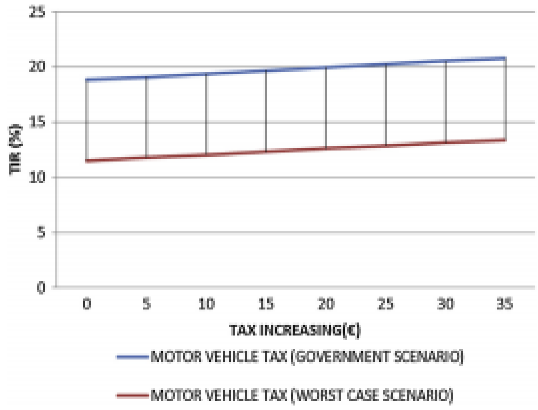

Fig. 16. TIR against motor vehicle tax.

However, their turnover will be increased due to the charging processes of EVs, ETs and EBs.

5.3. EV users

This model will be profitable as long as users get profits. They make money by selling electricity using V2G and through significant diesel savings. On the other hand, their main expenses are:

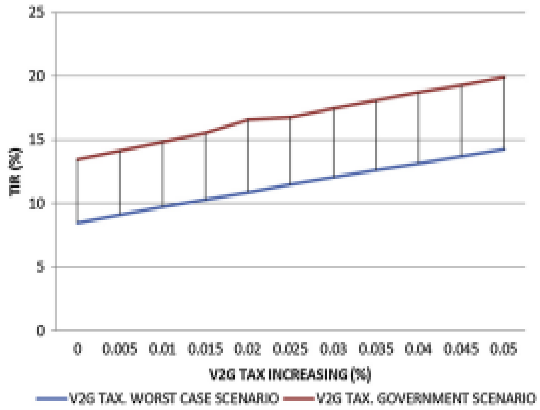

Fig. 17. TIR against V2G tax.

Table 7
Savings in diesel and petrol barrels.

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Saving in liters/day from veh. and taxi (l)	3536.90	4849.66	6162.43	7475.20	8787.97	10,100.74	11,495.42	12,808.19	14,120.96	15,433.73	16,620.76
Saving in diesel fuel/year from veh or taxi (220 days considered) (l)	778,117.12	1,066,926.08	1,355,735.04	1,644,544.00	1933,352.96	2,222,161.92	2,528,993.28	2,817,802.24	3,106,611.20	3,395,420.16	3,658,547.20
Saving in liters of diesel/year from buses	813,266	813,266	813,266	813,266	813,266	813,266	813,266	813,266	813,266	813,266	813,266
Total liters of diesel per year (220 days considered)	1,591,383.12	1,880,192.08	2,169,001.04	2,457,810.00	2,746,618.96	3,035,427.92	3,342,259.28	3,631,068.24	3,919,877.20	4,208,686.16	4,471,813.20
Barrels (one barrel equates to 38 l of diesel)	41,879	49,479	57,079	64,679	72,279	79,880	87,954	95,554	103,155	110,755	117,679

motor vehicle tax, registration tax, battery pay-off and charging costs. As proven in the profitability study (Excel file enclosed with this paper), a user will get 7,800 € once the battery is paid off. This conclusion is supported by various consultants who forecast a cost of 130–200 €/kWh for ion-lithium batteries in 2020–2025. According to the report by McKinsey & Company, EVs will be competitive if battery prices reach 205 €/kWh or less, and as a result EV users will not suffer from higher purchase costs in the future [66].

Finally, Table 7 shows the petrol savings obtained using this transport model, considering American refineries get roughly 38 l of diesel from one barrel [67].

This paper focuses mainly on the use of diesel as this will be more relevant than gasoline by 2020–2030.

6. Conclusions

Spain is affected by two key issues: high energy dependency and a significant fee deficit, which are both at worrying levels. A single solution can be applied based on a sustainable transport model composed of electric cars, buses and taxis, smart grids and vehicle-to-grid technologies. Its implementation faces several problems, one of which is the commonly held view that reducing petrol consumption will reduce income for the Government. Likewise, the investment to conduct this type of project is considerable. As a result there is doubt surrounding its profitability. This case study, which takes into consideration the scenario proposed by the Spanish Government and the forecasts made by the Spanish TSO, shows that it is possible to make this project profitable for EV users, the Government, aggregators and electricity companies, through the use of adequate regulatory policies. As a result, losses from petrol taxes will be recovered.

On the other hand, the fee deficit generated in the last 10 years as a result of imbalances between the incomes and costs of regulated activities reached 26,062 M€ in May 2013. The Results Section shows that León's fee deficit can be reduced by 43.5%–47.1%. In addition, implementation of the model leads to a reduction in petrol demand and, thus, a potential reduction in price. Furthermore, this profit could be used to reactivate financial aid for renewable energy facilities. This fact improves Spanish companies' competitiveness and decreases operational costs for electric vehicles.

As a result, the Spanish economy will enjoy increased protection against petrol price fluctuations. Expected TIR, NAV, payback and profitabilities are sufficient to assure that implementation of these models is considered, as well as providing the means to reduce the fee deficit. The authors are working on preparing future studies focused on rolling out these models to bigger cities such as Madrid and Barcelona.

Appendix A. Potential energy available for V2G

Estimating the available energy for joining in V2G is essential when analyzing the viability of this sustainable transport model based on SGs and electric technologies for León. Many factors influence the gathering of these data. Thus, this section will discuss which factors should be taken into consideration in this model and which ones could be neglected.

As a general rule, an EV has a 330 V traction battery. This direct current must be transformed into alternating current using a DC/AC transformer to feed the air conditioner, the reducer, and the electric motor. Likewise, an AC/DC converter is used to feed the battery and power calculators, the cooling system, and the vacuum pump (Fig. A1).

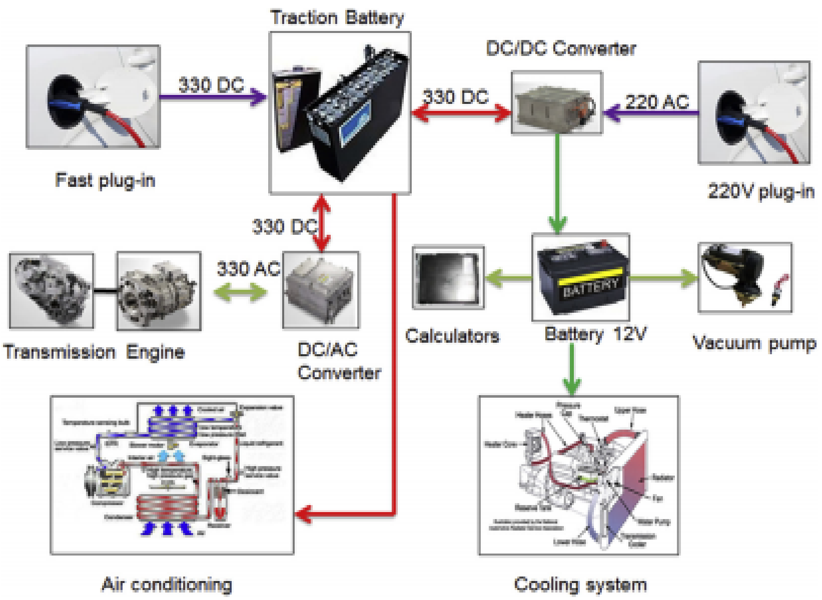

Fig. A.1. Possible electric/electronic configuration of an EV. Source PSA PEUGEOT CITROEN

Aerodynamic losses when driving are affected by the vehicle design [68]. These losses depend on the frontal area, drag coefficient, air density, and speed, some of which are fully linked to the design. They can be estimated using expression Eq. (A.1):

$$P_{aero} = A_{frontal} \cdot C_{drag} \cdot V^3 \cdot \frac{\rho_{air}}{2} \qquad (A.1)$$

Although not explicitly specified in expression Eq. (A.1), aerodynamic losses depend on temperature due to the temperature dependence of air density. In León's case, temperature is not considered a significant factor. As a result, it will not be considered.

Driver habits, such as abrupt acceleration, incorrect use of the gearbox, excessive speed, and extreme temperatures inside the car, can reduce battery autonomy from 10% to 30%, causing premature aging. In turn, smooth acceleration, moderate speed, and appropriate use of the gearbox, among other behaviors, could improve autonomy. Acceleration losses can be obtained by expression Eq. (A.2) [68]:

$$P_{accel} = V_{ave} \cdot M_{Gr.veh} \cdot a \qquad (A.2)$$

Running conditions are influenced by the inclination of the road and rolling resistance [68]. First, a very important energy demand occurs when the slope is more significant and as a result its autonomy is reduced. Inclination losses are given by Eq. (A.3):

$$P_{incl} = M_{Gr.veh} \cdot g \cdot V \cdot \sin\left(\frac{\beta_{incl} \cdot \pi}{180}\right) \qquad (A.3)$$

As a general rule, León is a very level city. However, 1° will be considered as the angle of incline.

Regarding the rolling resistance, the lower the temperature, the higher the losses are because of this factor. These losses can be estimated using expression Eq. (A.4) [68]:

$$P_{roll} = M_{Gr.veh} \cdot g \cdot \left(R_0 + R_1 \cdot V + R_2 \cdot V^2 + R_3 \cdot V^3\right) \cdot V \qquad (A.4)$$

Transmission inefficiencies are expressed as the ratio of the addition of power losses because of aerodynamic drag, rolling resistance, road inclination, and acceleration by the EV transmission efficiency. The transmission efficiency is given from the drive train efficiency data and the torque data. The torque converter speed output is expressed by equations Eq. (A.5) and Eq. (A.6) [68]:

$$\text{Torque converter speed} = V \cdot \frac{G}{\pi} \cdot d_m \qquad (A.5)$$

$$\text{Torque converter} = \frac{P_{move}}{G} \cdot \omega \qquad (A.6)$$

The charging process is influenced by several factors, including temperature and charging time, which will affect the final capacity. Depending on the battery type, the charging and discharging temperature conditions will be different. In the early mornings and early evenings, charging processes are performed at home; thus, temperatures below zero will not be reached. Charging at home also occurs for the rest of the day, even though the weather is cold. As a result, the temperature's effect during charging can be neglected.

The final total available power depends on various factors, including transmission performance (close to 1) and the consumption of different car components during the journey regardless of whether the EV is running, such as heated rear windows, headlight consumption and using a direct measure on an EV (Figs. A2 and A3).

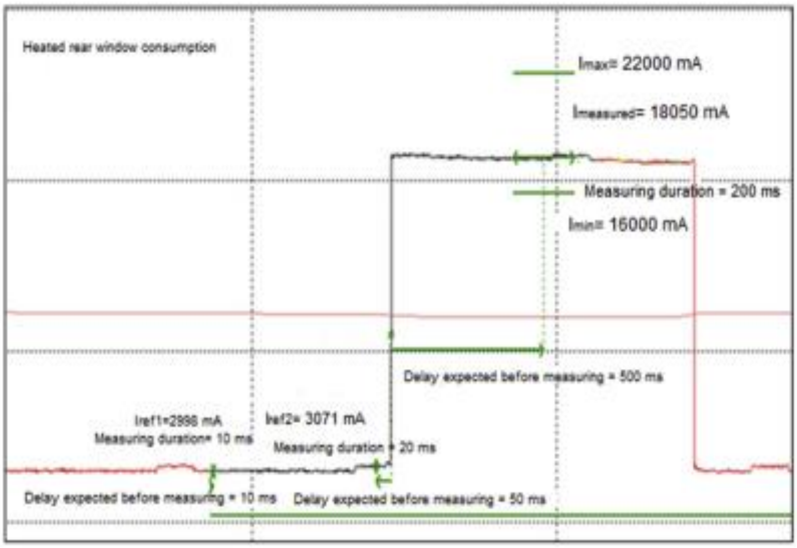

Fig. A.2. Heated rear window consumption.

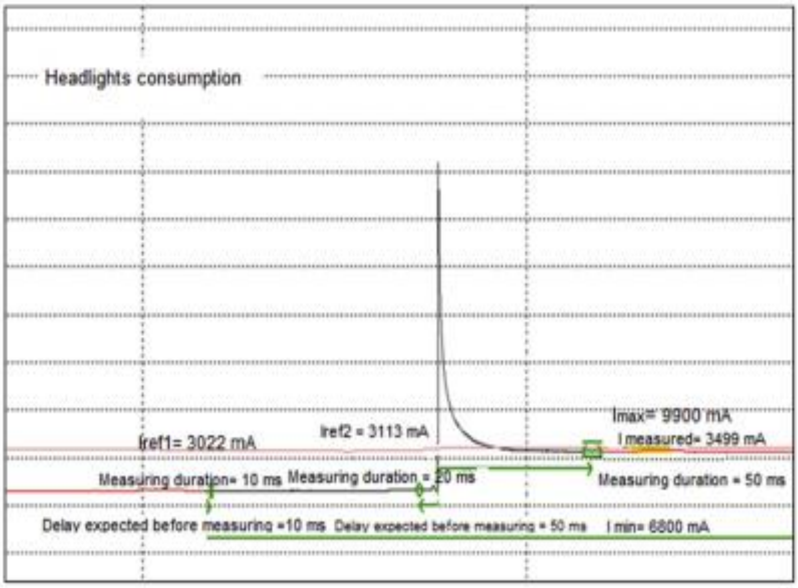

Fig. A.3. Headlight consumption.

Battery power is given by equation Eq. (A.7) [68] (Fig. A4, Fig. A5):

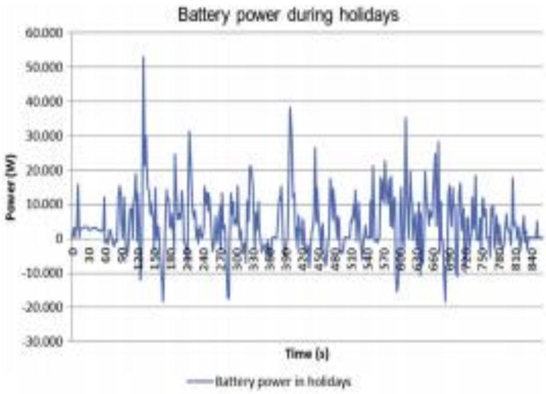

Fig. A4. Battery power during holidays

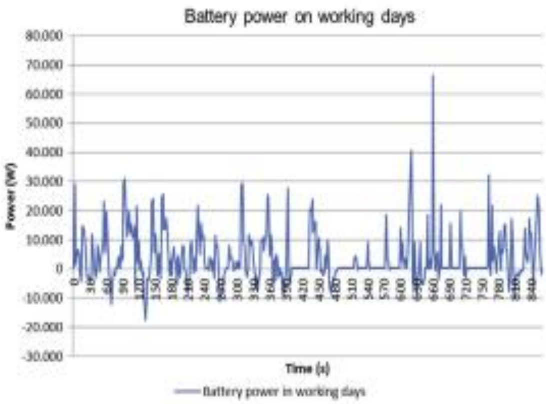

Fig. A5. Battery power on working days

$$P_{bat} = P_m + P_{res} \quad \text{(A.7)}$$

where P_m is an estimate that depends on whether the vehicle is being driven or whether the regenerative braking is active. In the former case, the motor's performance is not constant throughout the whole operation regime. Thus, it must be obtained using expression Eq. (A.8) [69]:

$$\eta_m = \frac{T_i \cdot w_i}{T_i \cdot w_i + k_C \cdot T_i^2 + k_i \cdot w_i + k_W \cdot w_i^3 + C} \quad \text{(A.8)}$$

where k_C, k_i, k_w and C are constants with values of 0.3, 0.01, 5E-06, and 600, respectively. Thus, the motor power is given by Eq. (A.9) [69]:

$$P_m = \frac{P_u}{\eta_m} \quad \text{(A.9)}$$

where P_u is the effective power. In the case of regenerative breaking, the motor's power will be decreased due to regenerative performance (considered to be 0.9 for the simulation).

The rate of discharging depends on the current value: the higher the current, the more rapid the discharge. This fact confirms that battery autonomy will be affected by driving habits, such as abrupt accelerations.

The average consumption used to traverse the established driving cycle is 1.0299 kWh for weekends and 1.2109 kWh for working days. Based on the data published by the Ministry of Industry in Spain, an average of 32 km is traveled by a vehicle daily. This value corresponds to 4 cycles and will cause a decrease of 4.1196 kWh during holidays and 4.8436 kWh on working days. The decreased voltage trend will not be considered, as these calculations are only intended to approximate the total amount of available energy to use in V2G. This estimation error is tolerable because the battery capacity will likely be higher by 2020. As a result, this rounding of 19.88 kWh on weekends and 19.1564 kWh on working days available for V2G is sufficient for the purposes of this paper.

Finally, a participation rate lower than 100% is considered to establish the energy available to be fed into the grid as certain users will not be willing to do this. As result, 220 days per year is taken as a basis for assessing the profitability of the project.

Appendix B. Supplementary data

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.energy.2013.11.077

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ANEXO II. Factor de impacto. Energy

Journal Citation Report

Clarivate

Journal Citation Reports Browse journals

Home › Journal profile

JCR YEAR

2020

ENERGY

ISSN

0360-5442

EISSN

1873-6785

JCR ABBREVIATION

ENERGY

ISO ABBREVIATION

Energy

Journal information

EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

ENERGY & FUELS - SCIE

THERMODYNAMICS - SCIE

LANGUAGES	REGION	1ST ELECTRONIC JCR YEAR
English	ENGLAND	1997

Publisher information

PUBLISHER	ADDRESS	PUBLICATION FREQUENCY
PERGAMON-ELSEVIER SCIENCE LTD	THE BOULEVARD, LANGFORD LANE, KIDLINGTON, OXFORD OX5 1GB, ENGLAND	11 issues/year

2020 JOURNAL IMPACT FACTOR

7.147

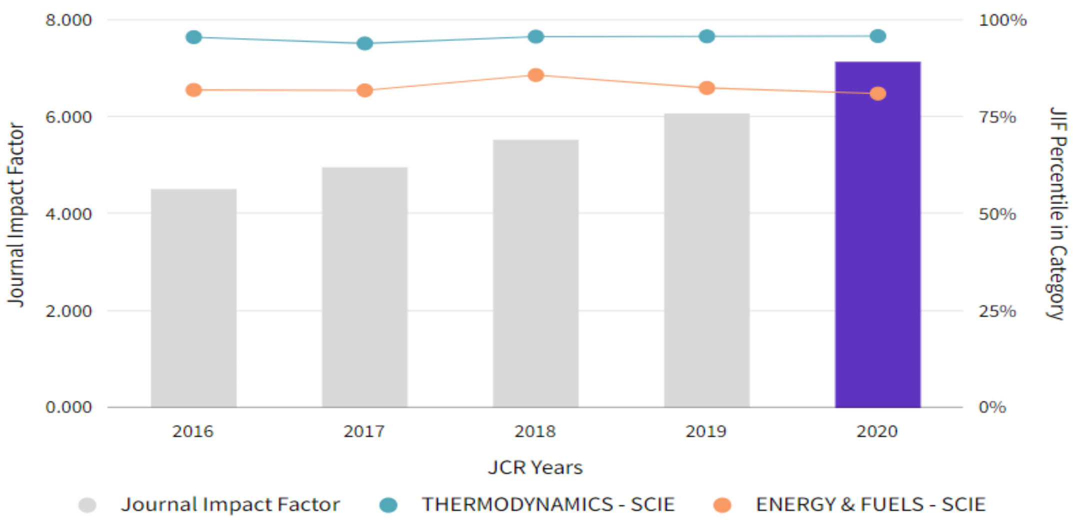
View calculation

JOURNAL IMPACT FACTOR WITHOUT SELF CITATIONS

6.118

View calculation

Journal Impact Factor Trend 2020 Export

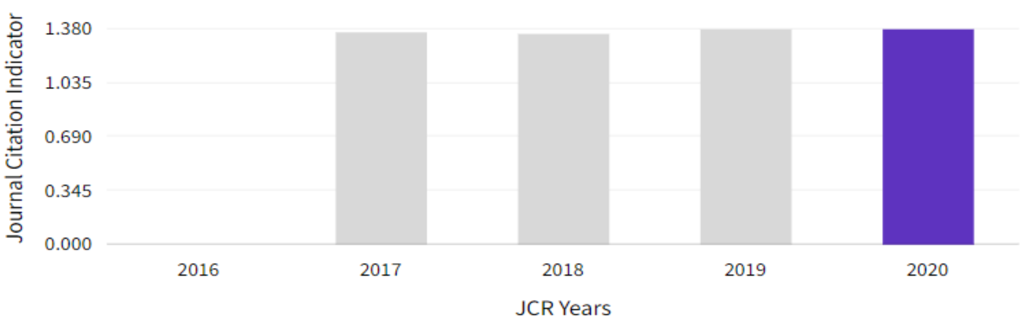


Journal Citation Indicator (JCI)

Export

1.38

The Journal Citation Indicator (JCI) is the average Category Normalized Citation Impact (CNCI) of citable items (articles & reviews) published by a journal over a recent three year period. The average JCI in a category is 1. Journals with a JCI of 1.5 have 50% more citation impact than the average in that category. It may be used alongside other metrics to help you evaluate journals. Learn more

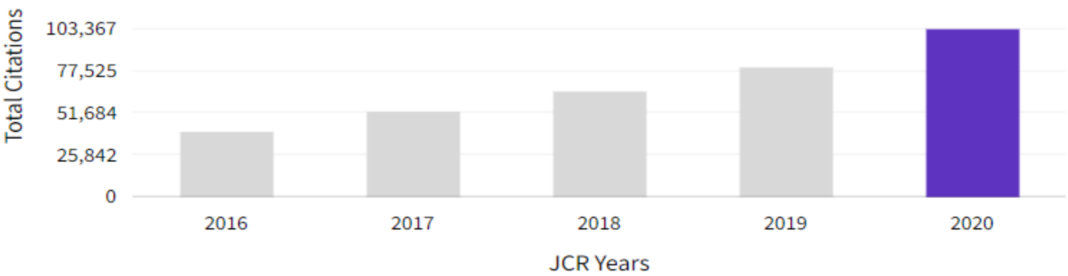


Total Citations

Export

103,367

The total number of times that a journal has been cited by all journals included in the database in the JCR year. Citations to journals listed in JCR are compiled annually from the JCR years combined database, regardless of which JCR edition lists the journal.



Rank by Journal Impact Factor

Journals within a category are sorted in descending order by Journal Impact Factor (JIF) resulting in the Category Ranking below. A separate rank is shown for each category in which the journal is listed in JCR. Data for the most recent year is presented at the top of the list, with other years shown in reverse chronological order. Learn more

EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

THERMODYNAMICS

3/62

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	3/62	Q1	95.97
2019	3/61	Q1	95.90
2018	3/60	Q1	95.83
2017	4/59	Q1	94.07
2016	3/58	Q1	95.69

EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

ENGINEERING, CHEMICAL

n/a

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	n/a	n/a	n/a
2019	n/a	n/a	n/a
2018	n/a	n/a	n/a
2017	n/a	n/a	n/a
2016	n/a	n/a	n/a

EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

ENERGY & FUELS

22/114

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	22/114	Q1	81.14
2019	20/112	Q1	82.59
2018	15/103	Q1	85.92
2017	18/97	Q1	81.96
2016	17/92	Q1	82.07

Rank by Journal Citation Indicator (JCI)

Journals within a category are sorted in descending order by Journal Citation Indicator (JCI) resulting in the Category Ranking below. A separate rank is shown for each category in which the journal is listed in JCR. Data for the most recent year is presented at the top of the list, with other years shown in reverse chronological order. Learn more

CATEGORY

THERMODYNAMICS

4/71

JCR YEAR	JCI RANK	JCI QUARTILE	JCI PERCENTILE
2020	4/71	Q1	95.07
2019	4/61	Q1	94.26
2018	5/60	Q1	92.50
2017	8/59	Q1	87.29

CATEGORY

ENERGY & FUELS

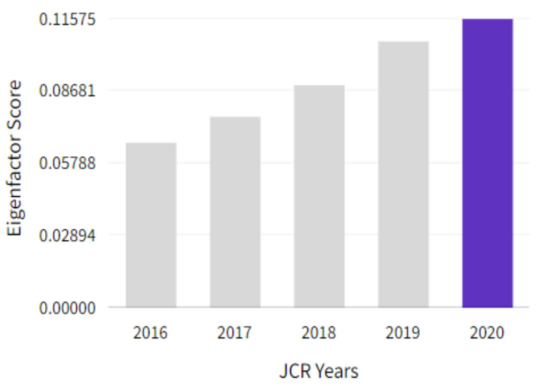
18/133

JCR YEAR	JCI RANK	JCI QUARTILE	JCI PERCENTILE
2020	18/133	Q1	86.84
2019	18/112	Q1	84.38
2018	17/103	Q1	83.98
2017	19/95	Q1	80.53

Eigenfactor Score

0.11575

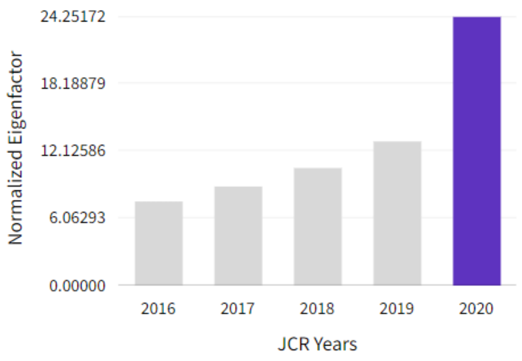
The Eigenfactor Score is a reflection of the density of the network of citations around the journal using 5 years of cited content as cited by the Current Year. It considers both the number of citations and the source of those citations, so that highly cited sources will influence the network more than less cited sources. The Eigenfactor calculation does not include journal self-citations.
Learn more



Normalized Eigenfactor

24.25172

The Normalized Eigenfactor Score is the Eigenfactor score normalized, by rescaling the total number of journals in the JCR each year, so that the average journal has a score of 1. Journals can then be compared and influence measured by their score relative to 1. Learn more



Article influence score

1.190

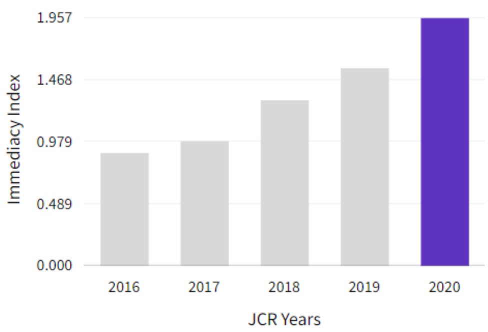
The Article Influence Score normalizes the Eigenfactor Score according to the cumulative size of the cited journal across the prior five years. The mean Article Influence Score for each article is 1.00. A score greater than 1.00 indicates that each article in the journal has above-average influence. Learn more

Immediacy Index

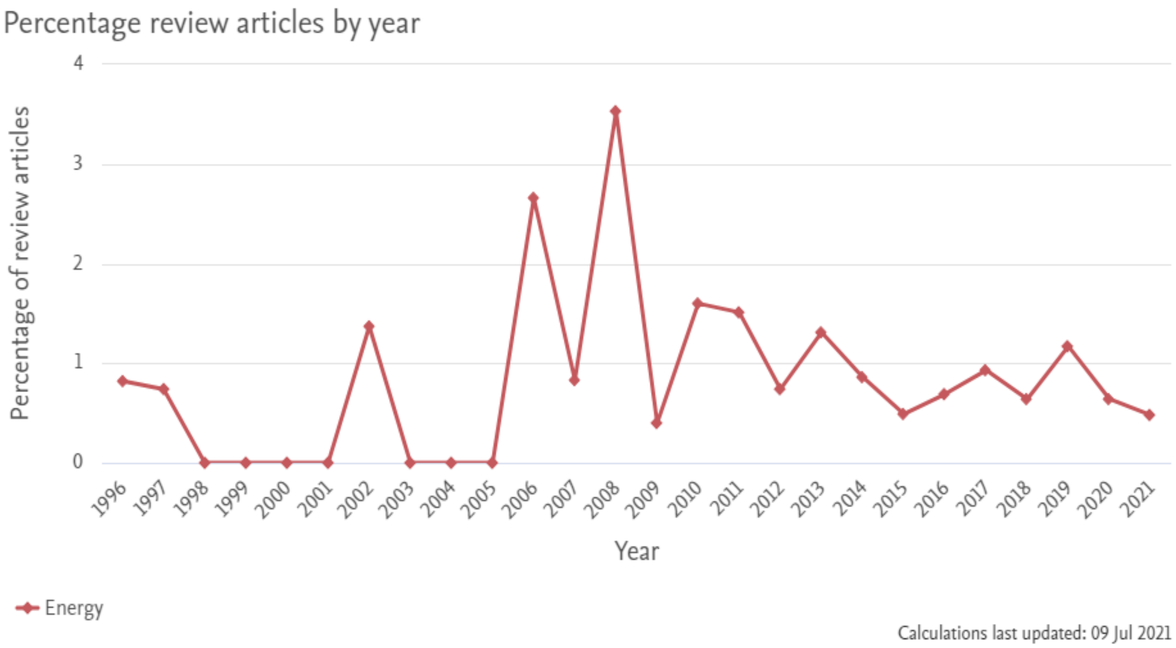
1.957

View Calculation

The Immediacy Index is the count of citations in the current year to the journal that reference content in this same year. Journals that have a consistently high Immediacy Index attract citations rapidly.
Learn more



Scopus


Percentage review articles by year
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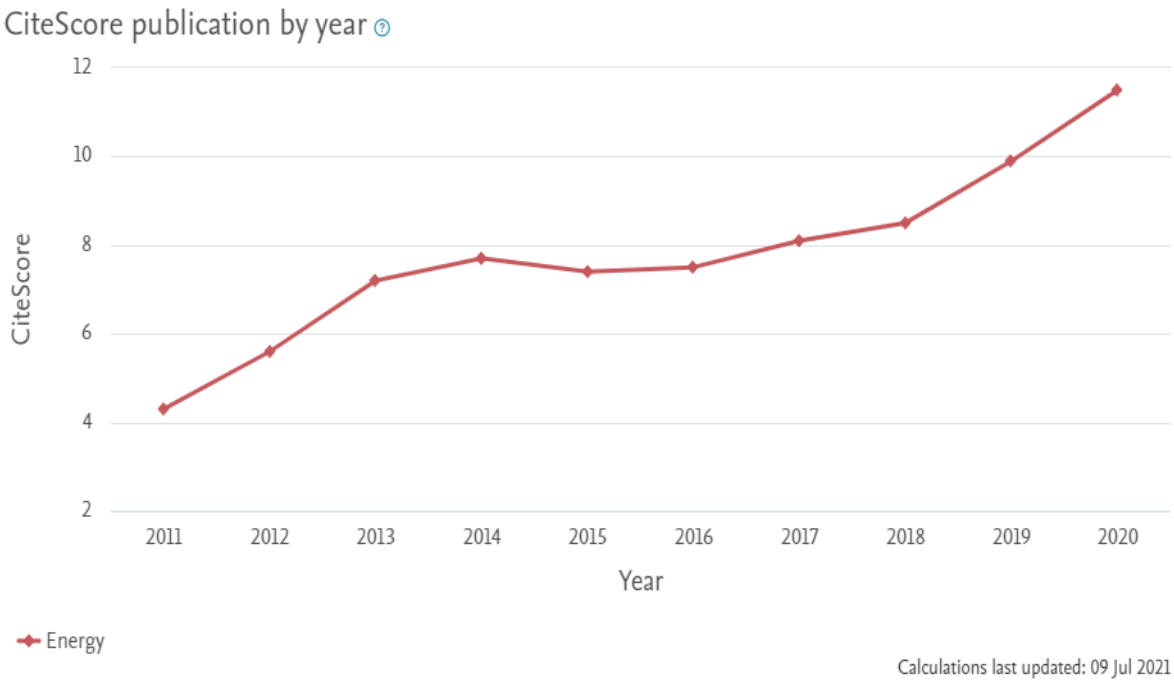
Calculations last updated: 09 Jul 2021


CiteScore publication by year
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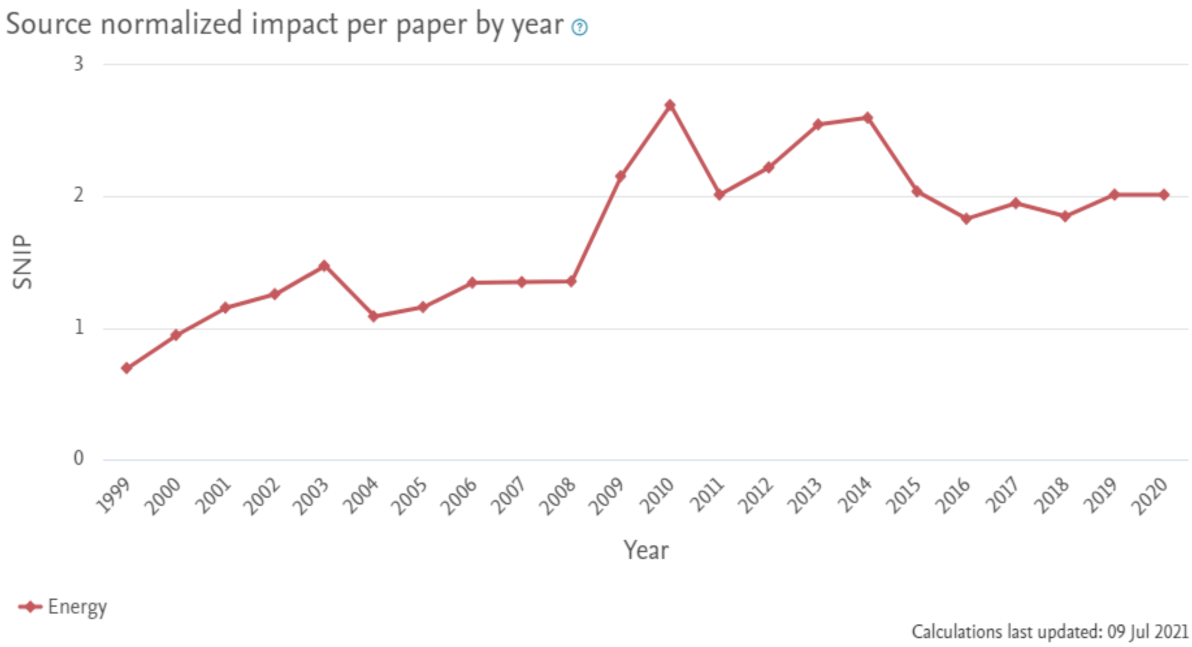
Calculations last updated: 09 Jul 2021



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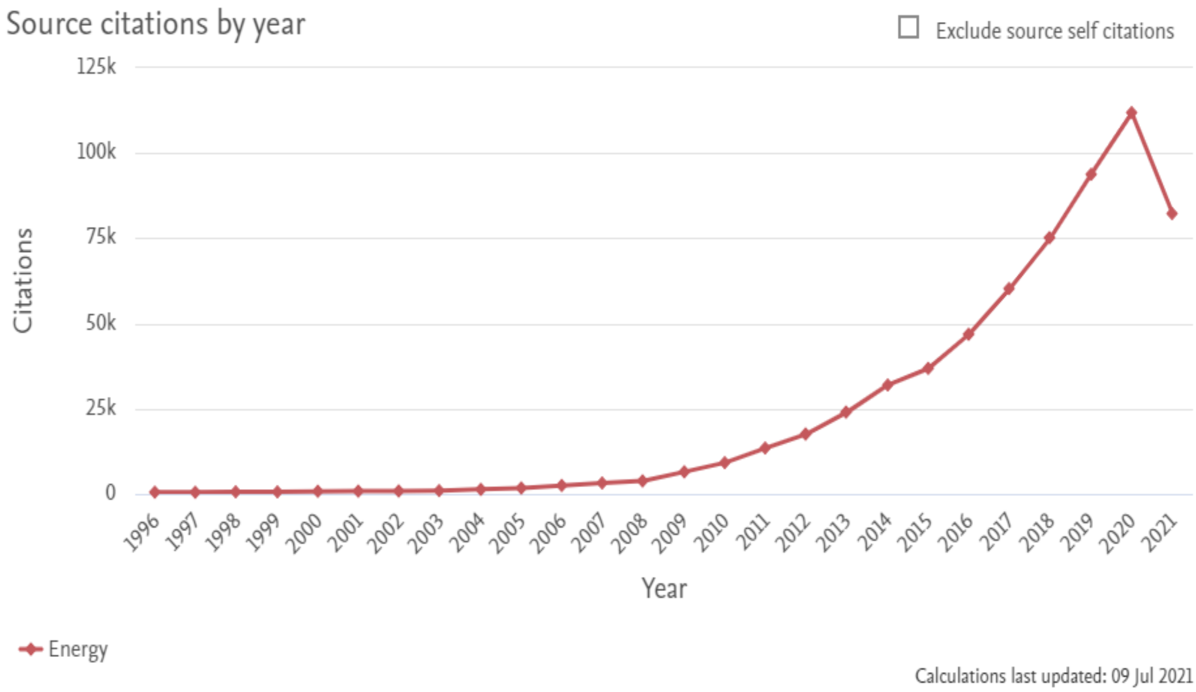

Source citations by year
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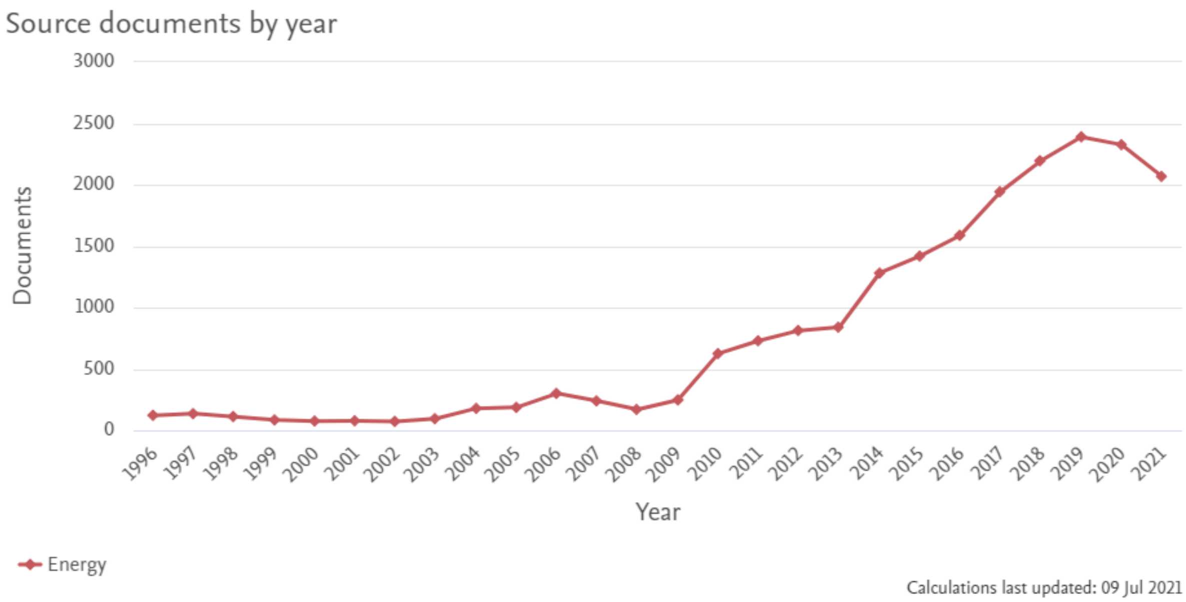

Source documents by year
Documents
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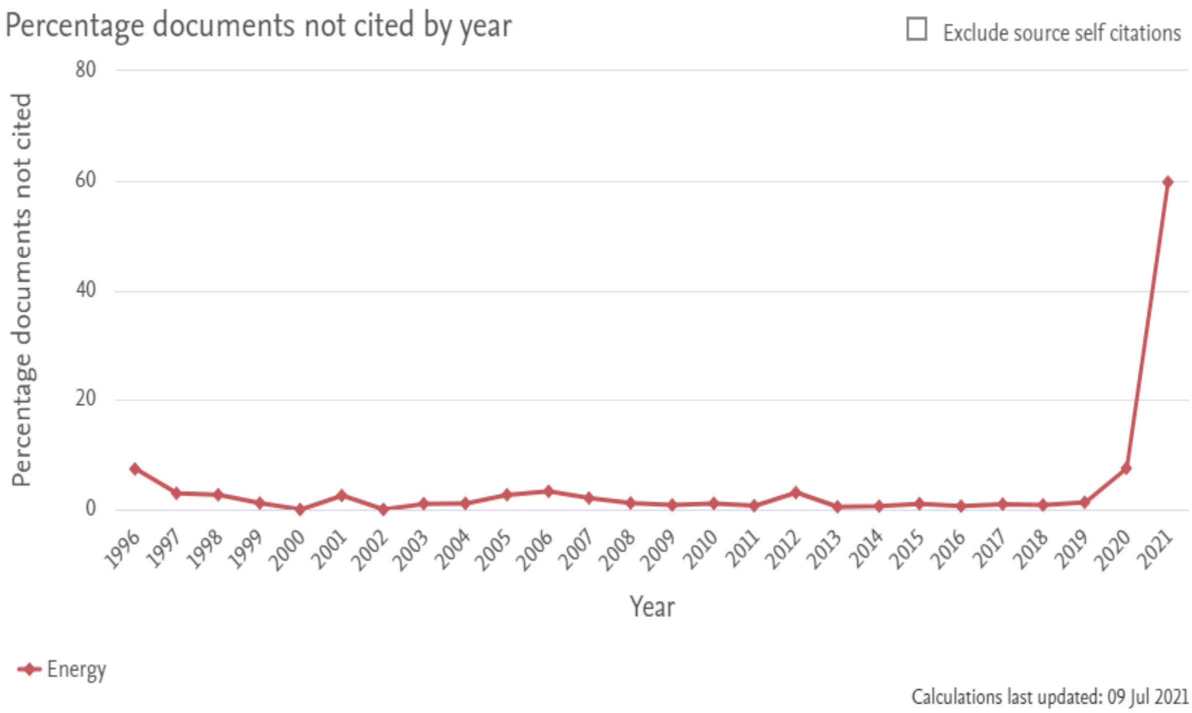

Percentage documents not cited by year
Exclude source self citations
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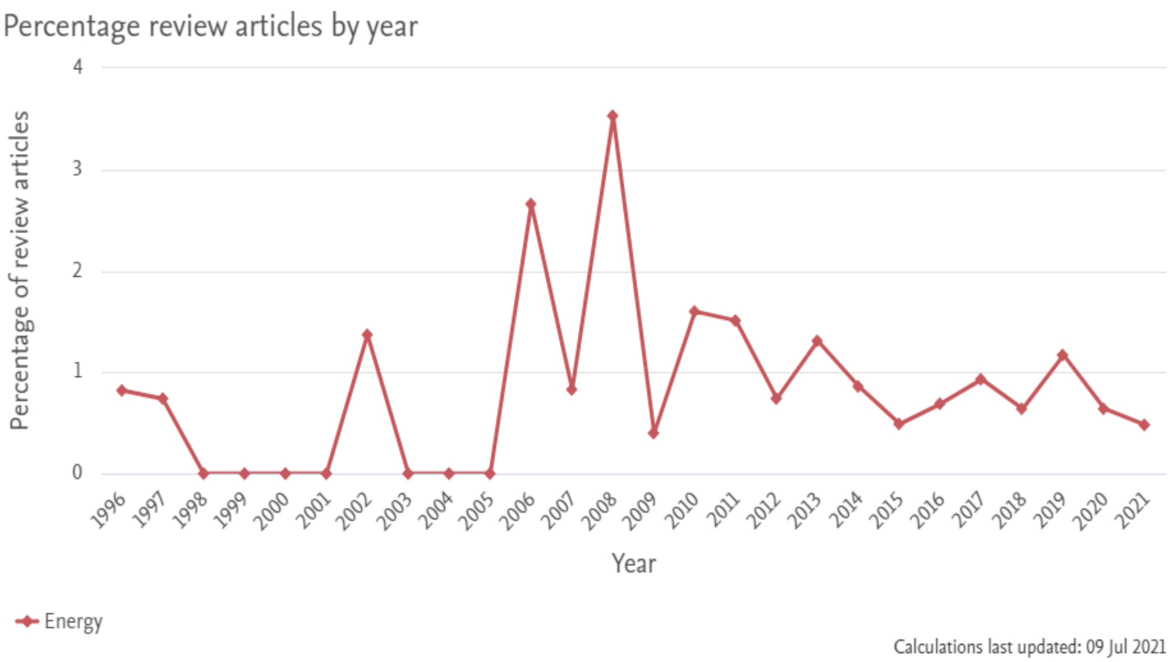
Calculations last updated: 09 Jul 2021



Percentage review articles by year
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Calculations last updated: 09 Jul 2021

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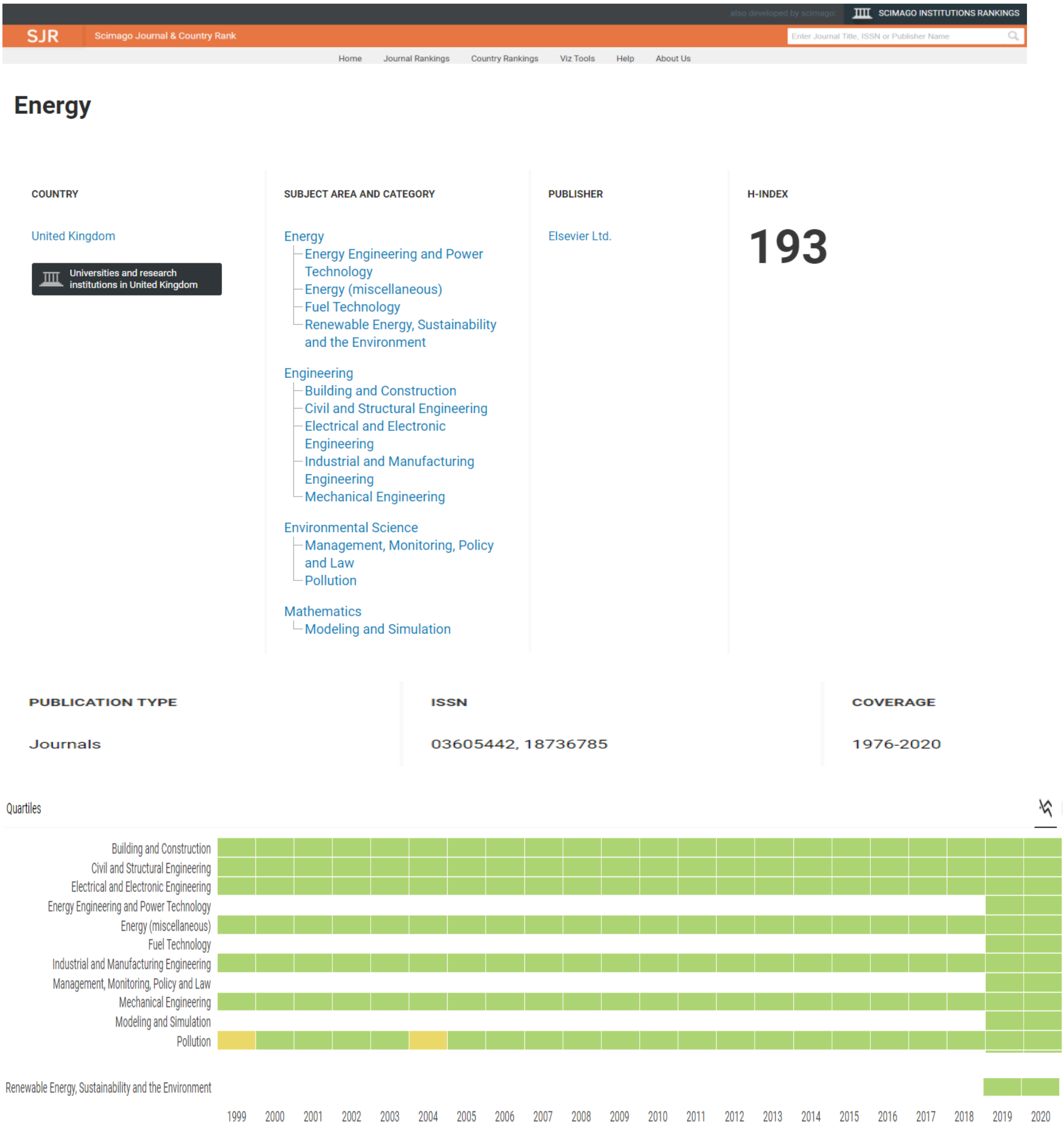
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SUBJECT AREA AND CATEGORY
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Energy Engineering and Power Technology
Energy (miscellaneous)
Fuel Technology
Renewable Energy, Sustainability and the Environment
Engineering
Building and Construction
Civil and Structural Engineering
Electrical and Electronic Engineering
Industrial and Manufacturing Engineering
Mechanical Engineering
Environmental Science
Management, Monitoring, Policy and Law
Pollution
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Modeling and Simulation
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193
PUBLICATION TYPE
Journals
ISSN
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1976-2020
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Energy Engineering and Power Technology
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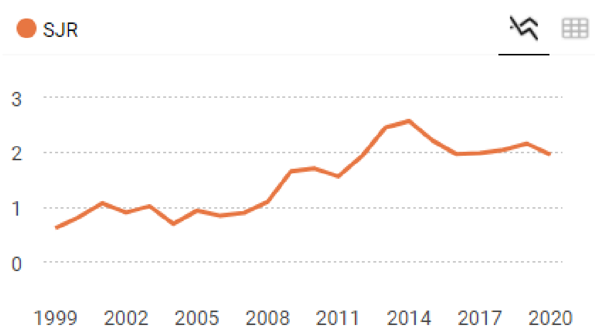
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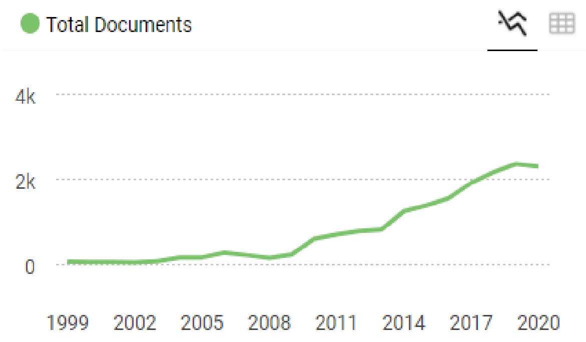
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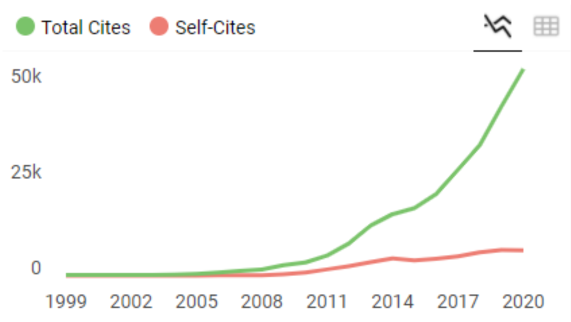
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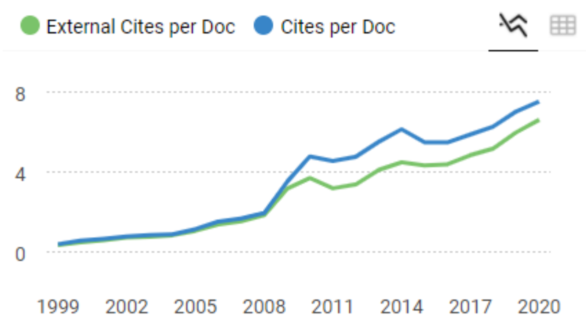
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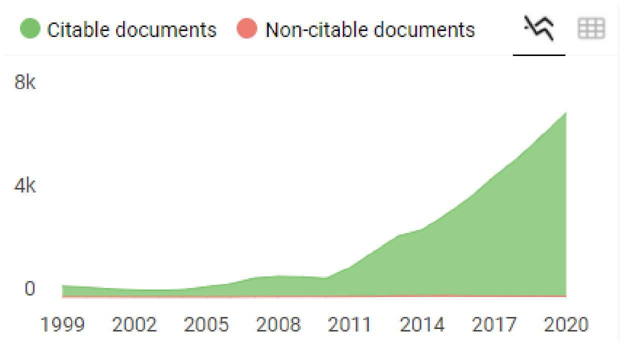
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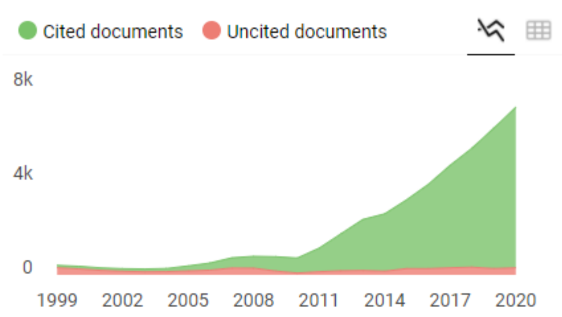
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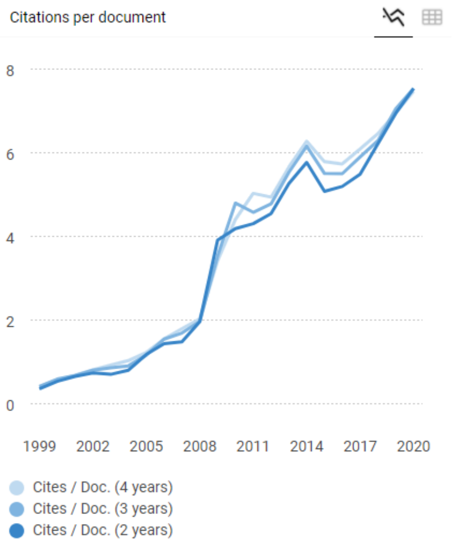

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Cites / Doc. (4 years)
Cites / Doc. (3 years)
Cites / Doc. (2 years)

ANEXO III. Copia de la publicación: "Application of rule-based expert systems in hardware-in-the loop simulation case study: Software and performance validation of an engine electronic control unit".

Received: 31 July 2018 | Revised: 28 June 2019 | Accepted: 1 July 2019
DOI: 10.1002/smr.2223

RESEARCH ARTICLE - EMPIRICAL

WILEY Software: Evolution and Process

Application of rule-based expert systems in hardware-in-the-loop simulation case study: Software and performance validation of an engine electronic control unit

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Abstract

Innovative techniques to validate software are needed to reduce cost and increase software quality.

This research aims to check if two rule-based expert systems (EXs) combined with dynamic-link libraries (dlls) perform better than other techniques widely employed in the automotive sector when validating the engine electronic control unit (ECU) software by using a hardware-in-the-loop (HIL) simulation.

To perform this research, 15 software modules (SMs) of different complexities were chosen to be validated in an HIL simulation by using different techniques such as the manual execution, the tester-in-the-loop, the model-based testing, a rule-based EX, and the combination of two EXs to establish the code and functional coverage, the productivity gain, the number of bugs found, potential limitations of each technique, and the success rate of the HIL simulation. The test cases used are described in-depth in Section 2.

The enhancement, which dlls and EXs offer, depends on the number of states in the functional model used in the EXs and the number of subintervals in which the SM inputs can be divided. A range between 6 and 16 more bugs can be detected when using two EXs. The HIL enhancement can reach 6%, 16.8%, and 18% depending on the SM complexity.

KEYWORDS

dynamic-link library, embedded software, expert system, model-based testing, software validation

1 | INTRODUCTION

1.1 | Engine electronic control unit software

The electronic architecture of today's vehicles is extremely complex. As a result, the number of electronic control units (ECUs) present in vehicles is increasingly high.[1,2] This trend will continue in the next years, thanks to driving assistance systems, which are essential for autonomous cars. ECUs are composed of hardware and software whose complexity depends on the function carried out in the network. Therefore, there are

Abbreviations: dll, dynamic-link library; ECU, electronic control unit; EX, expert system; HIL, hardware-in-the-loop; SM, software module multiple software running simultaneously and coexisting in a commercial car.[3,4] This fact forces manufacturers to improve the software quality and the validation processes.[5] In addition, it is not difficult to find estimates that indicate that the total number of lines of code present in the software ECUs of a vehicle can reach up to more than 100 million. In the future, these figures will even grow significantly up to 200 or 300 million in autonomous vehicles.[6]

Powertrain* control is a system in charge of transforming the driver's will into an operating point of the powertrain according to the performance established for the product (eg, consumption and emissions).[7] The key element of the control system is the engine ECU composed of complex hardware and software. The hardware is responsible for getting information from sensors after a filtering process to reduce noise in signals. The software processes all data received and handles actuators to reach the operating point. In addition, when a vehicle is in motion, the engine ECU (hardware and software) interacts with other ECUs to ensure the proper functioning of the car. This implies that each ECU should receive the information at a specific time. Therefore, the engine ECU (hardware and software) must be validated to assure that engine is properly controlled, the interaction with the rest of the ECUs is rightly performed, and the passengers' safety is insured. Otherwise, some failures could occur and lead to the situation in which the vehicle stalls. This fact makes the most safety critical parts of the software a hard-real-time (HRT) system.[7] In other words, the system is subjected to real-time constraints in which every critical task must be executed at a specific deadline to ensure the correct operation of the system. Thus, one can deduce that the software validation process is complex and needs improvements with the aim of reducing costs, increasing productivity and reliability in the automotive sector (see Garousi and Mäntylä[8] and Kasoju, Petersen, Mäntylä[9]).

This research is focused on the engine ECU software validation (one of the most complex software present in a vehicle) and shows solutions to the main difficulties associated with traditional software validation techniques as exposed in Section 1. The solution proposed in this paper is showing that two expert systems (EXs) working in cooperation and combined with dynamic-link libraries (dlls) perform better than traditional techniques such as the model-based testing or tester-in-the-loop among others.

1.2 | Techniques currently used

The engine ECU software validation is based on hardware-in-the-loop (HIL) simulation, combined with different techniques for generating test cases (see Appendix B). Three key stages must be considered when performing an HIL simulation: test-case generation, test-case execution, and validation of the execution results.[10-14]

One can find different definitions for the black-box concept such as "the black-box testing is a method of software testing that examines the functionality of an application without peering into its internal structures or workings."[15,16] Among others, there are three types of techniques used when applying the black-box one[17]:

a. Equivalence portioning

The inputs of the software module (SM) under validation are divided into partitions, and after having selected representative values for each partition, the test case is conducted. Then the software behavior is analyzed. The model-based testing can be defined as the automatic generation of software test procedures, using models of system requirements and behavior. To do this, a functional model must be implemented. This technique may be considered in this research as an equivalence portioning technique in the black-box testing. Because test cases are derived from functional models and not from the source code, the model-based testing is usually seen as one form of the black-box testing. The main advantage of this functional model is that all functional states and the transition from one state to another are indicated. Thanks to this, it is easier to assess the functional coverage as the number of states covered when validating an SM is known.

The EX combined with dlls consists of using an EX to assess if the software behaves as expected. The EX is built by using rules coming from the specifications and software requirements. The dlls are the Simulink model of the SM under validation that allows calculating the software outputs when performing the HIL simulation despite the SM interactions. This topic is analyzed in-depth in this research. The authors have considered this technique as an equivalence portioning one as it is exposed in this research.

b. Boundary value analysis

Boundary values for the SM inputs are determined, and the test case obtained is performed. Then the software behavior is analyzed.

c. Cause-effect technique

In the automotive sector, the test engineer usually has to validate cause-effect test cases that come from the software requirements. As a result, given a series of specific causes (conditions related to inputs), the validation process has to check the effect (software behavior). An

*Powertrain is composed of the clutch, gearbox, conical group, and propeller shaft. The reader can find more information about the engine control unit in Appendix A.

example of a possible test case could be: "In case of an ESP frame is absent, the stop and start function must be inhibited." The tester-in-the-loop, the manual execution, or automated can be considered as cause-effect techniques in this research.

All techniques that may be used to validate the engine ECU software have to face several issues such as the SM interactions that prevent reaching the values established in the test case, the type of bugs that can be found, and the problem of enhancing the code and functional coverage. Considering that the engine ECU software has up to 70 complex SMs, the interaction between SMs is continuously present and disturbs the validation process such as electronic noise. Consequently, given a test case, it is almost impossible to make the inputs reach the desired value. The main consequence is that the expected output set in the test case could be no longer available.

Some types of bugs are extremely difficult to detect by using HIL simulation unless a technician uses a significant amount of time to analyze the data acquisition. Figure 1 shows an example, the obtained result for an output for a variable of an SM when running the software in an HIL simulation (in red) and its expected value (in blue). As one can see, the results are different. This error represents an inaccuracy when it comes to calculating the gas speed in the exhaust pipe. This error could impact the amount of urea injected to treat NO_x. Because this bug is not linked to a functional bug, it is impossible to detect it by using the black-box technique. The detection of this type of bug involves checking and detailed analysis of the software code by running additional software.

Considering all aforementioned, the main limitations associated with these techniques currently used in the automotive sector when using the HIL simulation are depicted in Table 1. The aim of this research is to solve all these limitations by using two EXs working in cooperation combined with dlls. The fact of using two EXs allows improving the code and functional coverage and gaining a better control of the automation process, thanks to dlls. It also provides an opportunity to detect any type of bugs as exposed in-depth in Section 3.

This paper is organized as follows. Section 2 describes the method used in this research. Section 3 presents the results. Section 4 analyses the sensitivity of the results obtained in this research. Finally, Section 5 draws the main conclusions. The reader can find different appendices describing how the powertrain of a vehicle works (Appendix A) and the HIL simulation process (Appendix B).

1.3 | Related works

The engine ECU software validation is based on HIL simulation. Several stages must be considered when performing an HIL simulation such as test-case generation and test-case execution.[18-21]

A test case consists of a set of inputs and their expected outputs that the software should provide when working properly. In an HIL simulation, a test case is run, and the obtained result is compared with the expected one to check whether the software has operated properly for this specific test case.[22-24] There are many different ways to generate a test case, such as assigning specific values to all inputs of the SMs under validation to cover a functional model, as exposed later in this research, or assessing the software performance when checking each software requirement.[25-29] The former is very difficult to implement owing to SM interactions, as it will be discussed in this paper. The aim of this method is to

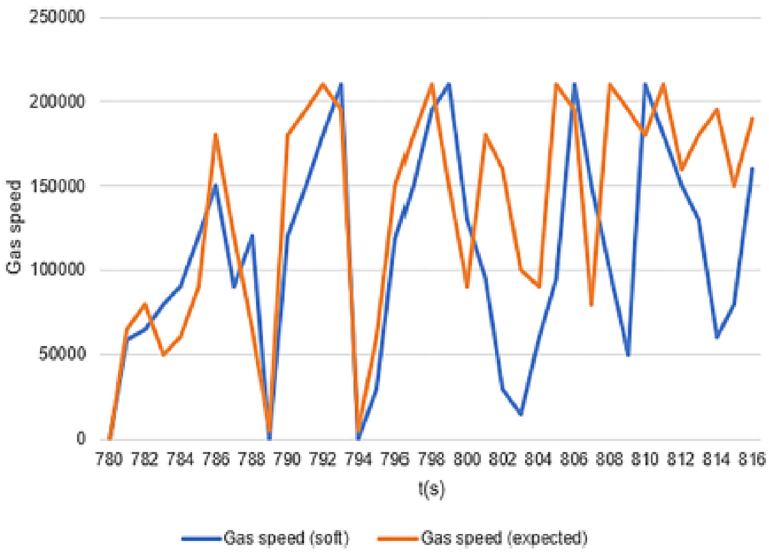


FIGURE 1 Bug not detected when using black-box technique

TABLE 1 Problems analyzed in this research

Limitations	Reason	Possible Solutions
Difficult to validate the software automatically	When the values set in the test case for the inputs are not reached, then the output values set in the test case may be no longer available. Consequently, no automatic validation can be performed.	DIls can perform this task as shown in this research as they recalculate the output values that the SM under validation should provide for the specific input values reached after the HIL simulation. Therefore, an automatic validation process can be carried out.
Possible bug performance detection improvement	If input values are different from the ones established in the test case, then the software performance behavior is unknown.	
Functional coverage unknown	A functional code coverage could be established by analyzing the black-box test cases before the HIL simulation. However, when reaching different values for the inputs after HIL simulations, then the use cases tested are different from the ones planned.	A performance rule-based EX can assess the functional coverage as exposed in this research. An EX can assess whether the SM under validation performances as expected or not, thanks to the rules used for its implementation. Thus, performance bugs could be detected. Considering the number of performance rules assessed, the functional coverage could be established.
Difficult to detect bugs linked to SMs that perform many calculations	The calculations may be performed wrongly, but they do not imply that the vehicle behaves in such a way that the client could detect any abnormality.	DIls can perform this task as shown in this research as they can be used for checking whether the SM under validation calculates all SM outputs properly.
Difficult to assess the code coverage accurately	There is no code model or something similar to use it for calculating the code coverage when using the black-box or similar techniques. It must be considered that there are many if-then structures in the software, which makes it extremely difficult to test all possible paths. However, the question is if the whole performance rules have been tested with a considerable number of software rules.	A software and a performance rule-based EXs can assess the functional and code coverage as exposed in this research. It can be employed to establish the code and performance coverage.

make the inputs reach specific values and check the outputs. The latter is widely used because the inputs of SMs do not need to reach exact values but approximate ones to check the software performance. As a result, it is more flexible.

The black-box technique has been used for a long time in the automotive sector, as discussed by Conrad.[30] Despite its widespread use, it is true that it has some weak points, as discussed by Chunduri.[31] In their dissertation, they consider that test cases based on the engineers' experience usually imply gaps and test redundancies. Thus, they proposed a methodology to improve the black-box technique and the test-case generation. To do this, they proposed to work on three factors: enhancing function requirements specification, establishing traceability across test levels, and obtaining comprehensive function test-coverage information. In addition, it is essential to remark that the test-case execution must not be too time-consuming. Consequently, more test cases can be run, and the code/functional coverage is improved. Some research has also been focused on this topic. Zhou et al proposed the optimized use of symbolic simulation with the aim of reducing the time required to generate a test case at the IEEE Conference.[29] As a result, given a model of a software function under validation, the time needed to cover the model will be reduced. Sopan-Barhate presented their theory about how to make the software validation process in the automotive sector more effective at the International Congress of Electronic Instrumentation and Control.[25] In their opinion, the main concerns linked to the software validation process are how to design representative test cases as well as how to prioritize the test-case execution based on priority levels, ensuring, at the same time, high code coverage rates. The solution proposed in their research is the use of orthogonal array testing.[†]

Model-based testing is a good technique to test SMs, and it allows the assessment of the code/functional coverage in an easy manner. Raffaëlli et al, at the Embedded Real Time Software and Systems Conference,[32] presented research focused on the usage of a functional model by running Matelo software.[33] The aim of this research was to accurately assess the code coverage, as all branches of the model could be tested. The application in an HIL simulation for a more complex ECU, such as an engine ECU, was not shown. Perez et al conducted a review on the current state-of-the-art techniques used for the verification and validation of embedded systems, including software developed in the automotive sector.[34] Their main conclusion shows the need of further research concerning automatic validation, safety tests, and model validations. In short, these concepts are clearly linked to the test-case generation and improvement in automation processes. The aforementioned aspects are analyzed in-depth in this research.

There are many ways for automating HIL simulation in the market.[35,36] The automation process is mainly based on black-box techniques such as those reported by Köhl et al: "As a rule, the tests specified by the ECU departments are first performed as black box tests on the network system (know-how on software structures is not taken)."[37] At the 52nd Congress of the ACM/IEEE Design Automation Conference, Petrenko and Nguena-Timo reported the main problems and solutions associated with software validation in the automotive sector, on the basis of the experience of General Motor Research and Development staff, powertrain software validation team of General Motors, and the Centre of Montreal

[†]"Orthogonal array testing is a black box testing technique that is a systematic, statistical way of software testing. It is used when the number of inputs to the system is relatively small, but too large to allow for exhaustive testing of every possible input to the systems. It is particularly effective in finding errors associated with faulty logic within computer software systems."

Research Informatics.[38] Their main conclusion was focused on the methodology known as the "tester-in-the-loop," in which the test engineer leads the system to a desired operation point, considered as a crucial one, with the aim of assuring the correct execution of the test case in such a way that the software behavior can be assessed. Once the crucial point is reached, a series of automated actions are executed to reach the goals previously established in the test case. Tatar and Mauss proposed at the ERTS Congress: Embedded Real Time Software and Systems the possibility of not using HIL simulation. Instead, by using a virtual platform, engine ECU software could be validated, thanks to the interaction with a car model.[39] As a result, many points could be tested. All the possible issues or bugs linked to the software integration on the hardware would not be detected. Koopman and Wagner exposed the main future issues when it comes to software validation in the Society of Automotive Engineers Congress.[40] One of the most important concepts introduced in their dissertation was the "driver-out-of-the-loop" concept. Currently, the ECUs are validated by considering the driver's actions on the vehicle (accelerations, braking, etc). If the vehicle is autonomous, these driver's actions are not relevant, and some external factors such as traffic and pedestrians must be considered to validate the software. As a result, they consider machine learning techniques as a key aspect in the future.

2 | METHOD

2.1 | Description

The aim of this research is to validate the following hypothesis:

> *Two EXs working in cooperation perform better than traditional techniques when validating an engine ECU software. In addition, two EXs can overcome the difficulties depicted in Table 1.*

To do this, a series of test cases are run by using the following techniques: the cause-effect one,[‡] the model-based testing one, one EX combined with dlls, and finally, two EXs combined with dlls by using the HIL simulation. Then the following parameters are measured for each technique to validate the hypothesis: code and functional coverage, productivity, bugs found, and automation process success.

2.1.1 | Data used in this research

The methodology proposed in this study has been tested in three types of functions or SMs chosen according to the number of calculations to be done as well as their complexity, number of inputs and outputs of the SM, and the accuracy required for the output resultsThey have been considered as representative for this case study by the authors and the company subjected to this research. Considering the experience of the company that is the subject of this case study, three types of SMs or functions can be distinguished as shown in Table 2.

It is important to establish this classification because the validation requirements as well as the characteristics of the SM clearly influence the time required to carry out the validation process, as well as the additional difficulties that may arise. For instance, some complex SMs imply that many kilometers must be covered. However, other SMs are quickly validated as they only require a few manipulations to make the engine ECU reach the desired operating point. Subsequently, five SMs of each type were selected, on the basis of different criteria such as test engineers' experience, the most problematic SMs in other projects, SMs that require systematic validations to ensure the vehicle safety, SMs that require frequent regression validations as well as those SMs that have never been implemented in previous projects and, in short, they are a novelty (see Table 2). Test engineers of the company subjected to this case study considered that the analysis of 15 SMs is sufficient to evaluate different methodologies according to their experience.

When generating test cases, three strategies were followed in this research:

1. Generating pseudorandom values for the SM inputs under validation in such a way that all paths of the models that belong to EXs are covered. For each combination of the inputs, the performance EX must assess the expected behavior of the vehicle (represented by an HIL bench) in cooperation with a software EX that will cover a software model to assure a high code coverage. The right outputs for all inputs generated in the test case are known by using the dlls. All aforementioned statements are exposed in Section 2.1. In this research, as exposed later, manual test cases were also generated in order to cover the functional and software models.
2. The company under this case study has a database in which the staff document different bugs found throughout the engine project. The main advantage of this process is to guarantee easy mainstreaming between projects. All data stored in this database are handled in meetings with the supplier responsible for coding the software and designing the hardware on a weekly basis. Test engineers design test cases on the basis of different inputs such as this database, functional defects found during driving tests, specifications requirements, as well as the defects found when the engine has been marketed. The goal is to keep the test-case libraries as complete as possible over time. When the test engineer has designed the test-case library for a specific SM, a validation process is carried out. The test engineer and the designer of the SM verify whether

[‡]This technique is used by running the test cases manually, fully automated or by using the tester-in-the-loop technique.

TABLE 2 Types of SM presented in the ECU software

Type of SM or Function under Validation	Characteristics	Validation Requirements	SM
Simple	(a) A reduced number of input and output variables present in the SM. (b) Small number of calculations to be done. Furthermore, they are not complex. (c) High accuracy needed for calculations in some cases. (d) Easy to identify the main functional characteristics of the SM. They are also easy to test by using an HIL bench.	SMs require a few manipulations to make the engine ECU reach the desired operating point. For instance, the SM in charge of detecting whether the accelerator pedal is blocked. The engine ECU must check a few parameters (brake and accelerator pedal state and the vehicle speed).	Such as: Temperature estimators Brake pedal monitoring
Fairly complex	(a) High number of input and output variables present in the module. (b) Moderate number of calculations to be performed. (c) Moderate accuracy needed for calculations. (d) Difficult to identify the main functional characteristics of the SM.	SMs require more manipulations to make the engine ECU reach the desired operating point. For instance, SMs related with treatment of exhaust gases.	Such as: Treatment of exhaust gases systems Torque engine limitation owing to the temperature of an engine component
Highly complex	(a) High number of input and output variables. (b) High number of calculations. (c) Calculation not necessarily complex. (d) High number of functional calculations. (e) Moderate/low calculation accuracy.	SMs need weeks to reach the desired operating point. For instance, the SM in charge of assessing the diesel dilution rate in the engine oil. If the dilution rate exceeds a threshold set by the manufacturer, the oil properties can be degraded and, thus, the engine may be damaged. The engine control unit decides how many kilometers the vehicle can cover depending on the dilution rate parameter. This decision could be made after the car has driven 20 000 km.	Such as: The SM in charge of controlling the oil rate diluted into diesel Torque structure

the use cases presented in the test-case library are representative enough. For each of the test cases presented in the database, it is possible to assign values to the SM inputs with the aim of checking the software rules.

3. Pseudorandom values are generated by Matelo software with the aim of covering the whole functional model. It must be reminded that this technique is an equivalence portioning one. As test cases are generated by Matelo, the functional model is covered. Matelo assesses the functional coverage automatically. Matelo could also be used to implement a software model. However, authors have not carried it out in this research.

Table 3 shows the number of tests considered in this research according to the type of SM.

The difference between the number of test cases for each type of SMs is because the fairly complex SM involves a greater number of use cases.

Table 4 indicates the methods followed to generate test cases for each technique.

TABLE 3 Number of tests used in this research

Type of SM	Number of Test
Simple	250
Fairly complex	1250
Highly complex	100

TABLE 4 Methods to generate test cases

Technique	Method
Cause-effect technique	A1
Model-based testing	A2
One EX combined with dlls	A3
Two EXs combined with dlls	A3

A1: A database in which the staff trace different bugs found throughout a project. In addition, several test cases come from the software requirements.
A2: Pseudorandom values generated by Matelo to cover a functional model.
A3: Pseudorandom and manual values generated by Python scripts.

It is important to analyze what A2 and A3 mean. In A2, Matelo can generate off-line (before the HIL starts) all necessary test cases with the aim of covering the functional model. In A3, Python scripts also generate test cases trying to cover the software model. The Python scripts generate pseudorandom values trying to reach software states not implemented in the model as exposed in Section 2.2. A software state not implemented in the model involves a use case not considered by the design team, in other words, a design error. In addition, a test engineer generates manually off-line test cases by establishing the most likely combination of variables by using fuzzy values to cover the functional and software states. This process consists of avoiding illogical situations such as engaging the fifth shift when the vehicle is at 5 km/h. These inconsistencies must also be taken into account when generating automatically test cases by using Python scripts. The fact of using fuzzy variables, as exposed later, allows increasing the combination of the inputs of the SM under validation. These test cases generated manually are run by using Python scripts.

For confidentiality reasons, the list of test cases cannot be published. However, Table 5 shows examples of test cases that could be used to check some functionalities of the software by using different techniques. It is important to remark that fuzzy variables are used when using EXs combined with dlls by increasing the number of combinations of the inputs provided by the SM under validation.

2.1.2 | Equipment

The following means used in this research are shown in Table 6.

2.1.3 | Methodology proposed

In this section, the key elements used in this technique are presented (EXs and dlls). Then, the process how they collaborate to run a test case is described.

TABLE 5 Examples of test cases

Feature to Be Checked	Actions to Be Done	Expected Results	Technique
Body control unit. Cyclic redundancy check invalid	Set a CRC invalid value of the frame BCM_A1	Check the inhibition of adaptive cruise control and stop and start function.	Cause-effect Model-based testing
Diesel particulate filter regeneration	1. Var1_veh_started = TRUE → Start the vehicle 2. Var2_temperature_exhaust_gas = 600°C → Do a driving cycle 3. Var3_vehicle_speed = 80 km/h → Press the brake pedal to reach 40 km/h 4. Var4_particulate_filter = 40 g → Do not overpass 2000 rpm	When the RG is performing the variable var1_out is activated.	Model-based testing
Diesel particulate filter regeneration	1. Var1_veh_started = TRUE → Start the vehicle 2. Var2_temperature_exhaust_gas = High → Do a driving cycle 3. Var3_vehicle_speed = High → Press the accelerator pedal to reach low speed 4. ar4_particulate_filter = High g → Do not overpass average rpm	When the RG is performing the variable var1_out is activated.	EXs combined with dlls

TABLE 6 Equipment used in this research

Item	Description	Phase Where the Item Is Used	Cost	Alternative
Software and hardware	An engine ECU software and hardware designed by the company subjected to this case study and by one of the most important European suppliers specialized in embedded systems.	It is mandatory no matter which technique is considered. Used during this research in all phases.	Confidential	–
HIL bench	HIL bench manufacturer dSpace, model dSpace Simulator Full-size.[41] Versatile HIL simulator capable of emulating the dynamic vehicle behavior.	Every time a test case is run. Necessary for the HIL simulation no matter which technique is used.	Depending on the characteristics of the HIL bench, the price can vary. Estimation for this case study: €100 000 each bench.	Mandatory to perform the HIL simulation. One can choose platforms such as Silver to test the software without using the HIL simulation.[42] However, the software and hardware integration are not tested.
INCA version 7.1.9 provided by ETAS (BOSCH)[43]	Software used to make measurements of different software variables stored in the engine ECU memory.	Every time a test case is run. Necessary for the HIL simulation no matter what technique is used.	The price depends on the number of licenses. For a big car manufacturer, an estimation of €5000 for each license can be made.	There are other alternatives proposed by other suppliers such as dSpace. Despite this, an ETK module provided by ETAS (assembled on the ECU) is always necessary.[44] That is why, most car manufacturers use INCA software.
Matlab R2013 and Microsoft Visual Studio 2015	Software necessary to create dlls	Every time a test case is run and the user wants to avoid the SM interaction problem.	The price depends on the number of licenses. This information was not provided by the company subjected to this case study.	There is no alternative as all the specifications used for coding the engine ECU software are designed by using Matlab. Dlls are generated from the model. Consequently, there is no option. Regarding Microsoft Visual Studio 2015, other compilers may be used. However, several errors were detected when building the dll. Matlab support advised the authors to use Microsoft Visual Study as a compiler.
Matelo	Software used for validation purposes being able to generate test cases.	Necessary to generate test cases when using the model-based testing technique.	The price depends on the number of licenses. Estimations of 20 licenses are €100 000.	By coding in Python, it is possible to create functional models and test cases. This option is not useful considering the time needed (not compatible with an engine software development planning).
Python scripts for automating the validation process	Python code needed to run a test case.	Used for all techniques employed in this research when automating test cases.	For free	AutomationDesk software.[45] This option was discarded as it is not for free. It must also be taken into consideration the staff's skills necessary to use AutomationDesk.
ControlDesk version 5.1 from dSpace[46]	This software is needed to build the HIL model that belongs to dSpace manufacturer. The HIL model was built by the company subjected to this case study.	No matter which technique is considered.	No information about cost was provided by the company subjected to this case study.	There is no alternative as the HIL bench used in this research came from dSpace supplier.

a. Expert systems

Two EXs are distinguished:

- Software EX

Its aim is to establish the software rules that must be applied to assure the software operation, such as a sequence of updating variables to be followed when a failure occurs. A software rule is a Simulink path to be followed to reach a specific operation point.

- Performance EX

The second EX is responsible for checking whether the vehicle responds as expected for a specific use case. It is important to establish the difference between the two systems. The first EX only verifies if the software rule is applied. The other one is abstracted from the software and only focuses on the fact of verifying the correct behavior from vehicle performance point of view. Properly coded software may exhibit wrong behavior owing to design errors as some use cases were not considered in the specifications used for coding the software.

- Dlls

As exposed in Section 1, it is highly unlikely to reach the operation point set in the test case because of SM interactions.[47] This fact implies that the automation process is not easy to be performed. Figure 2 depicts the process to automate a test case by using Python scripts. During the HIL simulation, the script is in charge of performing all the necessary manipulations on the driver-ECU interface model (Figure B2[§]) automatically. During this process, a data acquisition is performed by employing the INCA software. If these values are not reached after time out elapsed, the data acquisition is stopped and the dll is called. The dll represents the Simulink model of the SM under validation, and it allows assessing and providing the expected values of the SM for a specific state of the ECU. Thus, by using dlls, it is always possible to obtain a result after an HIL simulation. Thanks to this data acquisition and a C-file, it is possible to call the dll as shown in Section 2.3 where the reader can find some information about the practical implementation of this technique.

- EXs and dlls working in collaboration

Figure 3 describes the process.

- Phase 1. The software EX establishes the test case to be run as described in Section 2 (Table 4). It must be reminded that a rule corresponds to a Simulink path of the model of the SM under validation. This rule is communicated to performance EX with the aim of establishing the performance rule to be applied during the HIL simulation, in other words, the expected software behavior.
- Phase 2. The HIL simulation is performed trying to reach the operation point established in the test case.
- Phase 3. A test case is composed of a series of input values and the expected outputs. If the specific operation point is not met after a specific time elapsed (time out), then the expected output set in the test case may not be longer valid. The dll of the SM under validation allows assessing the right output values for the current engine ECU state. The software EX collects this information and assesses the software rule that was tested after the HIL simulation.
- Phase 4. The software EX sends a message to the performance EX about the software rule tested in such a way that the performance EX can update (if needed) the expected software behavior.
- Phase 5. Both EXs checked the HIL simulation results and decide whether the software behavior is correct and meet the specifications.

2.2 | Validation of the key elements: EXs and dlls

This section describes the validity of the different key elements involved in this research.

[§]It is recommended to read Appendix B to understand the HIL simulation process.

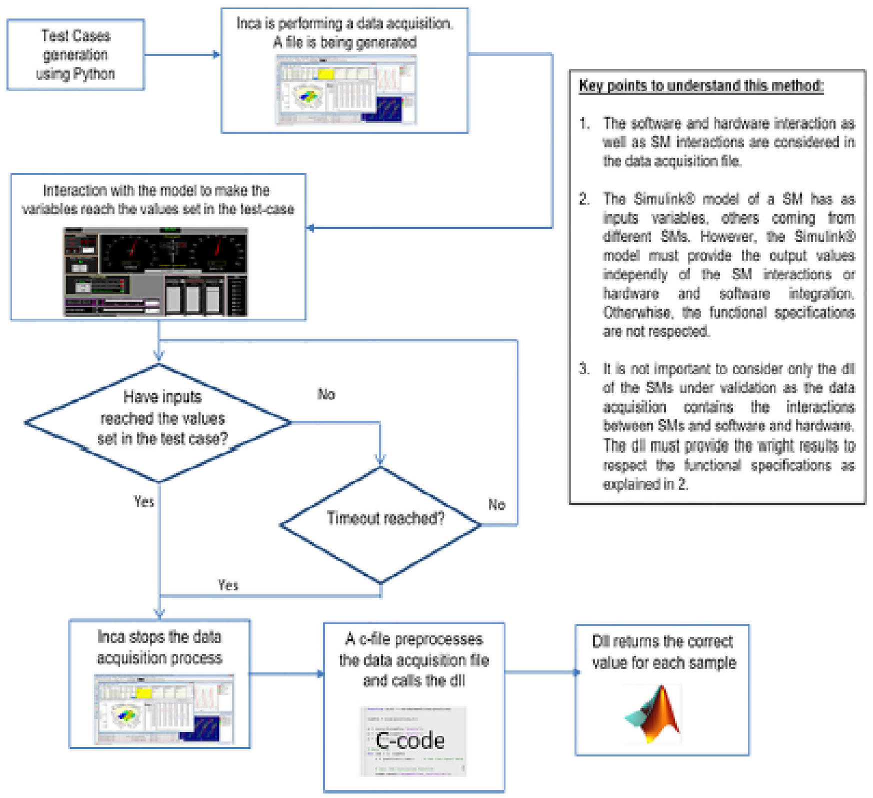


FIGURE 2 Use of dlls in an HIL simulation when performing a test case

2.2.1 | Expert systems validations

In this research, the aim of the rule-based EXs is to check whether the software runs properly, carrying out an automatic analysis of the HIL simulation results. The EX design is shown in Figure 4. As shown, there is a knowledge base composed of rules coming from functional or software requirements set by experts and designers at the beginning of the project.[48] These rules are the base of the expert knowledge. When it comes to the inference engine, it is composed of a functional or software models describing different states that the system can process when applying the rules presented in the knowledge base. It must be reminded that two EXs are designed for each SM under validation.

a. Software expert system

The aim of this EX is to check whether the software meets software specifications. To better understand this, Figure 5 must be analyzed. One can see a software model of a given SM, where S1 to S6 represent a state. In this case, the state represents a part of the Simulink model. The conditions to be met to pass from one state to another one come from the Simulink model used to code the software. As a result, depending on the HIL simulation, the values of the software variables of a given SM are analyzed in such a way that the final state is set. By checking different states covered after having executed a certain number of test cases, it is easy to have the first estimation of the code coverage. As exposed in the performance section, a test case could be run and the inference engine may not know in which software state the system is. This fact can occur, and it happens when a use case has not been considered by the design team. That is why all states in Figure 5 are linked to state 6 as it represents an unknown software state.

To obtain an accurate code coverage, two key actions have been performed in this research:

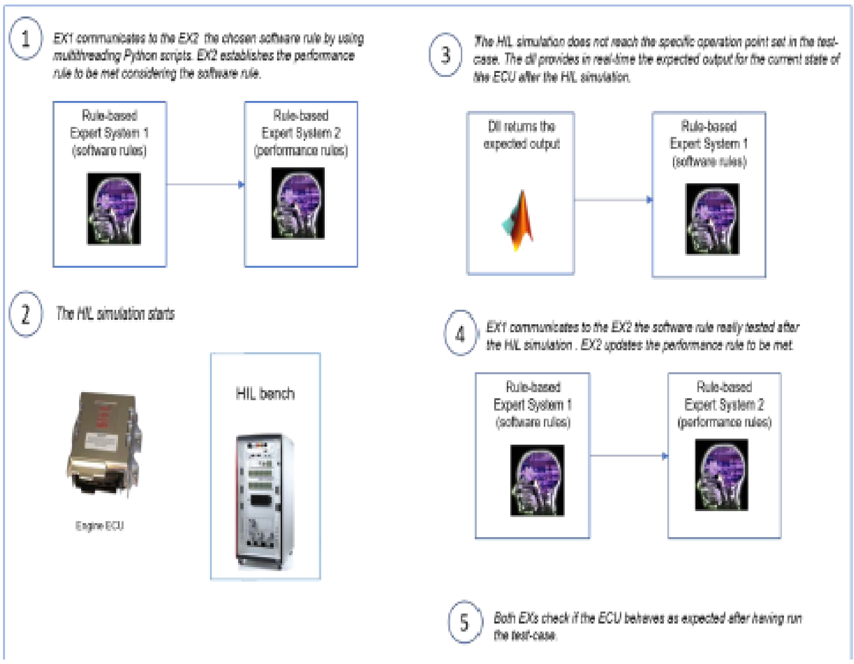


FIGURE 3 EXs working in cooperation

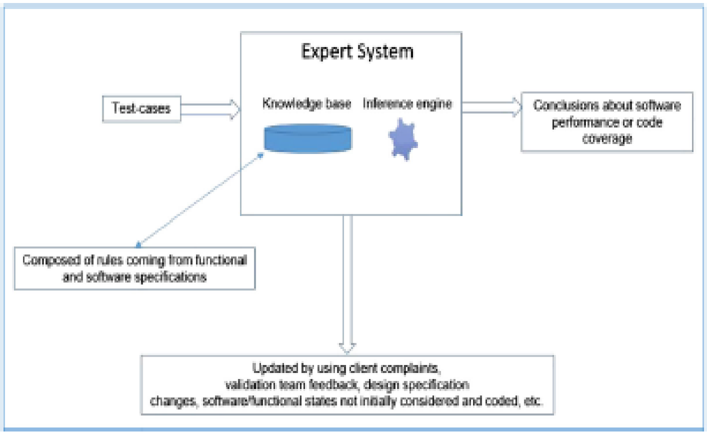


FIGURE 4 Scheme of the EXs used in this research

1. Generation of test cases in such a way that the range of possible values for a given variable is divided into intervals.[49] In this way, the probability of covering all paths of the Simulink model is increased.
2. Usage of as many states as necessary to describe the system.

These topics will be analyzed in Section 3.

3. Performance expert system

The performance EX is built by using functional states in which the vehicle can operate. Therefore, the model is not focused on part of the Simulink model of the SM under validation. The fact of covering the functional model allows assessing the functional coverage but not accurately

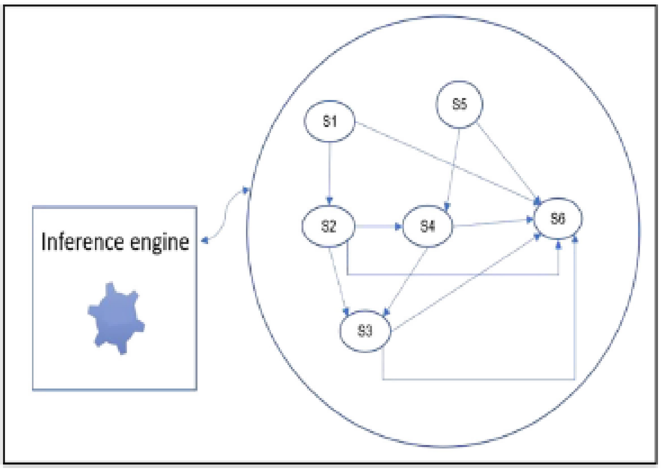


FIGURE 5 Inference engine in detail

as depicted in Figure 6, when assessing the transition from S2 to S4; it is unknown if the value for Out1 was obtained following the path 1 or the path2.

When a test case is analyzed by the performance EXs, after having applied different rules, the inference engine determines the state of the system. Therefore, the EXs decide whether the outputs provided by the software are coherent for the test case simulated. At this point, it is vital to verify in-depth the inference engine (Figure 5). As shown, all functional states (S1, S2, S3, S4, and S5) are related to a state called S6. S6 corresponds to an unexpected or unknown state, which represents a use case not considered by the designers. By using this state, test engineers can improve the EXs if needed. The S6 state will be analyzed in Section 3. In this research, the EX code is not provided as it belongs to the company's know-how and is confidential.

The validation process of both types of EXs is stimulated following these two phases:

- The established rules, used by the EX, are checked following a procedure consisting of a meeting between designers and testing engineers to assure the conformity of the EX. Then, the EX is implemented by using Python.
- The aim of the validation process is to check two key characteristics: firstly, to assure that the rules presented in the knowledge base are coherent and secondly, to verify that the EXs can assess the software performance properly. To do this, a set of data acquisitions, already analyzed by test engineers, is used for the aforementioned purposes. These data acquisitions came from the following:

1. HIL validation results that were performed manually by technicians and

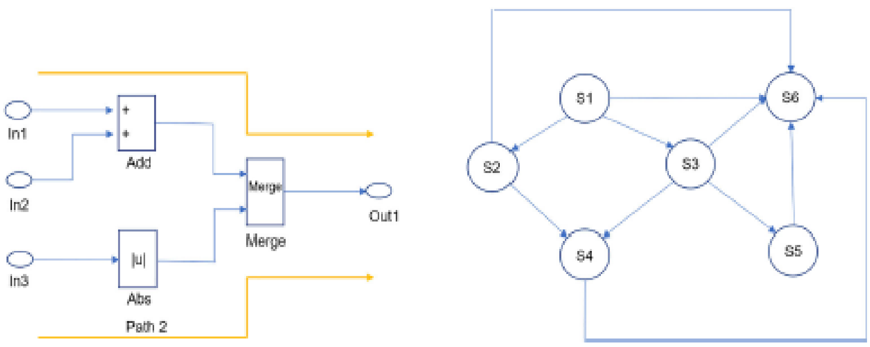


FIGURE 6 Scheme of a software EX used in this research

2. test driving results carried out in different parts of the world to check the ECU behavior when operating in altitude and extreme cold and hot weather.[50]

2.2.2 | Dynamic-link library validity

Dlls are a key element of this research. The reader may think that the fact of using dlls could keep the validation process from checking the SM interactions. This statement is not true for several reasons:

1. The effects due to inputs and outputs of SM interactions are collected in the data acquisition file as it is the result of the HIL simulation.
2. It is essential to distinguish some important points when it comes to designing the engine ECU software. Before integrating the software into the hardware, there is a process of building prototypes with the aim of checking whether the Simulink models work properly. Once this is checked, the decision of integrating software and hardware is made. Afterwards, the design specifications are written, all the SMs are assembled, and finally, a software is coded and the validation process starts. Therefore, the Simulink models are the transcription of the functional specifications of the engine ECU and must be met independently of the SM interactions, hardware design, task scheduling, software-hardware integration, etc. In addition, Simulink models are tested before sending the specifications to the supplier in charge of coding the software. Therefore, for a series of given inputs, the outputs provided by the Simulink models must be equal to the ones provided by the engine ECU software when no bug is discovered. Otherwise, the functional specifications are not met.
3. The fact of only considering one dll corresponding to the SMs under validation does not imply that software and hardware integration is considered as the inputs processed to the dll are the consequence of an HIL simulation. Therefore, the SM interactions are already considered in the data acquisition file. The software must provide the same output values as the Simulink model (dll). Otherwise, the functional specifications are not met.

2.2.3 | Measurement conditions

Before starting the HIL simulation, some conditions must be met. Otherwise, the result is rejected:

- The information provided by the probes must be equal in all cases (with and without dlls) when it comes to external factors such as air and pressure temperature and slope of the road.
- The engine ECU memory must contain no errors before starting the HIL simulation. If it does, then it must be erased by using the procedure established by the ECU supplier.
- All test-case executions must be conducted on the same HIL bench. This factor is important to assure that the same probes are being used during the whole research.

If a diagnosis defect appears when validating with dll and not when validating without dlls, or vice versa, then the test-case result is rejected and it must be executed again as the HIL model could have failed.

2.3 | Practical implementation

A key issue in any project is costs. Therefore, costs must be reduced as much as possible. Therefore, in this research, it has been tried to implement software validation by using Python packages. Each test case is run by using Python scripts and C-code. Firstly, as exposed in Section 2.1.3, the test case is performed by using Python scripts that interact with the HIL model with the aim of reaching the values established in the test case (see Appendix B). During this process, a data acquisition is completed in ascii format. Secondly, a C-code is used to call the dlls and to assess the software behavior.

2.3.1 | Python scripts when using two EXs

From a pseudocode point of view, a multithreading implementation was conducted. One can find the thread responsible for generating software rules that will be sent to two threads: the one in charge of automation control and the one that handles performance rules (Figure 7). The process is as follows. A software rule is chosen, and consistent inputs values for the variables involved in such rule are generated. Then a message is sent

```
Thread for controling expert system 1

rule= select_rule()
data_for_automation=generate_data_for_the_rule(rule)
send_message_expert_system_2()
wake_up_thread_automation()
waiting_for_automation_result()
if automation_OK then
    send_confirmation_message_expert_system_2()
else
    send_message_expert_system_2()
end
```

FIGURE 7 Pseudocode of software EX thread

to the EX 2 to set the rule to be applied according the one chosen by EX 1. Once done, the automation process can be conducted using an HIL simulation. EX 2 thread is waiting for the result. The automation thread sends a message indicating if the result was correct, that is to say, whether the system reached values close to the desired operating point. If so, the EX 1 communicates to EX 2 that the selected rule was correct. Otherwise, the EX 2 updates the performance rule to be applied according to the operation point that was reached in the HIL simulation.

The second thread is in charge of controlling the automation process (Figure 8), which starts when the EX 1 thread establishes the software rule to be tested (Figure 8 *waiting_message_from_expert_system_1*). Once the process starts, the automation thread tries to lead the system to the desired state set by the EX 1 thread. The automation process ends

a. when this operating point is reached. In this case, the software and performance rules for both EX must not be updated (Figure 7 *automation_OK*)
b. when a time out elapses as the operating point is not reached because of SM interactions. In this case, the software and performance rules initially chosen might be updated (Figure 7 *else*).

Finally, thread 3 is responsible for managing the performance EX (Figure 9). Its practical implementation is extremely simple, as it only runs when it is allowed by the EX 1. This can take place in two distinct situations: firstly, when the thread is instructed to select the rule to be applied according to the one set by EX 1 and secondly, when it is indicated to proceed to update the rule depending on the final engine ECU state, once the process of the HIL simulation is completed.

To implement a cross-thread communication, a submodule *event* from the Python threading package was chosen. Its main advantage is its ease of use. Using the *wait()* and *set()* methods, it is possible to keep a thread waiting while another performs other tasks. When the latter ends, using the *set* method, an event occurs to wake up all paused threads. In this case, its use is essential for several reasons:

```
Thread for controling the automation process

waiting_message_from_expert_system_1()
while time < time_out
    control_HIL_simulation()
end
sending_current_status_to_expert_system_1()
```

FIGURE 8 Pseudocode of automation thread

```
Thread for controling the expert system 2

waiting_message_from_expert_system_1()

select_rule()

waiting_message_from_expert_system_1()

update_rule()
```

FIGURE 9 Pseudocode of performance EX thread

1. The automation thread and the EX 2 threads must not start calculations until EX 1 has been initialized.
2. The thread in charge of handling EX 1 must not continue its execution as long as the automation process is finished.
3. The EX 2 thread must not continue its execution as long as a confirmation about the current status of the ECU done by EX 1 is received. The main raison is that a rule updated could be necessary.

2.3.2 | Dynamic-linked libraries

The implementation of dlls allows the use of the Simulink model on multiple computers without additional cost. The dll can be implemented by following the steps indicated in many Mathworks documentation available in their site. The only thing that the user really needs is the Simulink model to be converted into a dll. In this case, these models are available as they are sent to the supplier to code the software. As described in Matlab documentation, the dll can be called by using different programming languages. In this research, C-language has been used. This process is depicted in Figure 10. Firstly, when a test case is run, different software variables chosen by the user are recorded by using the INCA software (see Section 2.1.2). The result of this process is an ascii file that contains the variables (inputs and outputs of the SM under validation) and the specific time when each measurement was performed. Secondly, the ascii file is read by using a C-file in such a way that each line of the file is used for calling the dll (see phase 2, Figure 10). The dll must return the expected output for the inputs used to call the dll. Finally, a comparison is performed as depicted in Figure 10, phase 3. It must be reminded that the outputs of the SM are also available in the ascii file.

2.3.3 | Python scripts for the rest of applications

When using other techniques such as the model-based testing or the tester-in-the-loop ones, the number of Pythons scripts is reduced as only one script is needed to control the automation process of the test case. The aim of this script is to assure that the values established in the test case are reached despite the SM interactions. The process to call the dll described in Section 2.3.2 must be performed.

2.4 | Limitations

The main weak point of the method reported in this research is that the Simulink models are not always available in an engine ECU project for all SMs present in the software. This issue takes place especially in SMs designed and coded by the supplier as well as when validating networks such as CAN and LIN. Despite this, in this research, only roughly 7% of the SMs did not have a Simulink model. The reader could consider how the conformity of dlls is assured. However, if there is an error design in a Simulink model, this error will also be found in the software. Therefore, when doing the validation, there will be no difference between the outputs provided by the Simulink model and the software. However, it must be reminded that the conformity of Simulink models is checked in the software design process.[47] In addition, the performance EX can detect this situation, as discussed in Section 3.

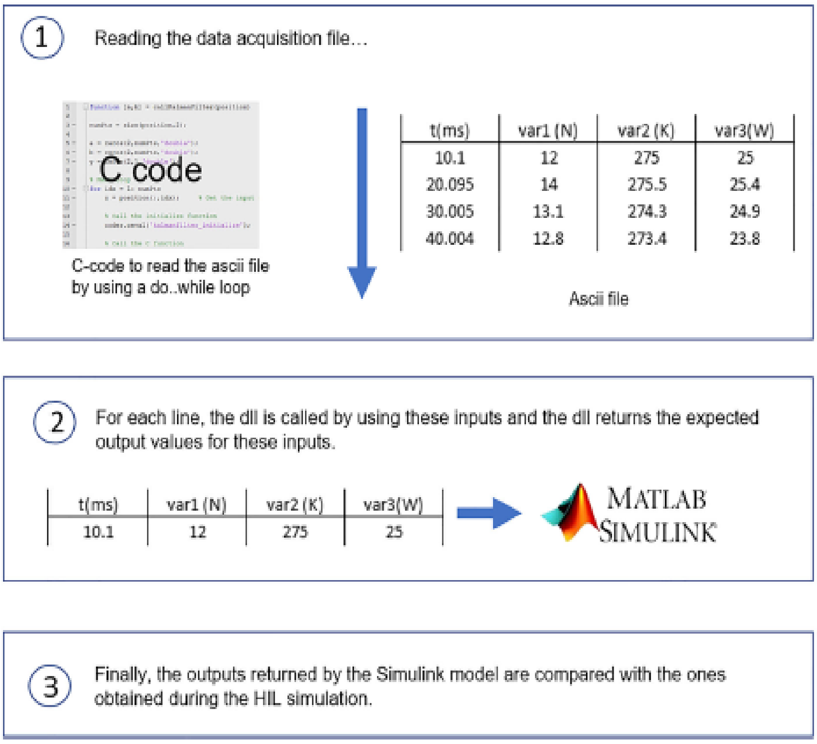


FIGURE 10 Interactions between the C-code and the dll

3 | RESULTS

The aim of this section is to analyze the results obtained during this research by doing a comparison between different techniques. Several topics are discussed such as the code and functional coverage, bug detection, design time, and the dll performance. All these factors are explained in Table 7.

3.1 | Functional coverage

The functional coverage would be evaluated as Equation (1). This equation is widely used in the automotive sector as it allows assessing the functional coverage in an easy way by using the software requirements. Table 8 depicts the total number of functional requirements linked to the SMs chosen for this research (Section 2.1.1).

$$FC = \frac{\text{Number of software requirements tested by a technique}}{\text{Number of software requirements indicated in Table 8}} \times 100. \quad (1)$$

Table 9 shows the results obtained for each technique.

3.1.1 | Cause-effect technique

The aim of the cause-effect technique is to check that the software requirements established at the beginning of the engine project are met. The test cases used in this technique are similar to the one shown as an example in Table 5. They come from a database in which the staff document different bugs found throughout the engine project as indicated in Section 2. In other words, all test cases are based on the experience of the company subjected to this case study. These test cases can be run by using a manual execution or can be automated by employing Python scripts.

The main limitation of the cause-effect technique is test-case redundancy as reported by Chundur.[31] This research confirms this statement. After having analyzed the test cases run by using this technique, the authors found many of them that tested the same software requirements. As exposed later, the root cause linked to this fact is the lack of functional models of SMs under validation. It must also be added that some

TABLE 7 Factors analyzed in this research

Factor	Definition
Code coverage	Number of Simulink blocks tested when an SM has been validated.
Functional coverage	Number of functional states covered when an SM has been validated.
Bug detection	Capacity of each technique to detect bugs.
Design time	Total time needed when using a specific technique. It comprises the total time for designing test cases, for coding and designing different elements such as EXs, time needed to execute a test case and validate the results.
Dll performance	This research aims to prove that dlls allow improving the automating process. This indicator is called dll performance showing the HIL results when using and without using the dlls in an HIL simulation.

TABLE 8 Number of total functional requirements

Type of SM	Number of Requirements
Simple	75
Fairly complex	400
Highly complex	510

TABLE 9 Functional coverage obtained for each research

	Simple SM		Fairly Complex SM		Highly Complex SM	
Technique	Number of Rules Tested	Functional Coverage, %	Number of Rules Tested	Functional Coverage, %	Number of Rules Tested	Functional Coverage, %
Cause-effect	64	85.3	312	78	357	70
Model-based testing	64	85.3	312	78	357	70
Performance EX combined with dlls	68	90.7	348	87	445	87.2
Software EX and performance EX combined with dlls	71	94.6	360	90	465	91.2

use cases not considered initially in the software requirements cannot be detected by the cause-effect technique. In addition, bugs linked to calculation errors (see Figure 1) cannot be found.

3.1.2 | Model-based testing

As already exposed in this research, a functional model is built by employing Matelo software. In addition, this software is able to generate test cases with the aim of covering the whole functional model. The functional coverage can be calculated easily by using Equation (1). Moreover, this technique allows detecting use cases not considered initially in the software requirements.

When using Matelo (the model-based testing technique), it is important to expose the problems found during this research. If the test engineer let Matelo generate test cases, this software will assign specific values for each input of the SM under validation. As a consequence, the problems of SM interactions are identified. That is why this strategy could not be used. To face this issue, one can use dlls combined with Matelo. In this case, Matelo will not generate the test case, but it will control the automation process. In order words, the test engineer must code a Python script to generate the test cases needed, and then Matelo will check the functional states covered as the automation is performed. In the present research, the test engineer codes Python scripts with the aim of running the same test cases as for the manual execution, the tester-in-the-loop, and so on. Therefore, the test cases are present in the database that is mentioned in Section 2.1.1.

3.1.3 | EXs combined with dlls

The software performance is assured by using an EX capable of detecting whether the software behaves properly when a test case is conducted. As discussed earlier, the unexpected behavior can come from a coding fault or design error. In both cases, the performance EX can detect them. The design process of the EXs was discussed in-depth in Section 2.2.1. Therefore, the results obtained when validating the EX are analyzed in this section. As done in the previous case, a validation and a test phase were performed. The main problems obtained for the former phase are depicted in Table 10.

When the errors indicated in Table 10 were corrected, the EX was assessed during the validation phase. In this case, the same number of test cases used when validating the software EX was performed. The acceptance process was the same as reported in the software EX validation process (Table 11).

When using a performance EX, in addition to the test cases depicted in Table 2, a certain number of test cases were conducted by assigning pseudorandom values to the inputs of the SMs: 25 for 20 simple SMs, 5 for fairly complex SMs, and 2 for highly complex SMs. Table 12 depicts the results obtained.

When both EXs are used together when performing an HIL simulation, the final results are enhanced, as more rules are checked as shown in this section (Table 13). The main reason behind this fact is that the higher the code coverage of the software EX, the higher the functional coverage obtained when carrying out HIL simulations. Therefore, it is essential that they work in cooperation. Another aspect that must be analyzed is why 100% functional coverage is reached when the software code coverage is not 100%. This fact can be easily explained as a specific variable can be activated by different software paths of the Simulink model. Figure 11 shows how output Out1 can be activated by two different paths. That is why the functional coverage is 100% but not code coverage. This fact supports the conclusion that the number of subintervals is essential to get a high code coverage.

TABLE 10 Errors detected when validating the EXs

Type of Error	Cases	Percentage	Explanation
Wrong syntaxes	6	5.5	Because the rules used to design the EXs are extremely complex, the programmer made coding errors.
Incoherence among rules	2	1.8	In some cases of wrong performance of the EX, incoherence between rules was found.
Misunderstanding of technical specifications	3	2.7	Because of innovative evolutions in some parts of the engine, some technical specifications were not understood properly.
Rules not coded or forgotten	1	0.9	This type of error was made owing to the same misunderstanding of technical specifications.

TABLE 11 Most important points checked during the validation meeting

Most important factors considered to validate the expert system
All safety concepts (ISO 26262) were modeled or considered in the EX.
All diagnoses that may be detected by the engine ECU during the validation process were considered in the EX.
The number of states is considered sufficient and representative enough by the project team.
All use cases are modeled and considered in the EX (a priori).
The transitions among all the states considered in the EX are defined and modeled properly.
The feedback of other projects was considered in the EX.

TABLE 12 Code coverage when an EX is used

Type of SM	Number of Rules	Number of Functional States Tested Not Checked When Using an EX	Functional Coverage
Simple	75	7	90%
Fairly complex	400	52	87%
Highly complex	510	65	87.2%

TABLE 13 Number of rules or functional states not checked when an EX is not used

Type of SM	Number of Rules	Number of Functional States Not Checked When Using Both EXs	Software Code Coverage	Functional Coverage
Simple	75	4	94.6%	100%
Fairly complex	400	40	90%	95%
Highly complex	510	45	91.2%	94%

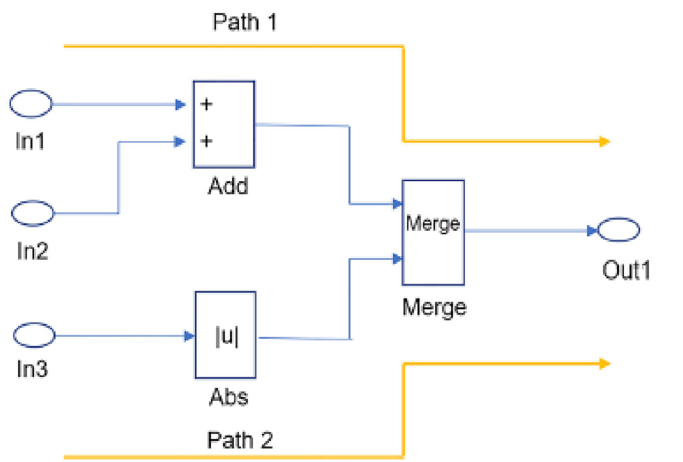


FIGURE 11 Activation of a specific variable

3.2 | Code coverage

The supplier responsible for coding the engine ECU software starts from the specifications composed of complex models that are provided by the car manufacturer. Thus, it is extremely difficult to reach a code coverage close to 100% as reported in previous research.[31] In addition, the validation process must be compatible with the project time frame. In order to assess the code coverage, Equation (2) was used, which establishes the relation between the total number of Simulink blocks to be tested (Table 14) and the total number of Simulink blocks tested.

$$FC = \frac{\text{Number of Simulink blocks tested by a technique}}{\text{Number of Simulink blocks indicated in Table 14}} \times 100. \quad (2)$$

The results obtained for each technique are shown in Table 15.

3.2.1 | Cause-effect technique

After having run all test cases to assess the functional coverage (Section 3.1), the number of Simulink blocks covered was calculated following Equation (2). It must be reminded that the code coverage is lower than the functional coverage because a specific software output can be

TABLE 14 Number of total Simulink blocks[a]

Type of SM	Number of Requirements
Simple	80
Fairly complex	350
Highly complex	530

[a]When a state flow is present, each state is considered as a Simulink block.

TABLE 15 Code coverage obtained for each research

	Simple SM		Fairly Complex SM		Highly Complex SM	
Technique	Number of Rules Tested	Functional Coverage, %	Number of Rules Tested	Functional Coverage, %	Number of Rules Tested	Functional Coverage, %
Cause-effect	63	78.7	265	75.6	410	77.3
Tester-in-the-loop	63	78.7	265	75.6	410	77.3
Model-based testing	63	78.7	265	75.6	410	77.3
Performance EX combined with dlls	74	92.5	295	84.3	435	82
Software EX and performance EX combined with dlls	76	95	313	89.4	425	80.2

activated by following different paths (Figure 11). As exposed in Section 3.1, the cause-effect technique implies redundancies. Consequently, the code coverage is not high. The main limitation associated with this technique is that it is based on the software behavior and not on checking the code coverage and the number of Simulink blocks covered.

3.2.2 | Model-based testing

The model used for testing the SM under validation can be built from two points of view. The first one focuses on the functional software behavior as described in Section 3.1. The other one focuses on the software structure, in other words, on the Simulink blocks without analyzing the purpose of each block. In this section, the second point of view is used. However, it faces the same problems already described when automating test cases because of the SM interactions.

3.2.3 | EXs combined with dlls

A realistic way to assess the code coverage is to check whether all subblocks that composed a Simulink model of a specific SM under validation are verified after having run all the test cases. In this research, two options were considered:

a. Division of the range of every software variable involved in the validation process into subintervals. The aim of this was to generate test cases that allow covering as many paths of the Simulink model as possible. This strategy is followed by commercial software such as Matelo.
b. Number of states. This is a key factor as it allows modeling in detail the software behavior by using functional states. As depicted in Figure 6, every path of a Simulink model may be represented by a functional state.

By changing the value of these factors, the code coverage was assessed. To do this, it was checked how many functional states were covered when conducting all test cases available to validate an SM following the strategies described in Section 2.1.1 to generate test cases. The obtained results are shown in Table 16. These figures show how the code coverage increases as the number of states goes up. This fact must be coherent with the functional coverage rate. This point will be analyzed in this section.

The code coverage could be calculated in a more accurate way. However, this implies that two main issues should be taken into account. Firstly, the number of test cases to be performed by using an HIL simulation increases, and the project time frame can be affected. In addition, some use cases are difficult to be simulated when using an HIL bench owing to the HIL model limitations, especially when it comes to SMs linked to advanced driver assistance systems. It must be reminded that these functions need a lot of information exchanged between different ECUs present in the CAN network. Secondly, the number of states should also be increased. However, it cannot be stated that the more states are used, the higher the code coverage is. As shown in Table 16, there is a limit at which the code coverage does not increase meaningfully (15 states for a simple function and 75 for a fairly and highly complex function). After analyzing the results, the conclusion was that many test cases were redundant. As mentioned above, some states are difficult to reach when using an HIL simulation owing to HIL model limitations.

When it comes to subintervals breakdown, the obtained results are shown in Table 17. The main conclusion is the higher the number of subintervals, then the lower code coverage is, as redundancy in test cases occurs. In this research, the authors proceeded to use a fuzzy logic to establish the optimal number of subintervals. More specifically, the speed was considered as low, average, and high, the water cooling temperature low, average, or high, and so on.

Figures 12 and 13 depict the results in a more visual way.

Finally, it is essential to check the validity of the software EX. The method followed to validate EXs was discussed in Section 2.2.1. Two phases were considered: a validation and a test one. On the one hand, the former consists of verifying test cases to assess the EX performance depending on the type of SMs under validation (60 for simple SMs, 40 for fairly complex SMs, and 10 for highly complex SMs). On the other hand, the latter seeks its acceptance after having tested 30 for simple SMs, 20 for fairly complex SMs, and 5 for highly complex SMs. It is vital to remark that all the points, tested to validate the system, covered all the functional rules. Thus, the functional coverage rate was 100%. In the first phase, a 17.3% error was obtained and in the second one, 0%. As a result, the EX was validated. Table 18 shows the results obtained during the first phase.

TABLE 16 Code coverage trend depending on the number of the states (measured in %)

Subinterval = 3																		
Number of States\Type of SM	**1**	**3**	**5**	**8**	**11**	**15**	**18**	**20**	**25**	**31**	**36**	**42**	**48**	**54**	**60**	**68**	**75**	**80**
Simple	1.5	6.3	14	45	75	95	95.2	95.3	95.3	95.4	95.4	95.4	95.5	95.5	95.6	95.6	95.7	95.7
Fairly complex	1.19	2.1	2.6	3.5	5.2	8.5	15	17	35.6	36.9	42.3	50	57.1	64.3	71.4	78.6	89.3	89.6
Highly complex	1.1	1.8	2.2	3.1	4.7	6.7	13.5	15.8	29.8	33.2	38.2	43.2	53.2	58.5	68.7	72.5	80	80.2

TABLE 17 Code coverage trend depending on the subintervals and the number of states (measured in %)

Subinterval = 4																		
Number of States\Type of SM	**1**	**3**	**5**	**8**	**11**	**15**	**18**	**20**	**25**	**31**	**36**	**42**	**48**	**54**	**60**	**68**	**75**	**80**
Simple	1	4	8	35	68	85	85.2	85.3	85.3	85.4	85.5	85.5	85.6	85.6	85.6	85.7	85.7	85.7
Fairly complex	1.2	2.1	2.3	3	4.2	7	12	14	30.2	31.2	36	45	52.2	56.3	62.3	70	83.2	83.8
Highly complex	1.1	1.2	2	2.5	4.1	5	11.6	12.5	18.2	23.5	29.2	34.5	40.2	43.5	48.5	53.1	58.2	58.8
Subinterval = 5																		
Number of States\Type of SM	**1**	**3**	**5**	**8**	**11**	**15**	**18**	**20**	**25**	**31**	**36**	**42**	**48**	**54**	**60**	**68**	**75**	**80**
Simple	1	3.5	7.2	30	51	72	72.1	72.2	72.5	72.6	72.6	72.6	72.7	72.8	72.8	72.8	72.8	72.9
Fairly complex	1.18	1.9	2.2	2.8	3.5	6.2	10.8	12.5	25.6	28.6	32	40	48.5	53.5	58	64.5	72.5	72.9
Highly complex	1.1	1.8	1.9	2.2	3.5	4.2	7	8.5	12.7	16.5	20.1	24.2	27.6	32.5	37.5	42.8	50	50.6

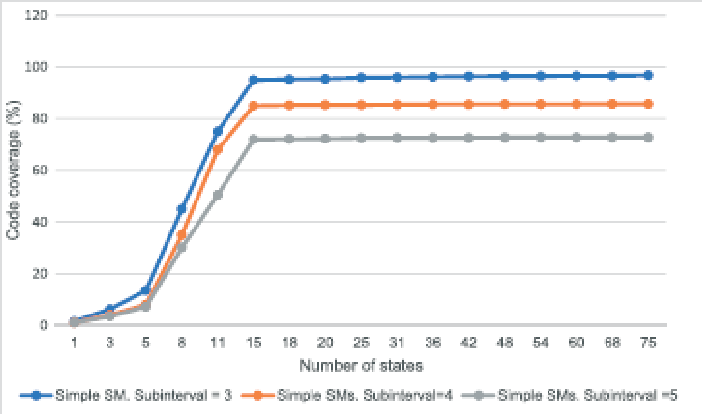


FIGURE 12 Code coverage rate versus the number of subintervals considered when validating a simple SM

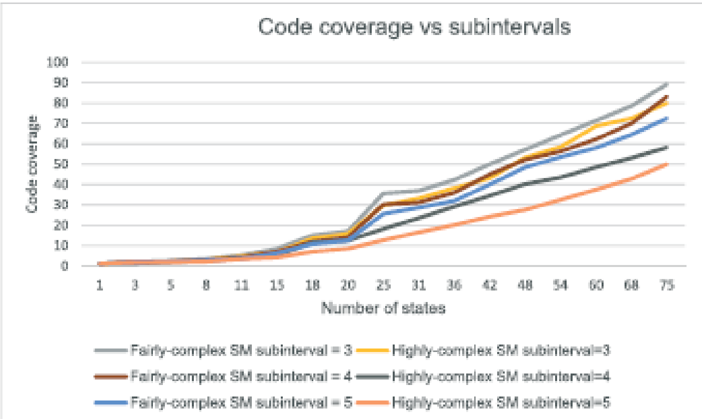


FIGURE 13 Code coverage trend vs the number of subintervals chosen when validating a fairly and highly complex SMs

Before using the EX, an acceptance process is perfomed, consisting mainly of a series of meetings in which some key factors are assessed. Table 11 depicts the most important ones. All the factors assessed cannot be indicated for confidentiality reasons. It is essential to remark that no bug or unexpected behavior of the EX was detected after its validation.

TABLE 18 Errors detected when validating the EXs

Type of Error	Cases	Percentage	Explanation
Wrong syntaxes	10	9.1	Because the rules used to design the EXs are extremely complex, the programmer made coding errors.
Incoherence between rules	6	5.5	In some cases of wrong performance of the EX, incoherence between rules was found.
Rules not coded or forgotten	3	2.7	This error is due to the same misunderstanding of technical specifications.

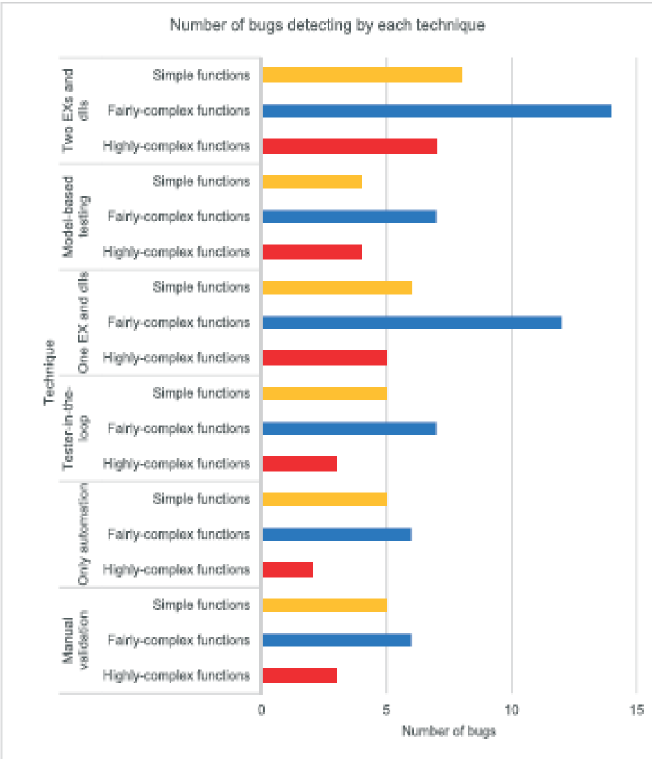


FIGURE 14 Capacity of bug detection

3.3 | Bug detection

When using one EX, the results obtained after executing the number of test cases specified in Table 2 are shown in Figure 14.

- The cause-effect technique (automated or not) and the model-based testing one

The use of Python scripts is a less efficient technique because it is complicated to make the system reach a specific operating point, especially when dealing with certain SMs, such as those related to after treatment of exhaust gas systems. It must be reminded that these SMs perform multiple complex and accurate calculations. As a result, this technique faces the SM interaction problem. Despite this, a test case can be executed by using an HIL simulation, thanks to dlls.[51] This statement is also true for model-based testing. The fact of reaching specific points remains difficult because of the SM interaction problem.

- The tester-in-the-loop technique and the manual execution one

The tester-in-the-loop technique offers better results as a technician or a test engineer can make the system reach a specific operating point. Then, a script is run to use all the necessary manipulations on the HIL model to end the test-case performance. This statement is also true for manual execution as a technician performs the whole test-case execution.

- Using EXs to validate the software

EXs performance must be analyzed. In the previous research, which is under consideration for publication, the authors probed how the use of a performance EX introduced significant advantages such as the capacity of detecting more bugs than other techniques. The question that might arise is if the addition of a software EX introduces significant improvements, which would justify its implementation. As shown in Figure 15, the answer is yes, as more six bugs were found. This fact supports the results shown in Table 19; the higher the code coverage, the more functional states are checked. Six bugs were detected by using two EXs. Figure 15 depicted a classification of these bugs. The term of *strategy chosen* showed in Figure 15 refers to the ability of testing more paths of the Simulink models (Figure 11), thanks to the use of software EXs that allow to increase the code coverage rate. The *rules not considered* concept refers to functional states reached during HIL simulations that had not been considered by the design team. The *value bugs* term refers to certain bugs detected when a Simulink block did not perform some calculations properly (Table 20).

3.4 | Design time

When it comes to proposing a methodology, it is necessary to assess the time required for its implementation. The results obtained in this research are shown in Table 21, which depicts the average time needed for each phase to be considered depending on the type of SMs.

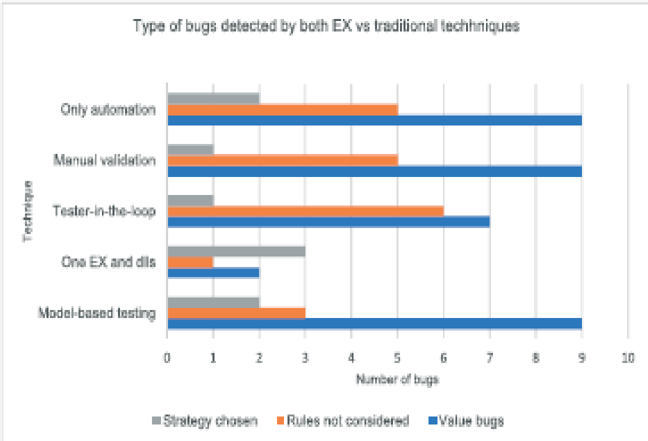


FIGURE 15 Types of bugs found

TABLE 19 Number of rules or functional states not checked when an EX is not used

Type of SM	Number of Rules	Number of Functional States Not Checked When Using Both EXs	Software Code Coverage	Functional Coverage
Simple	75	4	94.6%	100%
Fairly complex	400	40	90%	95%
Highly complex	510	45	91.2%	94%

TABLE 20 Most problematic Simulink blocks

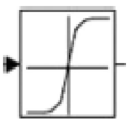
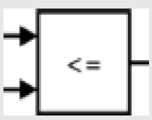
	Interpolator block. In this case, depending on the input values presented to the Simulink block, an output value is provided by applying an algorithm or an interpolation method.
	Matlab native comparator block. It has problems in all its versions (greater than, greater than or equal to, less than, less than or equal to). In engine ECU software, on many occasions, the value of a certain physical magnitude (eg, motor revolutions and vehicle speed) is compared with a calibration threshold.

TABLE 21 Implementation time for each technique

	Total Time for Designing Test Cases, h	Simple Functions 8	Fairly Complexity Functions 80	Highly Complex Functions 120
Time for designing and coding	Time for coding, design, and validation of one EX and Python scripts for the automation process, h	3	29	64
	Time for coding, design, and validation of two EXs and Python scripts for the automation process, h	4	35	70
	Time for coding, design, and validation of functional models and Python scripts for the automation process, h	5	34	72
	Time for preparing dlls, h	2	6	10
	Time for coding Python scripts, h	4	32	50
	Time for coding when using the tester-in-the-loop, h	2	25	35
	Total time for designing and coding when using one EX and dlls, h	13	115	194
	Total time for designing and coding when using two EXs and dlls, h	14	121	200
	Total time for designing and coding when using only automation (Python scripts), h	12	112	170
	Total time for designing and coding when using the tester-in-the-loop, h	10	105	155
	Total time for designing and coding when using the model-based testing, h	15	120	202
	Total time for designing when using manual validation, h	8	80	120
Test-case execution	Time for executing an automated test case when using one EX and dlls, h	0.28	12.5	72.6
	Time for executing an automated test case when using two EXs and dlls, h	0.32	13	73
	Time for executing an automated test case by using the model-based testing, h	0.34	13.2	72
	Time for executing a test case when using only automation (Python scripts), h	0.25	12.5	72
	Time for executing a test case by using the tester-in-the-loop, h	0.46	62	80
	Time for executing a test case when using manual validation, h	0.5	80	170
Validation	Time for validating the results with automation, h (1)	0.000 28	0.003 47	0.000 44
	Time for validating the results without automation, h (2)	1.67	20.83	2.33
Total time	Total time when using one EX and dlls, h	13.28	127.50	266.60
	Total time when using two EXs and dlls, h	14.32	134	273
	Total time when using only automation (Python scripts), h	12.25	124.5	242
	Total time when using the tester-in-the-loop, h	10.46	167	235
	Total time when using the model-based testing, h	15.34	133.2	274
	Total time when using manual validation, h	10.17	180.83	292.33

(1) In this case, the following data have been considered: 50 test cases for simple functions with an execution time of 0.02 s, 250 test cases for fairly complex functions with an execution time of 0.05 s, and 50 test cases for complex functions with an execution time of 0.08 s. The execution time has been measured by using the Python function time clock.

Firstly, the time needed for designing the test cases was estimated. Secondly, the time devoted to implement the EXs, the automation Python scripts, and the necessary scripts to apply the technical tester-in-the-loop were also established. All these aforementioned elements are included in the concept "Time for designing and coding." In the concept "test-case performance," the time needed to run the test case as well as the manual or automated execution is considered. The "validation section" shows the time required to perform the validation results automatically or manually. When analyzing the results, the following conclusions can be drawn. The tester-in-the-loop is slightly better than the manual validation, offering improvements of 7.6% for fairly and 19.6% for highly complex SMs. Logically, manual validation for simple SMs is the fastest method as it is not difficult to make the engine ECU reach a specific operating point. The use of Python scripts introduces improvements of 31% and 17.1% for fairly and highly complex functions vs manual execution. The one that introduces less time efficiency is the combination of two EXs, between 25.89% and the 6.61%. However, four conclusions can be drawn:

1. Two EXs can be implemented, and they are feasible as they outperform the manual execution.
2. The use of EXs is widely justified considering their capacity of bugs detection as discussed in Section 3.2. It must be reminded that during this research, a bug was detected, which implies that new software delivery would be required.
3. One can also deduce that although that the productivity drops slightly when using two EXs, the capacity of bug detections is improved.
4. The effort of using two EXs is similar to model-based testing.

Table 22 shows the results when comparing the technique proposed in this paper with others. The results are logical as the implementation of two EXs requires more time than that of other techniques. The main gain is made when test cases are automated.

TABLE 22 Comparison between the technique proposed and traditional ones

	Gain vs Tester-in-the-Loop			Gain vs Manual Validation			Gain vs Model-based Testing			Gain vs Python Scripts			One EX and DIs			Gain vs Two Expert Systems with DIs		
	Simple Functions	Fairly Complexity Function	Highly Complex Function	Simple Functions	Fairly Complexity Function	Highly Complex Function	Simple Functions	Fairly Complexity Function	Highly Complex Function	Simple Functions	Fairly Complexity Function	Highly Complex Function	Simple Functions	Fairly Complexity Function	Highly Complex Function	Simple Functions	Fairly Complexity Function	Highly Complex Function
Total time for designing and coding, h	−28.57%	−13.22%	−22.50%	−42.86%	−33.88%	−40.00%	7.14%	−0.83%	1.00%	−14.29%	−7.44%	−15.00%	13	115	194	−7.14%	−4.96%	−3.00%
Time for executing a test case, h	43.75%	376.92%	9.59%	56.25%	515.38%	132.88%	6.25%	1.54%	−1.37%	−21.8%	−3.85%	−1.37%	0.28	12.5	72.6	−12.50%	−3.85%	−0.55%
Total time, h	−26.96%	24.63%	−13.92%	−28.98%	34.95%	7.08%	7.12%	−0.60%	0.37%	−14.46%	−7.09%	−11.36%	13.28	127.5	266.6	−7.26%	−4.85%	−2.34%

Different questions must be analyzed to consider whether this technique is useful or not to be applied in an engine ECU project.

a. Is the time required to implement this technique compatible with an engine project planning?

It must be reminded that several projects are being developed at the same time by car manufacturers: diesel or gasoline engines. Between these types of engines, one can find considerable differences when it comes to torque structure or after treatment of exhaust gas systems. However, when comparing engines of the same groups, they are remarkably similar. As a result, an EX designed for a project can be used for another one. Then, only the automation and validation phases will be performed. As one can see in these phases, this technique outperforms the other ones. The main conclusion that can be drawn is that the proposed technique always meets the project planning especially when there are several engines developing at the same time.

b. Can this technique save money for a car manufacturer?

Not all bugs have the same importance. Some of them are minor bugs and even the manufacturer could decide not to fix them as the new software version implies high costs. On the other hand, there are other bugs that must be fixed as they are related to safety. During this research, this technique allowed detecting two bugs (linked to safety and after treatment of exhaust gas requirements) that would have required two new software versions.

3.5 | Dynamic-link libraries

The problem of SM interactions is resolved, thanks to the usage of dlls as proved in this research. It must be remarked that the obtained results are very similar no matter what technique is used provided that dlls are implemented as depicted in Tables 23, 24, and 25.

Several factors must be considered to better understand these results. Firstly, dlls are not needed when using the manual execution as the test engineer can control accurately the automation process. Secondly, the results for "Automated with a Python script and the use of dlls" are representative for no matter what technique is used, which implies that a Python script is run to perform the automation process such as the model-based testing and EXs. Finally, when using dlls, a 100% success rate is not achieved because of HIL model inaccuracies. The HIL model, which represents the vehicle dynamic, is not perfect. Therefore, from time to time, the engine ECU can detect failures, which implies that the test case cannot be properly run despite the dlls usage.

3.6 | Limitations

It is important to emphasize that the use of EXs does not allow the detection of any type of bugs. Indeed, the output provided by the software for a particular variable differs from the one expected. However, if this fault does not introduce any serious malfunction, the EXs will not be

TABLE 23 Comparisons of different techniques for validating simple functions

Methodology	Number of Cases in Which the Output Value Set in the Test Case Was No Longer Valid	Error Rate After 250 Simulations	Success Rate
Only but without using a dls	49	19.6%	80.4%
Tester-in-the-loop	5	10%	90%
Only automation and the use of dlls	13	5.2%	94.8%
One EX and dlls	12	4.8%	95.2%
Two EXs and dlls	13	5.2%	94.8%

TABLE 24 Comparisons of different techniques for validating fairly complex functions

Methodology	Number of Cases in Which the Output Value Set in the Test Case Was No Longer Valid	Error Rate After 1250 Simulations	Success Rate
Only but without using a dls	480	38.4%	61.6%
Tester-in-the-loop	350	28%	72%
Only automation and the use of dlls	125	10%	90%
One EX and dlls	126	10.1%	89.9%
Two EXs and dlls	124	9.9%	90.1%

TABLE 25 Comparisons of different techniques for validating highly complex functions

Methodology	Number of Cases in Which the Output Value Set in the Test Case Was No Longer Valid	Error Rate After 100 Simulations	Success Rate
Only but without using a dlls	61	61%	39%
Tester-in-the-loop	35	35%	65%
Only automation and the use of dlls	15	15%	85%
One EX and dlls	15	15%	85%
Two EXs and dlls	14	14%	86%

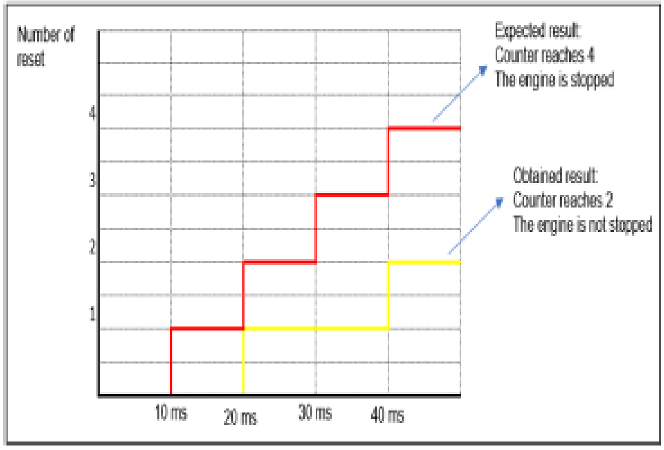


FIGURE 16 An example of a software bug detected by the EX that could not be detected by using traditional techniques

able to detect it. That is why, the use of the dlls is essential in this methodology. This type of bugs may be present in SMs that perform many calculations.

The reader might think that, in case of bugs in the Simulink model, the software will also contain these errors. As a result, no bug will be detected by using the method proposed in this research. This study has proven that this statement is true and that is why the performance EX must be used. In the engine ECU software, when some specific failures are detected, a software reset takes place. If, despite this, the failure still occurs, the ECU stops the car. Figure 16 shows a bug found during this research. The dll and the software did not increase a counter properly. The main consequence was that instead of counting until four software resets, they counted until two and the engine was not stopped. In this case, the dll and the software provided the same outputs. However, the EX detected this software bug.

Finally, the limitation associated with this methodology is no different to others that can be proposed as increasing the number of test cases to be conducted to ensure a code coverage of 100% is not compatible with the planning of an engine design project.

3.7 | Threats to validity

In this research, the authors have considered internal and external threats to carry out the threats to validity analysis. Table 26 describes the main variables to be controlled (predictors) to check the influence on the response variables (productivity gain, documentation quality, and bugs).[¶] Among these predictors, one can distinguish the sample used in this research, the staff's skills in Python, the SM chosen to be validated, the staff's experience in how the engine ECU operates, the reliability of measures done during the validation, and finally, the quality of the documentation furnished to technician or engineers to validate the software (test description, python scripts, etc).

All these factors are analyzed in the sensitivity analysis (Section 4). The authors described in-depth how all these factors impact the time needed to code Python scripts and, therefore, productivity (internal threats). Considering that one of the most important factors to be analyzed in this research is the number of bugs found when using two EXs working in collaboration, it is essential to check how these variables impact this factor. Figure 17 shows that the less quality the documents have, the fewer bugs are detected, and therefore, the performance decreases. The quality depends on the sample used in this research, the training in Python, the staff's experience in the engine control unit ECU, and the number

[¶] Considering the complexity of this case study, the number of variables used as predictors must be limited. Otherwise, it would be extremely complex to draw conclusions.

TABLE 26 Factors to be controlled when validating the engine ECU

ID Factor	Factor	Description
1	Sample used in this research	This research was performed in a software validation service that belonged to one of the most important manufacturers in Europe. The staff used in this research is composed of 40 people: 19 engineers and 21 technicians. Each person may have different skills, but this fact was considered in the sensitivity analysis in Section 4.
2	Training in Python	The more a validation department masters Python, the more sufficient the productivity gain is or the more extensive knowledge of an engine operation the staff can acquire, the less time they require to write the tests. Technicians and engineers having different levels in coding Python or in engine operation knowledge were chosen. Then the influence of all the aforementioned aspects was analyzed in the sensitivity analysis (Section 4).
3	SM chosen for the research	Not all SMs present in the engine ECU software have the same complexity. It is not possible to draw exactly the same conclusions for a simple SM as for a highly complex one. The authors have divided the SMs into three groups. The fact of not doing this implies that the productivity gain is not properly assessed.
4	Unreliability of measures	All measures were taken in the same conditions. To assure this, a procedure was written as the reader can see in Section 2.2.3, which describes when measures can be accepted and when they must be rejected it. In addition, EXs must be validated as exposed in Section 2. Otherwise, the conclusions could be completely random and wrong.
7	Staff's experience in the engine ECU field	The members of the staff of a validation service may change their positions in the company. As a result, the department may have more specialized people at a specific moment and vice versa in other occasions. This research was performed considering different scenarios depending on the staff's training as shown in the sensitivity analysis (Section 4).
8	Quality of documentations provided to the technician to validate the software	A validation department can have more or less staff. It must also be reminded that a validation department is of high cost for companies, so they try to limit the number of people who run the service. The authors have described the number of engineering hours needed to get high, average, or low quality when it comes to documentation and other inputs needed to validate the software.

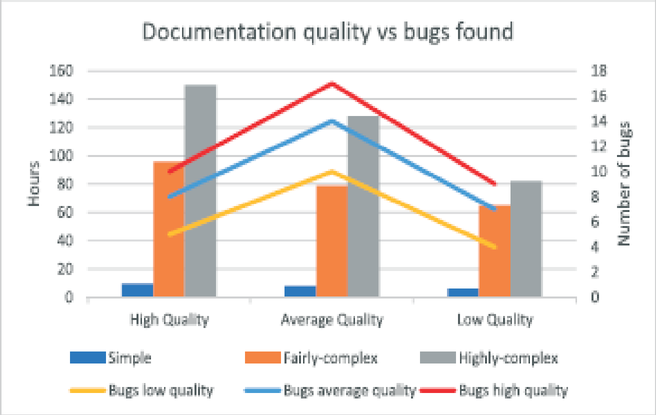


FIGURE 17 Documentation quality vs bugs found when using EXs

TABLE 27 Staff's training in Python

Group	Experience in Coding Python Scripts	Number of Members
Expert level	More than 2 y	10
Average level	Between 1 and 2 y	15
Low level	Less than 1 y	15

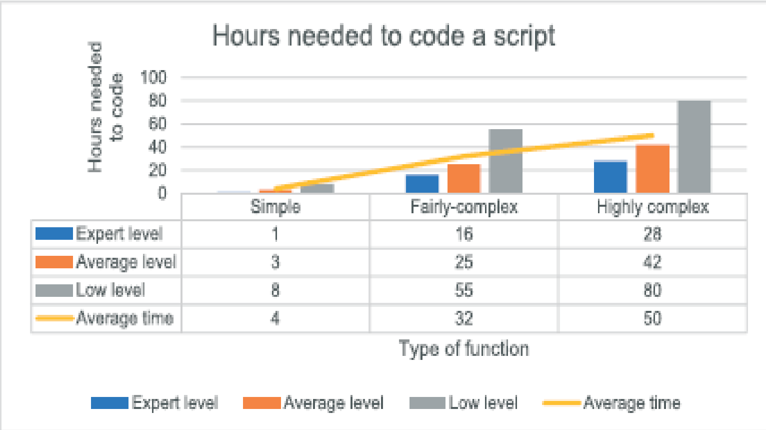
of people belonging to the staff. When it comes to external threats, it is of paramount importance to verify if the results can be generalized or if it is applicable to a larger group. Figure 17 shows that it can be applied as the quality depends on the number of members of the staff. This statement is based on the fact that the higher the staff is, the more hours can be devoted to improving the quality of documentation. Otherwise, the terms of the project will be prolonged.

4 | SENSITIVITY ANALYSIS

When automating a test case, it is necessary to make the vehicle reach specific operating conditions. To do this, there are two options: firstly, coding a high-quality script that can control all necessary parameters that could prevent the vehicle from achieving the desired operating point and secondly, the "tester-in-the-loop" concept can be applied. Thus, a technician makes the vehicle reach a desired operating point, and then an automation script performs all subsequent actions to run the test case completely.[40] In this research, these SMs were automated in the company subjected to this case study by using Python scripts. The key to achieve this is to code libraries that can carry out specific interaction with the vehicle model interface (Figure 1), such as heating the NO_x probes. Therefore, quick and robust scripts can be coded. However, the time needed to code Python scripts depends on the programmer's experience.[52] As shown in Table 27, the staff of the validation software validation service of the company subjected to this case study has been classified as expert, average, and low level when it comes to their experience in Python.

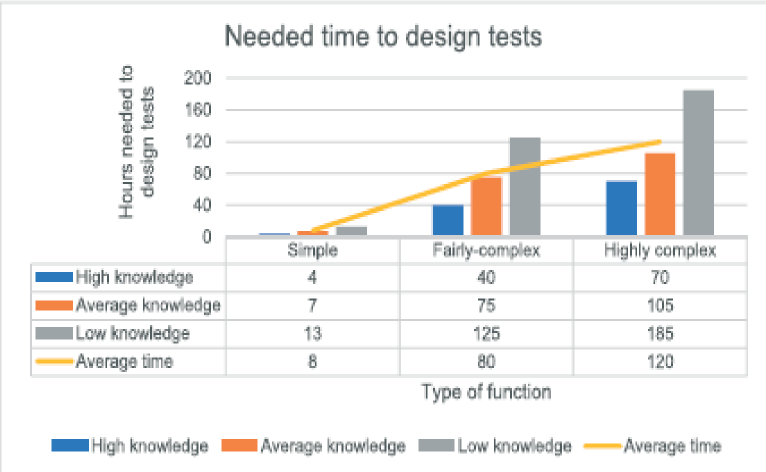
Figure 18 depicts the obtained results.

Clearly, training in Python scripts is a key aspect to be taken into account to improve productivity when it comes to software validation.



	Simple	Fairly-complex	Highly complex
Expert level	1	16	28
Average level	3	25	42
Low level	8	55	80
Average time	4	32	50

FIGURE 18 Time needed to code a script depending on staff's training



	Simple	Fairly-complex	Highly complex
High knowledge	4	40	70
Average knowledge	7	75	105
Low knowledge	13	125	185
Average time	8	80	120

FIGURE 19 Needed time for designing test cases vs functional and physical knowledge about a SM

However, training in Python is not the only key factor to improve the quality of software and time frame of the project. Knowledge about physical phenomena controlled by the SM under validation has a great influence on the time needed to design tests. For example, if a test engineer needs to design tests for validating the urea injection for the nitrogen oxide treatment, if he knows the physical foundation of the function, besides knowing the software architecture, the time needed to design a test case is reduced. To verify this, expert python test engineers were chosen to code python scripts to automate simple, average, and complex functions. However, these engineers had high, average, and low knowledge about the function to be automated. The obtained results are shown in Figure 19. Consequently, in addition to SM knowledge, another potential method of improvement is provided by the expertise in the physical phenomena linked to a combustion engine.

The number of engineering hours dedicated to design the tests used during the validation process depends on the final quality of the test documentation provided by the technician. If schedules, notes, and comments are attached, the cost increases. Figure 20 shows the total amount of engineering hours spent to design the tests depending on the final quality provided. In this research, the quality was measured by using a checklist built by the validation expert engineer of the powertrain software validation service.

Taking together Figures 18 and 19, the total number of hours needed to design the test cases (test-case design and the time needed to code the Python scripts) is shown in Figure 21. Significant productivity improvements when comparing with the black-box technique can be obtained when the training of the staff is improved: 13.5% for complex functions, 10.9% for fairly complexity functions, and 16.6% for simple functions considering the average knowledge case. These figures are based on the scenario of high Python skills as well as good knowledge of the SM under validation.

FIGURE 20 Engineering hours spent for test design depending on the type of software module to be validated in black-method

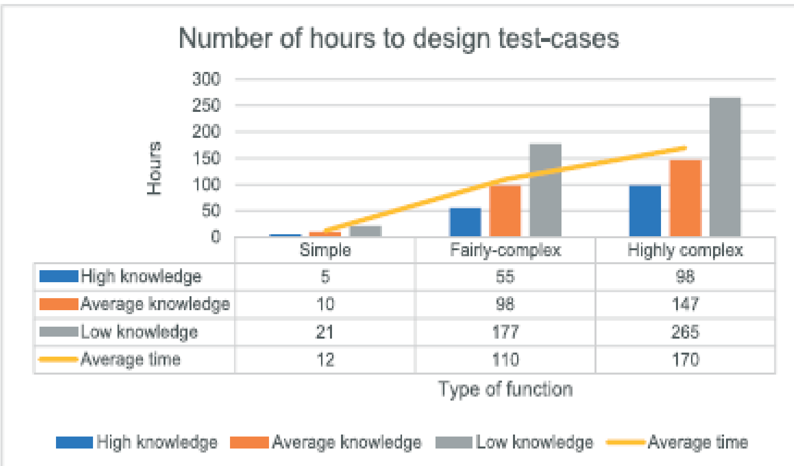


FIGURE 21 Total number of hours to design the test cases (design and script coding time)

5 | CONCLUSIONS

Several issues that the automotive sector must face when validating the ECU software are how to design representative use cases, how to properly automate the HIL simulation because of the interaction of SMs, and how to be able to find coding and performance bugs when running a test case.

This research, conducted at the second most important European car manufacturer, is focused on the software validation of an engine ECU by using dlls and two rule-based EXs, one for detecting performance bugs and the other for finding code bugs. This combination allows the detection of software performance and coding bugs. In this research, the use of dlls and two EXs were compared with other techniques such as the tester-in-the-loop, automation by using Python scripts, and a performance EX and automation by using Python scripts without EXs. The results obtained show that dlls and two EXs are able to detect six bugs more than the use of dlls and a performance EX can, 14 bugs more than the tester-in-the-loop can, 16 bugs more than the automation by using Python scripts can, 15 bugs more than a manual execution can, and 14 bugs more than the model-based testing can. Dlls and EXs working in cooperation enhance the code coverage regarding the other techniques. This enhancement depends on the number of states in the functional model used in the EXs and the number of subintervals in which the SM inputs can be divided as shown in this research.

Dlls and Python scripts can be used combined with different techniques such as the using of a performance EXs or two EXs. The obtained results show that the methodology proposed in this research enhances the HIL success rate compared with the tester-in-the-loop technique by up to 6% for simple validation SMs, by 16.8% for fairly complex SMs, and by 18% for highly complex SMs despite the SM interactions. When it comes to automation without using dlls, the methodology proposed in this research enhances the HIL success rate up to 14.4% for simple validation SMs, by 27.4% for fairly complex SMs, and by 47% for highly complex SMs despite the SM interactions.

Even though EXs and dlls require more time to be implemented for highly complex and simple functions, the deadline of the project was met. When it comes to fairly complex functions, there is a productivity gain considering the number of SMs to be tested in an engine ECU software project versus the tester-in-the-loop and manual execution. In addition, the time needed to implement the model-based testing technique is similar to the one needed for two EXs. It must be reminded that the fairly complex SMs are the majority in the engine ECU software.

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How to cite this article: Ortega-Cabezas PM, Colmenar-Santos A, Borge-Diez D, Blanes-Peiró JJ. Application of rule-based expert systems in hardware-in-the-loop simulation case study: Software and performance validation of an engine electronic control unit. *J Softw Evol Proc*. 2019;e2223. https://doi.org/10.1002/smr.2223

APPENDIX A

ENGINE CONTROL UNIT OVERVIEW

Powertrain[#] control is the system in charge of transforming the driver's will into an operating point of the powertrain according to performance established for the product (eg, consumption and emissions).[7] The key element of the control system is the engine ECU composed of hardware and software. The hardware is responsible for getting information from sensors after a filtering process to reduce noise in signals. The software processes all data received and handles actuators to reach the operating point.

Controlling a combustion ECU is a difficult task owing to the huge number of physical processes involved. The air is filtered and leads to a turbocharger when it enters the engine through the intake duct. The aim of this element is to compress air to increase the density and improve the intake process in the cylinders. As a result, the temperature rises but should not be excessive as detonations could occur in the combustion chamber. These phenomena damage engines as the combustion process causes high pressure and temperature gradients. Therefore, there is a heat exchanger to cool the air before entering the combustion chamber. Depending on the requests of the driver, a greater or lower engine torque is generated, involving adaptation of the airflow in the combustion process. To do this, a motorized throttle is controlled depending on the pedal accelerator position. Once the amount of air required is established, the process of air-fuel mixing begins, which depends on the type of injection. The final mixture is more or less homogenous according to the engine type (diesel or petrol). When the combustion process has occurred, the gases are expelled by the exhaust manifold. A turbine is needed to provide the necessary energy to make the turbocompressor work properly. The ECU sets the amount of gases that will go through it (by using the waste-gate valve) to reach the optimal operating point for the powertrain. The gases left are driven to the exhaust gas recirculation (EGR) valve or directly to the exhaust pipe. This process must be performed within appropriate parameters of pressure. Therefore, the system is equipped with two pressure sensors, to control turbo overboost and the pressure in the intake duct. Finally, it is important to explain the role of the dump valve. When a gear shift takes place, the motorized throttle is closed. In the meantime, the turbocompressor continues sending air to the intake duct. Thus, overpressurization occurs. However, there is also a depressurization owing to the air or air-fuel aspiration by the cylinder. This difference in pressure can cause an inversion flow in the compressor. As a result, it can be irreparably damaged.

Engine ECU functions are not limited to combustion control. The treatment of combustion gases (catalysts, diesel particle filter, and urea injection), pump fuel from the tank to the injection ramp, operation of fans for the thermal control of the engine, dilution control of oil in the diesel owing to regeneration of the diesel particle filter are controlled by the ECU. Thus, software validation is extremely complex and difficult to test owing to the huge number of variables involved in its operation (approximately 40 000) each one representing a physical parameter. In fact, it is an HRT system. In other words, the system is subject to real-time constraint.

APPENDIX B

HIL SIMULATION PROCESS

The main advantage of HIL simulation is that the element in charge of controlling a complex plant (a vehicle, a nuclear reactor, etc) interacts with the plant by using sensors and actuators. This technique is considered as the most representative one before testing the software directly on the system to be controlled.[52]

In this research, three main elements are used to conduct the HIL simulation, as shown in Figure B1. First, the HIL simulator represents a model simulating the dynamic behavior of a vehicle (the element to be controlled). Second, the engine ECU is responsible for controlling the vehicle dynamic depending on the operation state as well as the driver's requests. Third, a driving interface is used by a driver to control the vehicle (to speed up, slow down, stop the vehicle, etc). This interface is equivalent to any industrial control system panel.

The goal of the software that the engine ECU runs is to properly control the vehicle or HIL model. Each of the 40 000 variables presented in the source code represents a physical magnitude or a vehicle parameter to be controlled. Some of them are stored in EEPROM and others directly in RAM. During the simulation process, the technician can check the values of all of them by using additional software installed on his computer. Although there are multiple options in the market, in this research, INCA was chosen because of implementation reasons in the company that is the subject of this case study. It is important to highlight that the results of this research are not directly linked to INCA use. Therefore, any software that can read the memory positions of the engine ECU (dSpace, etc) can be used to obtain the results in this study.

It is essential to distinguish different types of variables present in the engine ECU software, to better understand the difficulties linked to administration of a test case in a HIL simulation:

a. *Calibration variables*. They allow setting up the engine ECU. They can be modified by the user at any time. In other words, it is not mandatory to make the engine ECU reach a specific operating point to be allow modifying a calibration variable.

[#]Powertrain is composed of the clutch, gearbox, conical group, and propeller shaft.

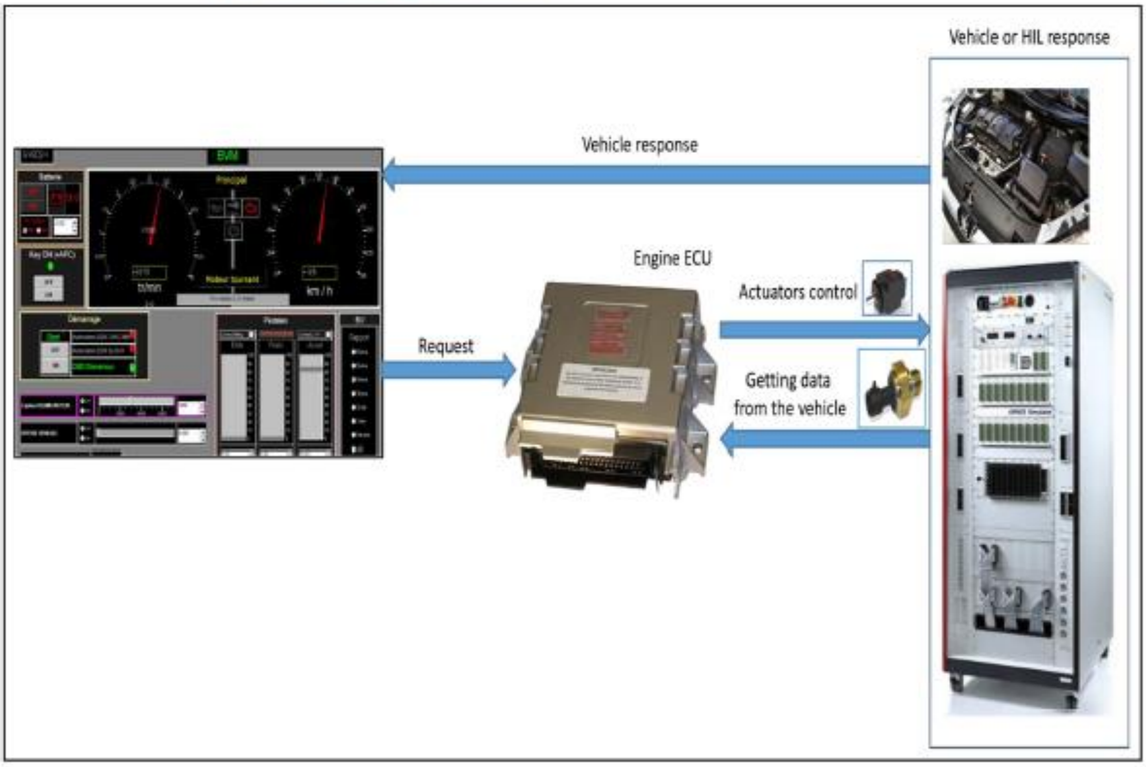


FIGURE B1 Interaction between the interface model, the engine ECU and the HIL bench

b. *Measuring variables*. These variables are write access denied. In other words, the variables can be read but not modified directly by the users. In most cases, they are modified through driver-vehicle (or model) interaction

c. *Cartographies*. These variables are similar to calibration variables. However, they are usually more difficult to set up as they handle functions of several variables.

d. *By-pass*. In some cases, it is necessary to disable a module or activate it easily to make a measuring variable reach a desired value.

Most of the variables presented in the engine ECU software are measured and therein lie the complexity of software validation. To modify them, specific values must be sent to the inputs of the engine ECU until a desired operation point is reached, owing to the interaction of different modules. The only way to send information to the engine ECU inputs is through the driver's interface model (Figure B2), which allows generating signals, simulating sensors, and preforming different actions such as accelerating, braking, activating the cruise control, and disconnecting the battery. The engine ECU must process the information coming from the HIL bench and perform the needed action on the actuators to operate the vehicle properly. During this process, the internal variables of the different SMs will be updated.

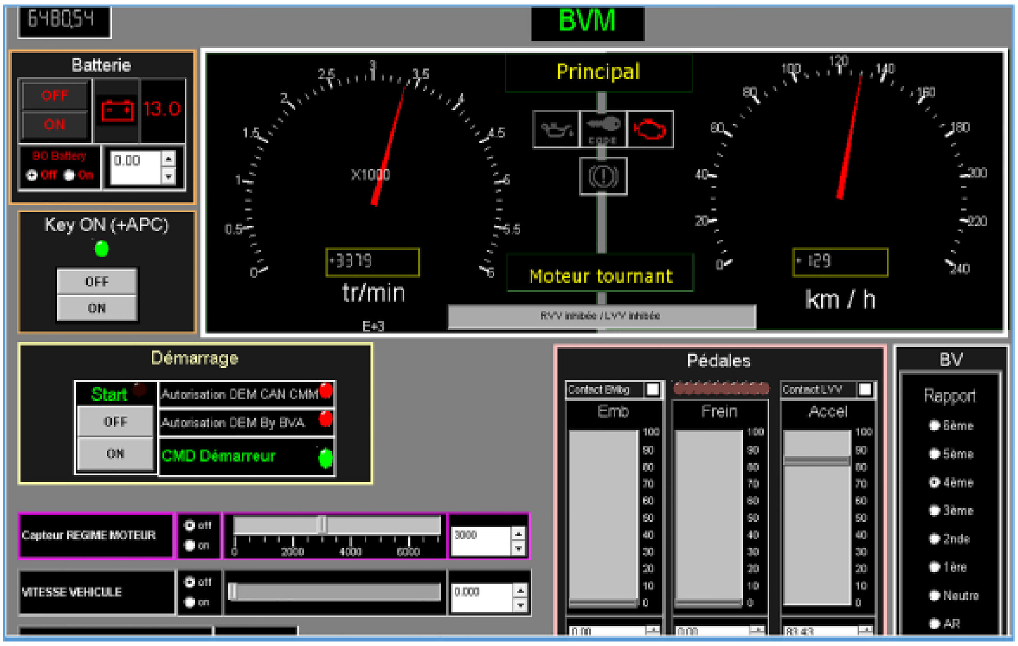


FIGURE B2 Vehicle model interface

ANEXO IV. Factor de impacto. The Journal of Software: Evolution and Process

Journal Citation Report

Clarivate

Journal Citation Reports Browse journals

Home > Journal profile

JCR YEAR

2020

Journal of Software-Evolution and Process

View title change

ISSN

2047-7473

EISSN

2047-7481

JCR ABBREVIATION

J SOFTW-EVOL PROC

ISO ABBREVIATION

J. Softw.-Evol. Proc.

Journal information

EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

COMPUTER SCIENCE, SOFTWARE ENGINEERING - SCIE

LANGUAGES	REGION	1ST ELECTRONIC JCR YEAR
English	ENGLAND	2012

Publisher information

PUBLISHER	ADDRESS	PUBLICATION FREQUENCY
WILEY	111 RIVER ST, HOBOKEN 07030-5774, NJ	12 issues/year

2020 JOURNAL IMPACT FACTOR

1.972

View calculation

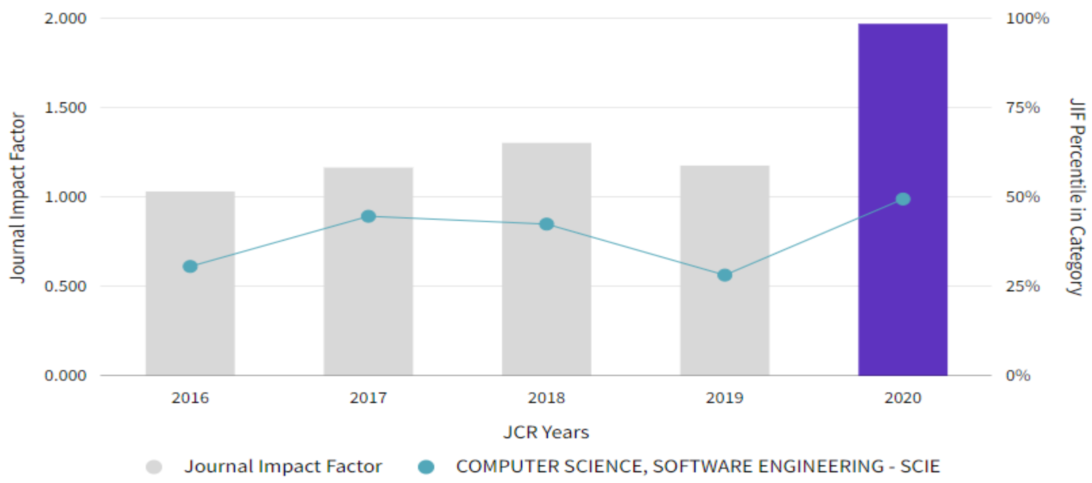
JOURNAL IMPACT FACTOR WITHOUT SELF CITATIONS

1.596

View calculation

Journal Impact Factor Trend 2020

Export

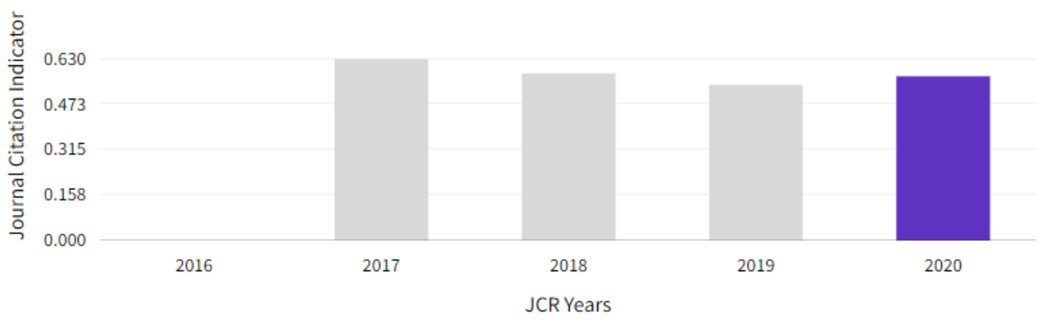


Journal Citation Indicator (JCI)

Export

0.57

The Journal Citation Indicator (JCI) is the average Category Normalized Citation Impact (CNCI) of citable items (articles & reviews) published by a journal over a recent three year period. The average JCI in a category is 1. Journals with a JCI of 1.5 have 50% more citation impact than the average in that category. It may be used alongside other metrics to help you evaluate journals. Learn more

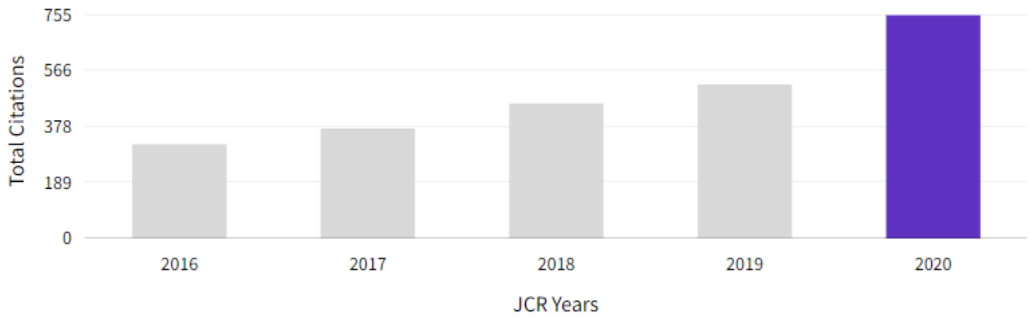


Total Citations

Export

755

The total number of times that a journal has been cited by all journals included in the database in the JCR year. Citations to journals listed in JCR are compiled annually from the JCR years combined database, regardless of which JCR edition lists the journal.



Rank by Journal Impact Factor

Journals within a category are sorted in descending order by Journal Impact Factor (JIF) resulting in the Category Ranking below. A separate rank is shown for each category in which the journal is listed in JCR. Data for the most recent year is presented at the top of the list, with other years shown in reverse chronological order. Learn more

EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

COMPUTER SCIENCE, SOFTWARE ENGINEERING

55/108

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	55/108	Q3	49.54
2019	78/108	Q3	28.24
2018	62/107	Q3	42.52
2017	58/104	Q3	44.71
2016	74/106	Q3	30.66

Rank by Journal Citation Indicator (JCI)

Journals within a category are sorted in descending order by Journal Citation Indicator (JCI) resulting in the Category Ranking below. A separate rank is shown for each category in which the journal is listed in JCR. Data for the most recent year is presented at the top of the list, with other years shown in reverse chronological order. Learn more

CATEGORY

COMPUTER SCIENCE, SOFTWARE ENGINEERING

72/127

JCR YEAR	JCI RANK	JCI QUARTILE	JCI PERCENTILE
2020	72/127	Q3	43.70
2019	73/103	Q3	29.61
2018	71/101	Q3	30.20
2017	73/99	Q3	26.77

Eigenfactor Score

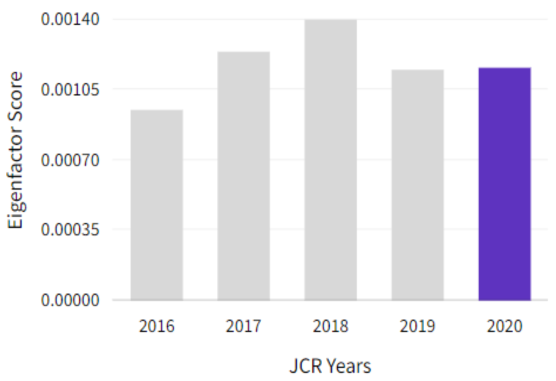
0.00116

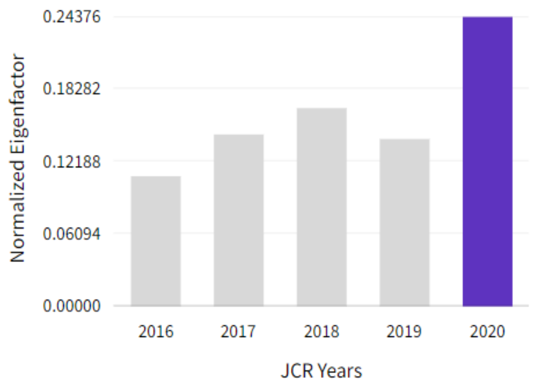
The Eigenfactor Score is a reflection of the density of the network of citations around the journal using 5 years of cited content as cited by the Current Year. It considers both the number of citations and the source of those citations, so that highly cited sources will influence the network more than less cited sources. The Eigenfactor calculation does not include journal self-citations. Learn more

Normalized Eigenfactor

0.24376

The Normalized Eigenfactor Score is the Eigenfactor score normalized, by rescaling the total number of journals in the JCR each year, so that the average journal has a score of 1. Journals can then be compared and influence measured by their score relative to 1. Learn more





Article influence score

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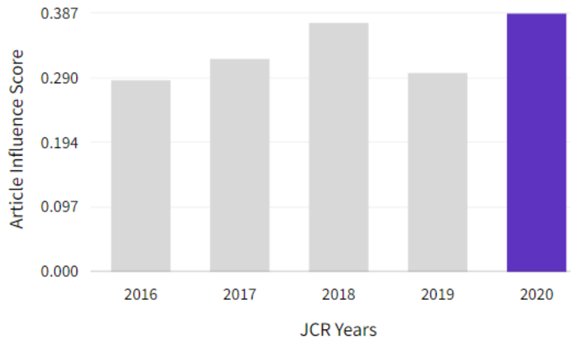
The Article Influence Score normalizes the Eigenfactor Score according to the cumulative size of the cited journal across the prior five years. The mean Article Influence Score for each article is 1.00. A score greater than 1.00 indicates that each article in the journal has above-average influence. Learn more

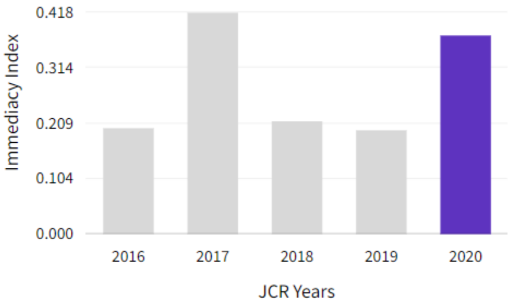
Immediacy Index

0.375

View Calculation

The Immediacy Index is the count of citations in the current year to the journal that reference content in this same year. Journals that have a consistently high Immediacy Index attract citations rapidly. Learn more





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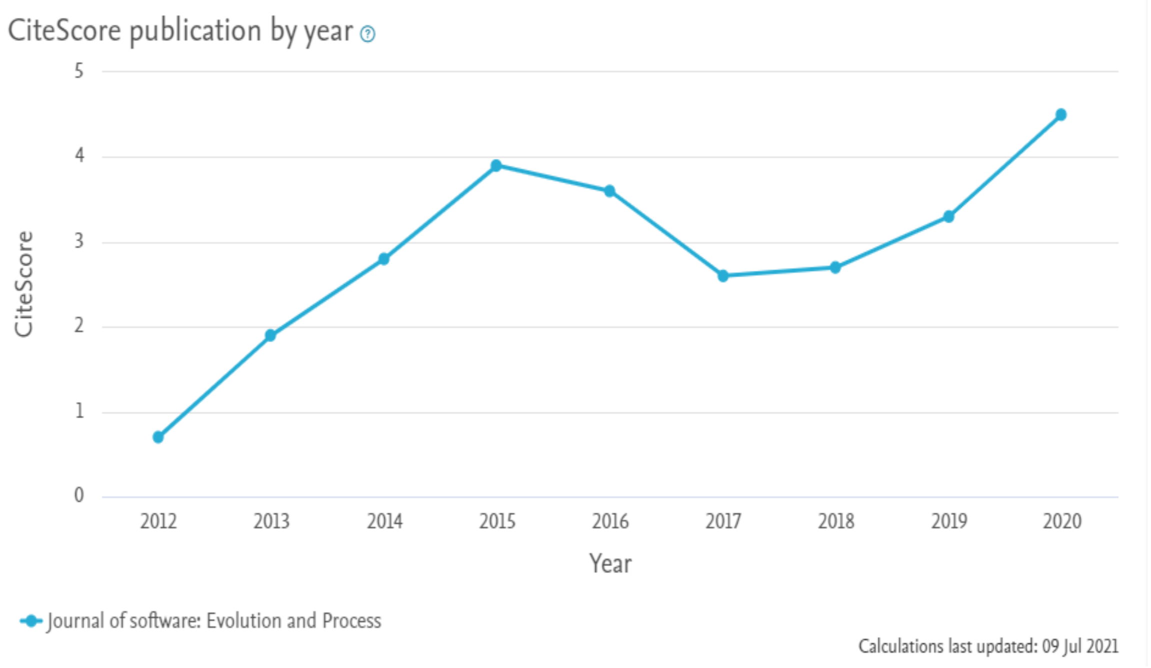
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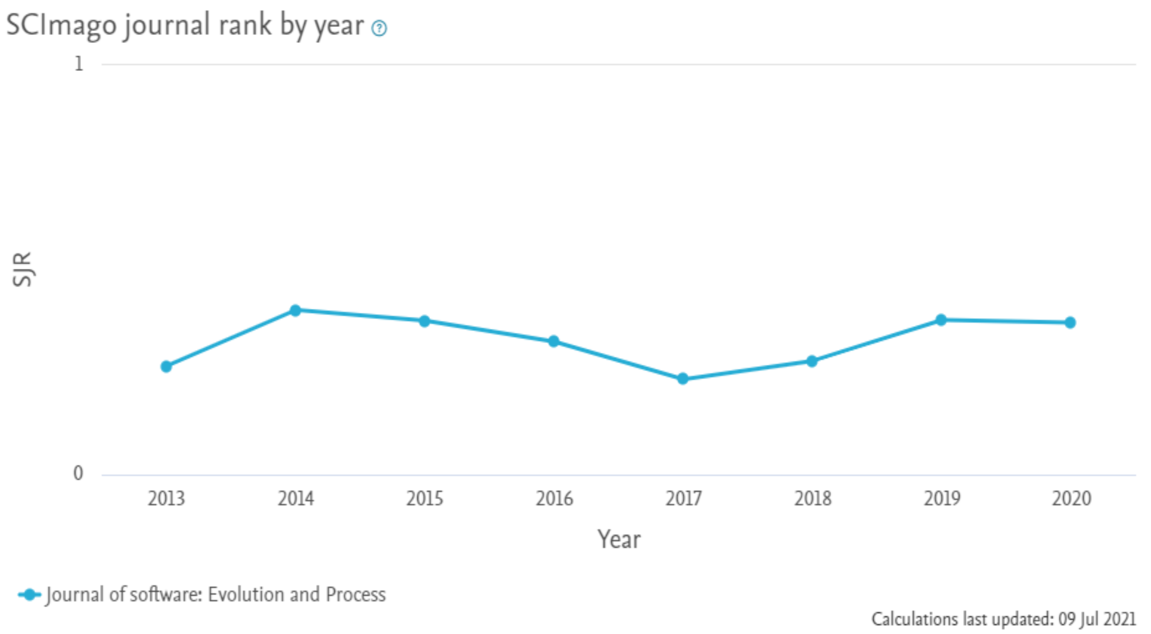
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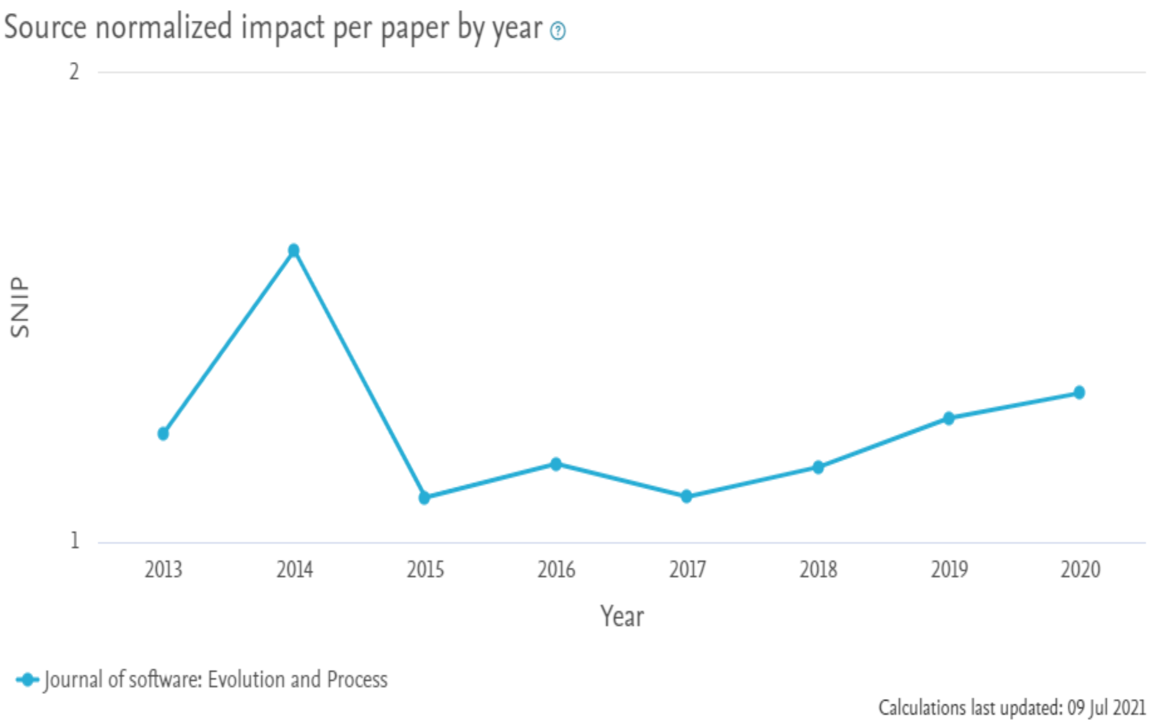
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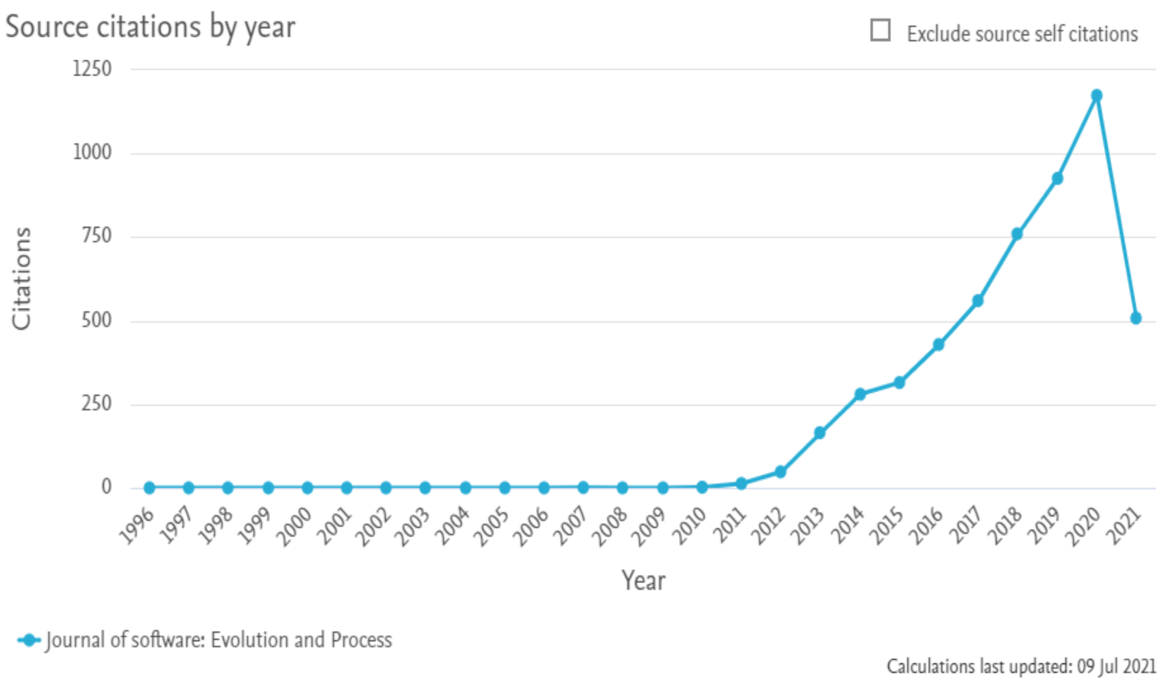
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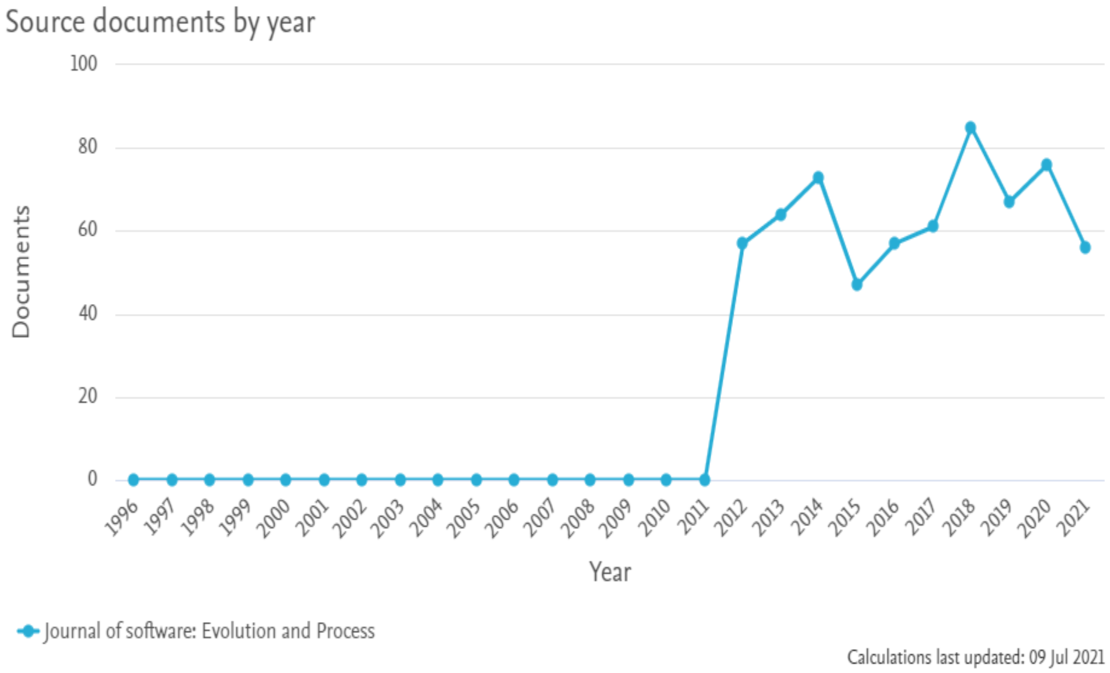

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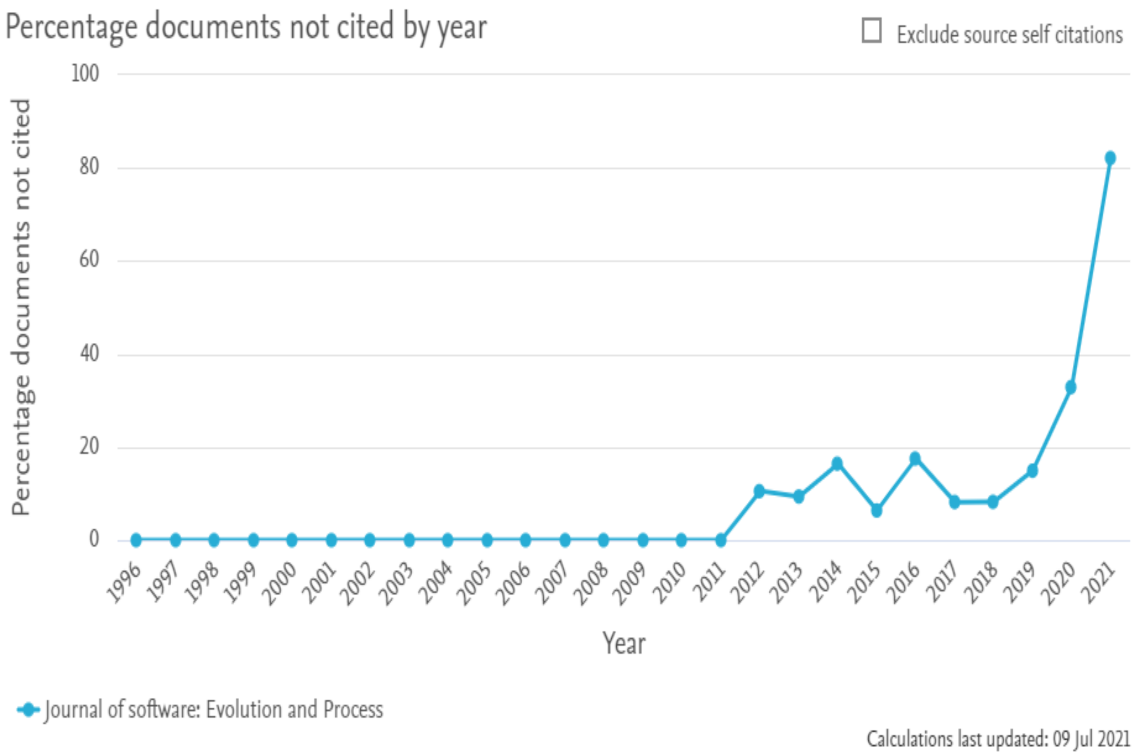

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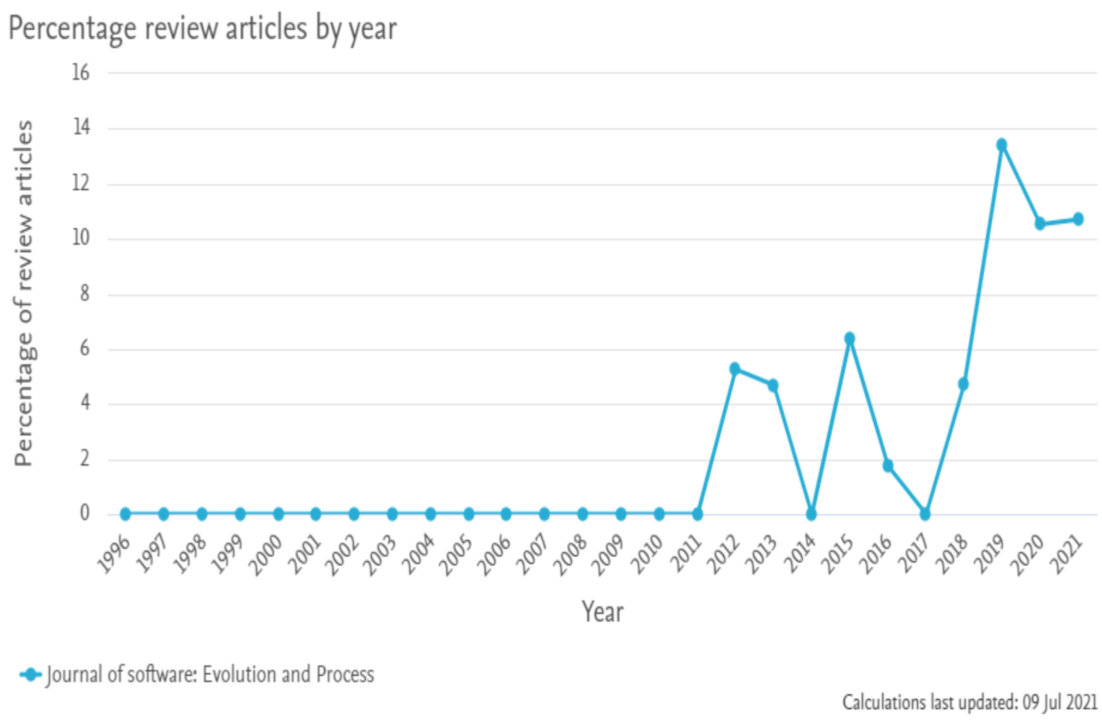
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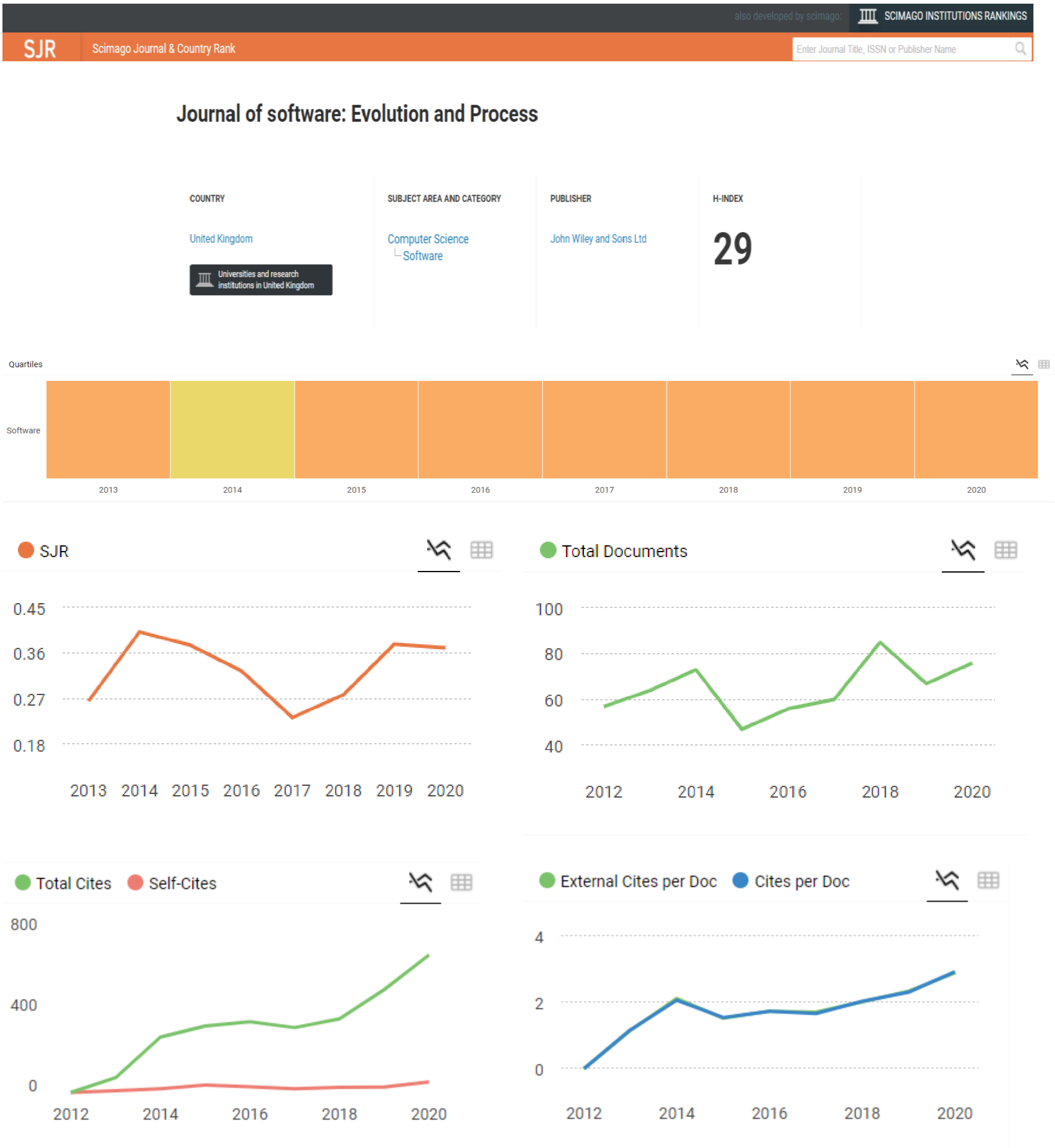

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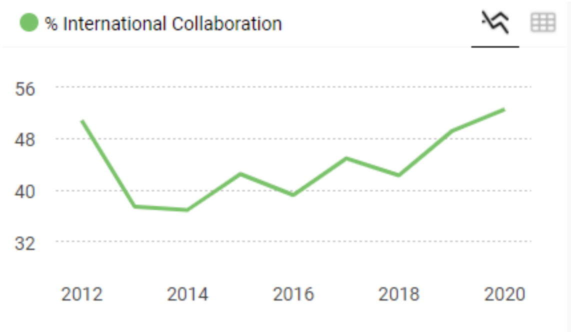

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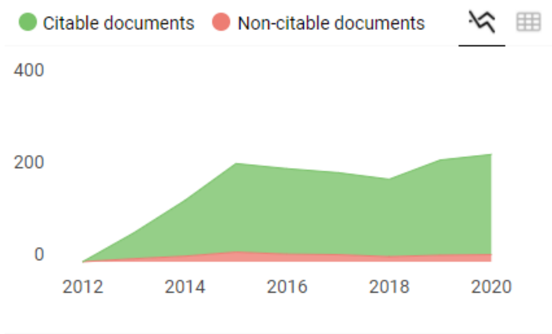

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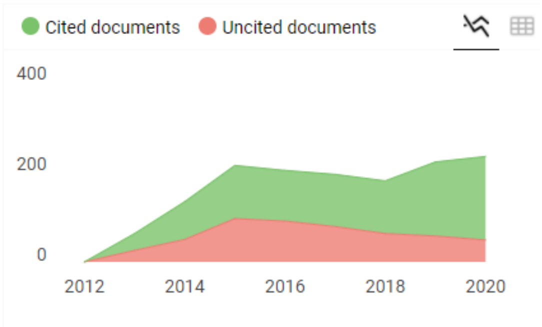

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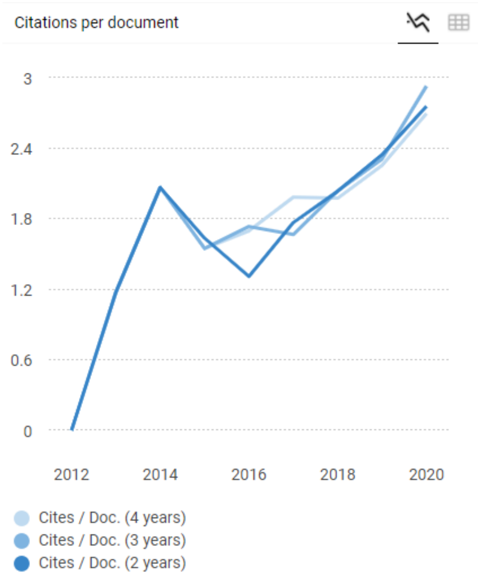

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ANEXO V. Copia de la publicación: "Contribution of Driving Efficiency and Vehicle-to-Grid to Eco-Design"

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Contribution of Driving Efficiency and Vehicle-to-Grid to Eco-Design

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Abstract: Designing eco-friendly products involves energy efficiency improvements. Eco-friendly products must consider not only raw materials and manufacturing processes to improve energy efficiency but also energy needed when designing them. This research shows how eco-routing (ER), eco-charging (EC), eco-driving (EDR), vehicle-to-grid (V2G) and electric vehicles (EVs) can contribute to the reduction of energy consumption during product design. To do this, a group of 44 engineers assigned to the project was chosen to assess the total energy available for V2G when driving EVs from their homes to the design center by using ER, ED and EC by running an application coded by the authors. The energy stored in EVs was used to quantify the reduction in energy consumption of the buildings present in the design center. The results show that the energy saving ranges from 2.89% to 6.9% per day—in other words, 93 kWh per day during the design process. In addition, the fact of making the design process greener implies that renewable energies (REs) are integrated better during the design process. By running the application, drivers are informed about the RE mix when the charging process takes place. Finally, this research shows that current policies make V2G and vehicle-to-home techniques not compatible.

Keywords: eco-design; energy efficiency; eco-routing; eco-charging; eco-driving; renewable energies

1. Introduction

Eco-design allows implementing eco-friendlier products as environmental impacts are considered during the design phase [1,2]. Several factors which influence eco-design have been identified in several research [3–6]. Among them, one can find: manufacturing without producing hazardous waste, using clean technologies, reducing product chemical emissions and product energy consumption, using recycle materials and reusing components, designing products for ease of disassembly and reusing or recycling products at the end of their lives [7]. Some proposals have been made to improve these factors. Morgan and Liker [8] pushed to use lean manufacturing in design when developing products. As detailed by Rosen and Kishawy [9], this usage could imply that several alternatives used during the project can be assessed and, consequently, costs and benefits of eco-design can be set. When it comes to energy efficiency, research is mainly focused on final products and manufacturing processes. The former deals with the energy labelling concept which allows companies to create labels indicating the product energy efficiency [10]. The latter includes reducing energy consumption during the manufacturing process. Seow et al. described a new outlook called "Design for Energy Minimization" aiming to provide transparency regarding energy consumption during the manufacturing process to help inform design decisions [11]. Ka-Leung-Moon et al. proposed guidelines for the design and production of sustainable energy-saving fashion products [12]. Renewable energy (RE) integration plays an important role in eco-design. As detailed by Crul, Diehl and Ryan [13], considering that the number of products that need electricity is increasing rapidly, it is of paramount importance to incorporate them in the design process. In their dissertation, they proposed guidelines to integrate REs in the final product. Finally, waste is an important topic to be considered. For example, cybersecurity is a source of waste as detailed later. Tecchio et al. performed a detailed analysis of the potentials of material efficiency to guarantee waste prevention and material reuse [14].

In addition to the manufacturing process, one can find many activities which generate pollutants during product design. Among them, one can find: software validation processes, prototype product testing and building energy consumption [15–17]. Even emissions generated when engineers involved in projects commute to work impact eco-design. Software validation is an essential activity when designing automotive electronic control units (ECUs) [15,18]. To do this, prototype vehicles and a considerable number of hours of hardware-in-the-loop simulation are needed [19,20]. Consequently, pollution is caused. When designing combustion engines, activities such as engine tuning and driving tests cause pollution. However, the engine design process lacks both guidelines and policies to limit emissions during engine development contrary to the vehicles which have already been marketed and whose emission limits are clear and strict. Building efficiency is an essential topic which contributes to emission reduction as detailed in the literature [21–23]. Finally, the vehicles used by the engineers who are involved in any projects are a source of pollution when commuting to their work. Some factors analyzed in this study such as the number of engineers participating in the project and the location of their homes regarding the design center may decrease or increase emissions.

Eco-routing (ER), eco-driving (EDR) and eco-charging (EC) have an impact on energy efficiency when it comes to eco-design as analyzed in this research. EDR includes all driving habits which could reduce energy consumption and emissions. Nowadays, most cars are equipped with the system that informs how efficient the way of driving is. Qi et al. [24] investigated EDR by quantifying the energy potentially saved when applying to electric vehicles (EVs). Sabrina et al. [25] also proposed a similar work in which continuous and on-demand feedback on driving behavior and safety was conducted. Zhan et al. [26] discussed how systems in charge of monitoring the EV battery improve energy efficiency. ER helps the driver to find the most efficient route to go from point A to B considering several parameters such as real-time traffic conditions, road types and gradient, passengers' and cargo weight. Nunzio, Thibault and Sciaretta [27] implemented a new model based on speed fluctuations and a road network infrastructure to set the best route. The University of California has worked on systems which are able to collect energy consumption data in real-world driving conditions with the aim of integrating them into eco-route algorithms [28]. In this research, EC measures the contribution of RE when charging EVs, showing the optimal moments to do this.

Energy consumption of buildings can be reduced by following several options. Haque and Raham described in their study a comparison between solar photovoltaic mini-grid pumped hydroelectric storage versus battery storage [29]. Their main conclusion was that pumped storage is almost half as efficient yet more expensive than conventional battery storage. Another option to reduce energy consumption is the usage of buildings which integrate photovoltaic energy as described by Haque, Rahman and Ahsan [30]. Vehicle-to-grid (V2G) technology allows a better integration of REs and energy peak reduction [31,32]. Nevertheless, V2G technology is completely influenced by policies and battery degradation as detailed by Uddin, Dubarry and Glick [33]. Consequently, it is of paramount importance to analyze V2G from different social dimensions [34].

Finally, cybersecurity aims to protect ECUs from being violated by modifying the internal code and calibration. Of course, this could lead to critical situations where someone could take control of the vehicle. Several strategies can be followed. For example, a gateway can be integrated into the network architecture with the aim of keeping ECUs from being accessed in a reading or writing mode from an external computer unless this computer is connected to the manufacturer's network. Generally, an ECU stores several keys needed to assure its integrity. If an ECU fails, it must be analyzed whether there is a hardware or software problem. To do this, the security must be disabled. After that process, the ECU is not allowed to be installed in the vehicle again. As shown in this research, at that moment, the ECU is scrapped.

This research formulates a proposal to reduce emissions by using energy savings during product design based on ER, EDR, EC, EVs and V2G. This study, which was done on an ECU supplier in Europe when developing new products, has three goals. Firstly, it proposes an algorithm based on EVs, ER, EDR and EC with the aim of improving energy efficiency and RE integration in the product design process by using the Here® application programming interface (API) provided by Here® (Eindhoven, Holland), the data published by the French system operator (The system operator is responsible for coordinating electricity supply and demand in real time in a manner that avoids fluctuations in frequency or disruption of supply. This requires maintaining a continuous balance between the electricity supply from generators and demand from consumers, while ensuring that appropriate reserves are available to manage any system events.) and neural networks [35]. Secondly, this study shows how ER, EDR, EC and V2G contribute to eco-design by reducing emissions during product design. In addition, compatibility between V2G and vehicle-to-home (V2H) is analyzed. Finally, this research also describes how cybersecurity impacts eco-design and how it could involve more waste generation.

The paper is organized as follows. Section 2 describes the method used in this research. Section 3 displays the results obtained. Section 4 discusses these results and, finally, Section 5 draws the main conclusions of this research.

2. Methods

This section is organized as follows. Section 2.1 describes the method used in this study. Section 2.2 explains the trips made as well as the number of engineers chosen for this study. Section 2.3 displays the equipment employed. Section 2.4 describes the algorithm implementation. Section 2.5 displays the method used to analyze data statistically. Section 2.6 briefly introduces the concept of V2G. Section 2.7 analyzes the main topics linked to cybersecurity.

2.1. Overview of the Methods Used

When it comes to the method (Figure 1), two key points must be considered to assess the contribution of ED, EDR and EC to eco-design. The former consists of choosing the optimal locations and the number of engineers participating in this research. The latter shows how the algorithm works and its implementation. To do this, the Here® API was used to determine the best route considering EC, EDR and ER models based on data from the vehicle control unit (VCU), traffic state, drivers' habits (the way of using the accelerator or brake pedals among other data), current battery capacity and potential recharge needs among others [35–37]. In addition, the EC concept shows drivers when a recharge process might be necessary, taking into account when the RE contribution is higher.

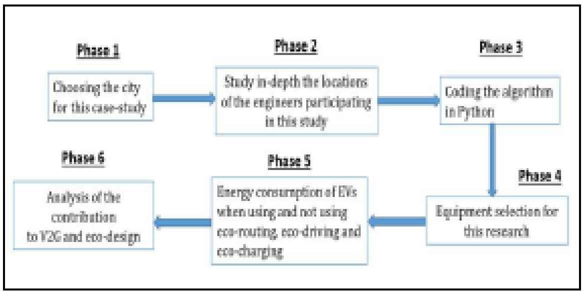

Figure 1. Method followed in this research.

2.2. Description of Trips

Figure 2 and Table 1 depict the number of engineers participating in this study, the locations where these engineers live and the distance from each location to the design center. These locations were chosen to cover all parts of the city (north, south, east and west of Toulouse) and the number of engineers was assigned depending on traffic conditions in such a way that the more traffic jams were close to the location, the bigger number of engineers was chosen. All vehicles used were equipped with a 40-kWh battery. Their autonomy was close to 250 km. The maximum speed was 144 km/h, and the engine torque was around 320 Nm.

Figure 2. Locations of engineers assigned to the project.

Table 1. Distance between locations and the design center.

From	To	Distance (km)	Number of Engineers
Location A		24	10
Location B		20	8
Location C	Design center	26	8
Location D		22	12
Location E		19	6

The trips were made in 2019 with the aim of collecting important data such as energy consumption by using the equipment described in Section 2.3.

2.3. Equipment

The following means were used in this research:

1. The software and hardware of a VCU used by the company subjected to this case-study was designed by one of the most important European suppliers specialized in embedded systems;
2. All vehicles employed in this study were EVs equipped with a 40-kWh battery;
3. Throughout this research, it is necessary to make measurements of different software variables stored in the VCU memory. In this study, the Inca® software provided by ETAS® (Stuttgart, Germany) was used as it allows reading memory locations/software variables in real time [38]; Here® and Open Charge Map® APIs with the aim of choosing the best route and showing the closest battery charger locations [35,39]. Open Charge Map is a non-commercial, non-profit, electric vehicle data service hosted and supported by a community of businesses, charities, developers and interested parties around the world;
4. The MDA® software provided by ETAS® (Stuttgart, Germany) to analyze all data acquisition [40].

2.4. Algorithm Used in This Research

The algorithm provided in the Supplementary Data and used in this research is depicted in Figure 3. First of all, the energy consumption models available in the Here® API are tuned [36]. Then, the driver sets the destination by using a web interface. Afterwards, the algorithm assesses the optimal route for the driver. To do this, the Here® API is called by the Python code by using the Routingmode parameter [35]. This parameter has an attribute named Type which can take three types of routes: the route that requires the least amount of travel time, the shortest one which reduces and optimizes the distance covered and finally the balanced mode which searches for the correct balance between distance and time (only for trucks). The way how the algorithm works to determine the best routes belongs to the Here® know-how. The Python code receives from the Here® API the potential routes (the shortest, the fastest and the balanced one) to the destination and the energy consumption for each one. The application chooses the one with less energy consumption as explained later. Appendix A provides further information about how to set up Here® to help the reader to reproduce the experiment. Finally, the algorithm runs a block called eco-charging which aims to calculate the RE contribution and energy structure generation (wind power, photovoltaic, etc.) by using neural networks. The driver is, therefore, informed about when the charging process is greener.

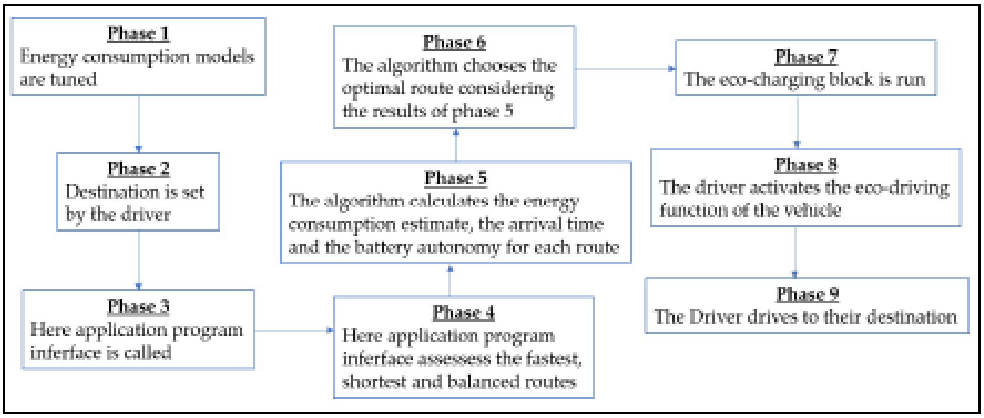

Figure 3. Algorithm description.

Here® API provides energy consumption models that allow assessing energy consumption by using several parameters such as speed, auxiliary energy consumption (radio, cooling/heating, accelerations, decelerations, etc.). The way of tuning these models implies that the value of each parameter in kWh is provided depending on the speed value (if possible, as not all parameters are linked to speed such as auxiliary systems). In this research, these values were established by performing data acquisition after the drivers participating in this research made each trip 50 times in different periods and traffic conditions (Section 2.2). As shown in Figure 4, the Inca® software installed in a laptop as well as input/output from ETAS® supplier modules were used to perform the data acquisition. Finally, the tuning engineers of the company that collaborated in this study assessed the factors' values by analyzing the data acquisition by using the MDA® software provided by ETAS® (Stuttgart, Germany) and internal procedures. To introduce this information by using the Here® interface is easy. First of all, the reader must indicate to Here® that the standard energy consumption model will be used. Figure 5 shows an example that helps the reader to reproduce this study. Once these factors are tuned and introduced in the Python code, Here® returns the energy consumption estimate for each type of route (the fastest, the shortest and the balanced one). Consequently, the one with less energy consumption is chosen. Taking into account the initial battery capacity before the trip, the algorithm can determine if a charge is needed during the trip.

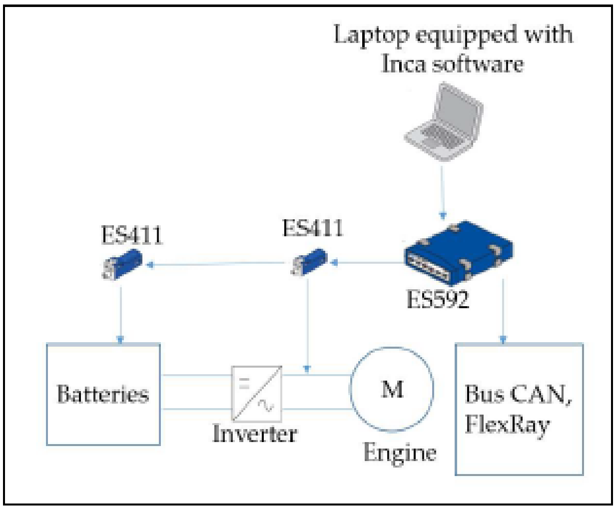

Figure 4. Connection of the laptop to the electric vehicle (EV).

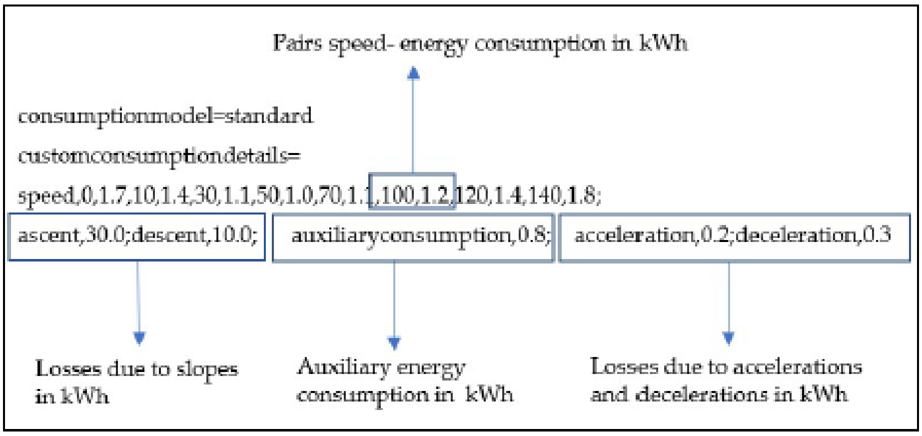

Figure 5. How to configure the energy consumption model.

Finally, the EC block is run, and the eco-score (how REs are integrated into the charging process) is assessed. The aim of this block is to determine the RE contribution when the charging process may take place considering the battery capacity. In addition, an estimate of energy structure (wind power, fuel, etc.) is made. The block is depicted in Figure 6. In phase 1, several factors are analyzed such as the battery capacity and the energy consumption for a specific journey, among others. It must be reminded that the energy consumption was estimated earlier by using the energy consumption model. Furthermore, the most likely time when the charging process takes place can be assessed (phase 2). Therefore, the RE contribution and most likely energy source mix (coal, solar energy, gas, etc.) can be obtained as detailed later by using gated recurrent unit (GRU) networks and nonlinear autoregressive (NAR) neural networks (phase 3) [41–45]. Finally, the EC is assessed considering the RE contribution. In addition, the algorithm proposed in this paper provides information about different parameters such as chargers thanks to Open Charge Map API [35].

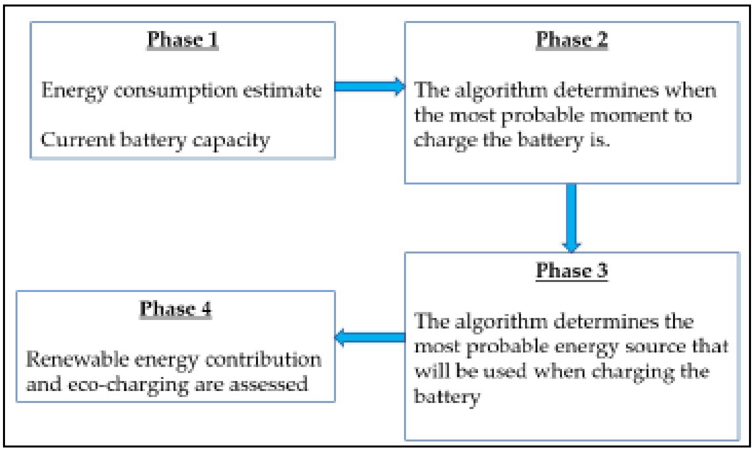

Figure 6. Emissions estimated by using several parameters.

The EC score measures how green the charging process is considering the RE contribution. It can be assessed as given by Equation (1):

$$Eco - charging = \frac{RE_{c,t}}{RE_{max,d}} \tag{1}$$

where $RE_{c,t}$ is the RE contribution to the total electricity demand at t (in MW) and $RE_{max,d}$ is the maximal RE contribution (in MW) during the day when the charging process takes place. Both parameters are calculated by using neural networks. RE contribution is measured by using Equation (2):

$$RE_c = \frac{RE}{RE + NRE} \tag{2}$$

where RE_c is the RE contribution (in %), RE is the total electricity generated by RE sources (in MW) and NRE is the total electricity generated by non-RE such as coal (in MW).

$RE_{c,t}$ and $RE_{max,d}$ are estimated as follows. The French system operator publishes files on a daily basis in which one can find the CO_2 generation structure and the total electricity demand of the day [46]. It must be taken into account that electricity demand and total RE contribution are stationary series. In other words, the pattern is repeated. Only some aspects have to be considered such as weekends and seasons. Anyway, two electricity consumption peaks can be found every day. Consequently, NAR networks are needed to model the electricity demand prediction for a specific day from a desired time (for example, departure planned at 7 p.m.) to midnight. The Python code analyzes the results returned by the neural network and determines the maximum RE contribution of the day. Finally, Equations (1) and (2) are assessed.

Typical recurrent networks present problems when it comes to long-term predictions due to the vanishing gradient problem. Engineers face this problem when training recurrent neural networks with gradient-based learning methods and backpropagation. When using this method, each of the neural network's weights receive an update proportional to the partial derivative of the error function with respect to the current weight in each iteration of training. In some cases, the gradient will be vanishingly small. Consequently, the weight does not change its value, and might stop the neural network training. To enhance long-term predictions, long short-term memory or GRU can be used. In this research, GRUs have been chosen, as they are more efficient (they require less memory). GRU is a recurrent neural network architecture that uses update and reset gates (Figure 7).

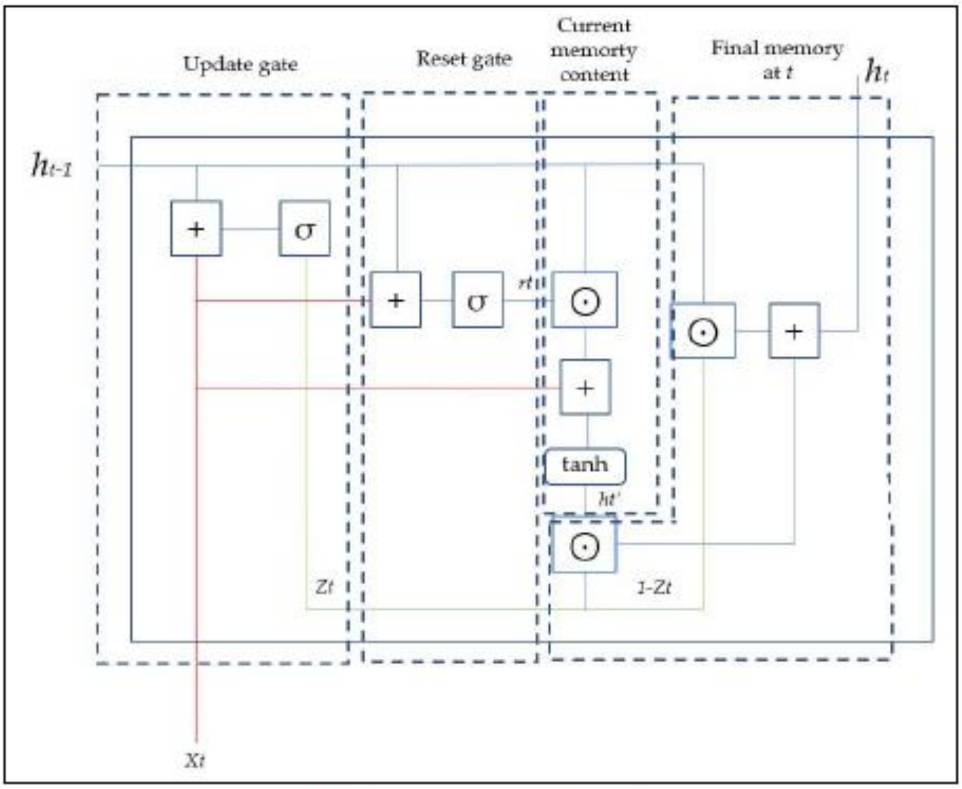

Figure 7. Gated recurrent unit (GRU) architecture.

Mathematically, the process is as follows:

(a) Update gate for time step t

The update gate z_t is calculated by following Equation (3):

$$z_t = \sigma \times \left(W^{(z)} \times x_t + U^{(z)} \times h_{t-1}\right) \quad (3)$$

where x_t is the inputs presented to the network, $W^{(z)}$ is its weight matrix, h_{t-1} holds the information of the previous step $t-1$ and $U^{(z)}$ is its weight matrix. Both results are added, and a sigmoid activation is applied to squash the result between 1 and 0. The update gate allows determining how much of the past information should be passed along to the future.

(b) Reset gate for time step t

It is given by Equation (4).

$$r_t = \sigma \times \left(W^{(r)} \times x_t + U^{(r)} \times h_{t-1}\right) \quad (4)$$

The meaning of this factor is the same as for Equation (3) except r_t which is the reset gate. The reset gate corresponds to the past information which must be forgotten.

(c) Current memory content

The new memory content h'_t uses the reset gate to store relevant information from the past.

$$h'_t = \tan \mathrm{h}(W \times x_t + r_t \times U \odot h_{t-1}) \quad (5)$$

The meaning of this factor is the same as for Equations (3) and (4). $\odot$ represents the Hadamard product.

(d) Final memory at a current step

In this step, the vector h_t is calculated by using Equation (6). This vector holds the information for the current unit and passes it down to the network. To do this, the update gate is needed.

$$h_t = z_t \odot h_{t-1} + (1 - z_t) \odot h'_t \tag{6}$$

The GRU network was coded in Python. Figure 8 shows the pseudocode. To reproduce the results, the reader must have the data published by the French system operator for the last four years. The first three-year data are used for inputs of the network and the last-year data are employed as targets to train the network. It is of paramount importance to rescale all data to make them range between 0 and 1 to assure the network performance. The network parameters are set up by using the keras package. First of all, with the Sequential parameter, the code specifies that the model is sequential, and the output of each layer is the input for the next layer. In this study, the authors have used the Dropout function which is a technique where randomly selected neurons are ignored during training. This means that their contribution to the activation of downstream neurons is temporally removed on the forward pass and any weight updates are not applied to the neuron on the backward pass. The main advantage of this technique is that the network becomes less sensitive to the specific weights of neurons. The method used to analyze the error loss is the mean squared error which is widely recommended for regression problems. The method used to optimize the model is Adam which is an optimization algorithm that can be used instead of the classical stochastic gradient descent procedure to update network weights iteratively based on training data. It offers many advantages such as straightforward implementation and computational efficiency, among others. Other comments can be found in the pseudocode (Figure 8).

The algorithm estimates the structure generation for the next two hours (Figure 9) by using the data published by the French system operator (CO_2 generation structure and the total electricity demand of the day) and NAR networks. These networks are useful when handling time series and predictions. These networks have been created and trained in an open loop. In this case, the targets are used as feedback. Then, the networks are verified in a close loop [41–43,47]. Mathematically, NAR networks can be expressed by

$$\hat{y}(t) = f(y(t-1) + y(t-2) + \ldots + y(t-d) + \varepsilon(t) \tag{7}$$

where f represents the network response taking into account the previous input data, and $\varepsilon(t)$ is the difference between the predicted value $\hat{y}(t)$ and the actual y. The number of delays establishes the d values to be considered for the prediction. The number of hidden layers and neurons per layer is flexible to achieve the best performance of the neural network under design. This number must be carefully chosen to avoid an increase in the neural network complexity. The effect of choosing the value of the delay parameter is shown in Figure 10. As one can see, a high d implies that the predicted line series line changes slower. On the other hand, when d is lower, the predicted line series follows the real power wind value more accurately. However, if d takes a very low value, then the predicted line series does not follow the real power wind value. The main explanation is that d determines the weight given to past values. Consequently, significant changes in trend are not detected which could happen due to weather conditions. That is why, NAR networks are used in this research as an estimation and the accuracy remains on GRU networks. Anyway, this is not an issue as Matlab® allows correcting predictions if predicted values are known. This is the case of this application as it can predict $t+1$, $t+2$, $t+3\ldots$ at a specific moment t. However, when the moment is $t+1$, the neural network can be updated as the predicted $t+1$ value and the real $t+1$ are known in real time (the French system operator publishes the needed data in real time). To reproduce the results of this study, the authors obtained good predictions for the next 2 h with $d = 3$ when using the data belonging to 2019 published by the French system operator. The pseudocode of the NAR network is shown in Figure 11, coded by using Matlab® (Natick, MA, USA) The NAR networks were trained by using the trainlm function which implies that bias and weights are updated according to Levenberg–Marquardt optimization. It is the fastest backpropagation algorithm even if it may require more memory than other methods.

```
#Import packages. Here some examples

Import numpy
Import pandas
import keras
import tensorflow
import sklearn

#import data published by the French System Operator
pd.read_csv(file_2016) # used as inputs
pd.read_csv(file_2017) # used as inputs
pd.read_csv(file_2018) # used as inputs
pd.read_csv(file_2019) # used as targets

#Prepare data to be used as inputs of the LSTM network
X=reshape_data_inputs_inputs # used as inputs

#rescale data to 0-1 scale
minimum = amin(X, axis = −1).reshape
maximum = np.amax(X, axis = −1).reshape()
X = (X-minimum)/(maximum-minimum)
Y = (Y-minimum)/(maximum-minimum)

#network parameters. A model is a stack of layers
model = Sequential()

#Adding layer with the number of inputs specified
model.add(GRU(128, input_shape = (data), return_sequences = True))
model.add(Dropout(0.1)) # Dropout = 10%

# Boolean. Whether to return the last output in the output sequence, or the full sequence.
model.add(GRU(64, return_sequences = True) #Adding layer with the number of inputs specified
model.add(Dropout(0.1)) # Dropout = 10%


# Boolean. Whether to return the last output in the output sequence, or the full sequence.
model.add(GRU(32, return_sequences = True)) ) #Adding layer with the number of inputs specified
model.add(Dropout(0.3)) # Dropout = 30%

#Optimizer choice and error measurement method
model.compile(loss = 'mean_squared_error', optimizer = 'adam')

#Training
his = model.fit(X, Y, batch_size = 2, nb_epoch = 5, verbose = 1)# , callbacks=[TQDMNotebookCallback()])

#Plot error
plt.legend("mean squared error", loc="upper left")
```

Figure 8. Pseudocode for the GRU networks.

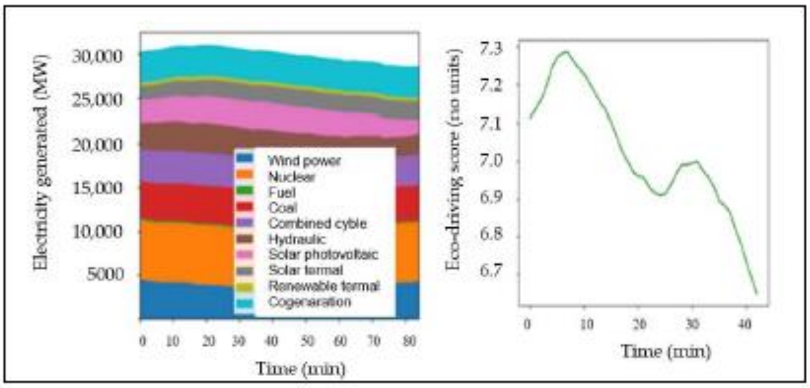

Figure 9. Interface of the application: eco-driving (EDR) and energy structure generation.

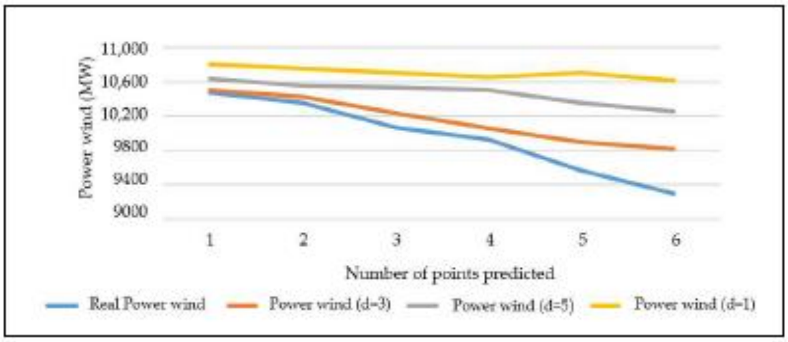

Figure 10. Prediction vs. real values depending on the delay parameter.

```
%Pseudocode for Matlab®

data = French_system_operator_data; % loading data

net = narnet(1:3,10); % three delays and 10 hidden layer size. Train in open loop and training function
trainlm

[Xs,Xi,Ai,datas] = preparets(net,{},{},T); % preparing data to train

net = train(net,Xs,datas,Xi,Ai); %train the network

[Y,Xf,Af] = net(Xs,Xi,Ai); %network performance assessment

perf = perform(net,datas,Y)

[netc,Xic,Aic] = closeloop(net,Xf,Af); %predicting results in close loop
```

Figure 11. Pseudocode for nonlinear autoregressive (NAR) networks.

2.5. Data Analysis

As detailed in the result section, the data obtained in this research seem to be close to a normal distribution. Consequently, a method must be set to confirm this assumption. To do this, the package named PASSWR belonging to the R software was used. This package includes commands such as EDA which provide a lot of information to perform exploratory data analysis such as kurtosis, skewness and p-value. Kurtosis is a statistical measure that defines how heavily the tails of distribution differ from the tails of a normal distribution. Therefore, kurtosis identifies whether the tails of a given distribution contain extreme values. For a normal distribution, its value is 3. There are three types of kurtosis: mesokurtic when kurtosis is close to 3; leptokurtic when values are quite higher than 3; and platykurtic when the extreme values are less than the normal distribution. Skewness essentially measures the symmetry of the distribution. For a normal distribution, its value should be close to 0. At this point, it is important to highlight that symmetry does not imply that the data correspond to a normal distribution. Thus, these two parameters must be analyzed carefully. Finally, the p-value or probability value is the probability of obtaining test results at least as extreme as the results actually observed during the test, assuming that the null hypothesis is correct.

Plots are also of paramount importance when analyzing the data. In this research, three plots were used: histograms, Q-Q plots and boxplot. A histogram is a graphical representation which organizes a group of data points into user-specified ranges. The Q–Q plot, or quartile–quartile plot, is a graphical tool used to assess if a set of data plausibly came from some theorical distribution such as a normal one. Finally, a box plot is a graphical rendition of statistical data based on the minimum, first quartile, median, third quartile and maximum. In this graph, the top of the rectangle indicates the third quartile, a horizontal line near the middle of the rectangle indicates the median and the bottom of the rectangle indicates the first quartile.

Figure 12 shows an example of how a dataset corresponds to a normal distribution by using PASSWR.

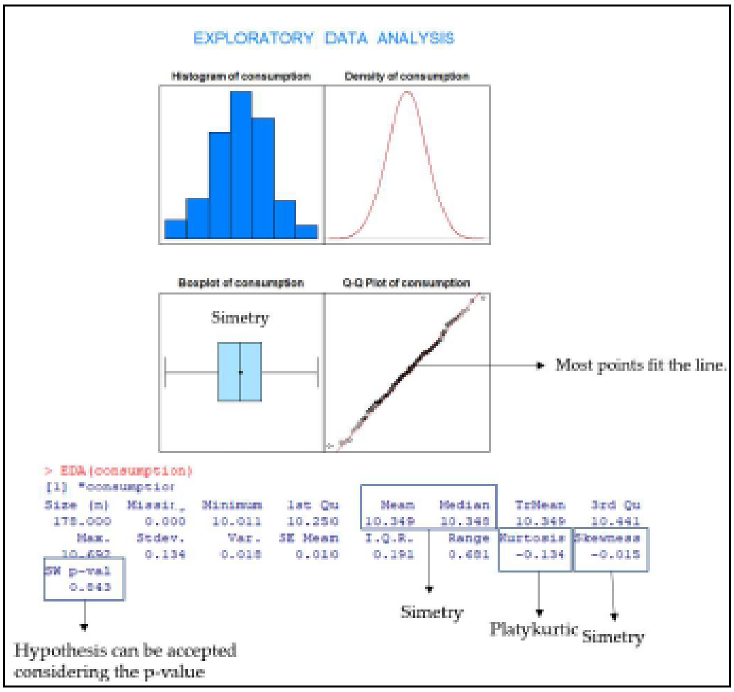

Figure 12. Example of the exploratory analysis performed in this research.

2.6. V2G

The energy consumption of 5 buildings located in the design center and the contribution of V2G to reduce their energy consumption during product design were analyzed. Among the means that consume electricity in these buildings, one can find those that consume a great amount of energy such as test benches and, on the contrary, a considerable number of others such as computers, faxes and photocopying machines, which have much lower energy consumption. It is of paramount importance to assess the amount of energy that the EV can inject to reduce emissions and energy consumption during product design.

2.7. Cybersecurity

In this research, some data about the number of ECUs scrapped due to cybersecurity reasons will be shared. All these data are normalized considering the annual production (Section 3.4).

3. Results

This section is structured as follows. Section 3.1 shows the energy saving obtained when using EVs and the algorithm proposed in this research. This first analysis is of paramount importance because it allows assessing the amount of energy available for V2G. In addition, the trips from the design center to the factory are also discussed. Section 3.2 analyzes the energy consumption of the buildings located at the design center. The participation in V2G depends on energy policies. However, it must be highlighted that the charging process must be performed when the RE contribution is significant. Section 3.3 will also try to analyze that. Section 3.4 estimates waste due to ECU scrapped for cybersecurity reasons.

3.1. Distribution of Engineers

The project considered in this research deals with designing an ECU. As shown in Figure 2 and Table 1, the reader can find the city and the location of all engineers participating in this project. Table 2 shows the statistical results achieved when processing the data obtained during the trips with no traffic jams. Without any traffic jams, the time needed to go from each location to the design center is very similar. Skewness is close to zero. Consequently, the distribution is symmetric. Kurtosis values show that the data distribution tails do not differ from normal distribution ones. The *p*-value represents the null hypothesis: the data follow a normal distribution. The null hypothesis can be considered as true if p-value > 0.05. Considering that the skewness and the kurtosis are sensitive to the sample size, the normality test was also confirmed by using Q–Q plots and a histogram which confirmed the normal hypothesis.

Table 2. Statistics parameters obtained without any traffic jams.

Factor	Location A		Location B		Location C		Location D		Location E	
	N.A. (1)	A.U. (2)	N.A. (1)	A.U. (2)	N.A. (1)	A.U. (2)	N.A. (1)	A.U. (2)	N.A. (1)	A.U. (2)
Mean	8.9	8.7	7.8	7.5	9.9	9.6	8.4	8.1	7.2	6.9
Std deviation	0.2	0.15	0.18	0.15	0.16	0.12	0.19	0.15	0.16	0.12
Kurtosis	3.9	4.1	3.7	4.5	4.1	4.2	4.1	3.9	4.1	4.3
Skewness	−0.135	−0.121	−0.041	−0.032	−0.025	−0.015	0.035	0.03	0.08	0.045
p-value	0.412	0.452	0.425	0.454	0.325	0.343	0.385	0.410	0.396	0.332

(1) N.A. means no algorithm is used. (2) A.U. means the algorithm is used.

Tables 3 and 4 show the statistical results achieved when processing the data obtained during the trips with traffic jams and mixed conditions. The way of interpreting the results is similar to Table 2. Q–Q plots and histogram confirm the assumptions.

Table 3. Statistics parameters obtained with traffic jams.

Factor	Location A		Location B		Location C		Location D		Location E	
	N.A [(1)]	A.U. [(2)]	N.A. [(1)]	A.U. [(2)]	N.A. [(1)]	A.U. [(2)]	N.A. [(1)]	A.U. [(2)]	N.A. [(1)]	A.U. [(2)]
Mean	12.5	10.3	10.8	8.7	13.2	11.5	11.2	9.4	11.5	8.3
Std deviation	0.9	0.89	0.98	0.95	0.75	0.81	0.99	0.88	1.15	1.01
Kurtosis	3.2	3.4	3.15	3.35	3.25	3.45	3.185	3.36	3.15	3.58
Skewness	0.281	0.112	0.231	0.189	0.261	0.185	0.259	0.189	0.262	0.215
p-value	0.356	0.411	0.389	0.422	0.321	0.468	0.369	0.498	0.311	0.336

[(1)] N.A. means no algorithm is used. [(2)] A.U. means the algorithm is used.

Table 4. Statistics parameters obtained in mixed traffic conditions.

Factor	Location A		Location B		Location C		Location D		Location E	
	N.A [(1)]	A.U. [(2)]	N.A. [(1)]	A.U. [(2)]	N.A. [(1)]	A.U. [(2)]	N.A. [(1)]	A.U. [(2)]	N.A. [(1)]	A.U. [(2)]
Mean	10.8	9.2	9.5	8.1	12.1	10.5	10.6	8.8	10.1	7.5
Std deviation	0.6	0.5	0.9	0.6	0.75	0.65	0.85	0.5	0.65	0.58
Kurtosis	3.5	3.7	3.45	3.98	3.8	3.9	3.68	3.56	3.98	3.99
Skewness	0.145	−0.081	0.158	0.148	0.225	0.118	2.435	0.195	2.72	0.238
p-value	0.359	0.401	0.256	0.385	0.458	0.453	0.399	0.401	0.358	0.367

[(1)] N.A. means no algorithm is used. [(2)] A.U. means the algorithm is used.

3.2. *Building Energy Consumption*

The design center is composed of five buildings with different configurations. Table 5 shows the characteristics of each building. These items were chosen after having analyzed the energy consumption data provided by the company participating in this research. Only the most highly energy-consuming items were considered.

Table 5. Characteristics of buildings.

	Building 1	Building 2	Building 3	Building 4	Building 5
Number of floors	1	1	1	2	2
Number of meeting rooms	2	4	3	8	12
Number of offices	10	12	10	20	40
Type of heating system	Electric	Electric	Electric	Electric	Electric
Type of cooling system	Electric	Electric	Electric	Electric	Electric
Lighting	Fluorescent low-power energy consumption lighting system	Fluorescent low-power energy consumption lighting system	Fluorescent low-power energy consumption lighting system	Fluorescent low-power energy consumption lighting system	Fluorescent low-power energy consumption lighting system
Number of people in the building	20	25	20	40	80

Figure 13 depicts the energy consumption for each building. These values were obtained by using electric meters installed in the design center, the number of hours of operation considering timetables and average energy consumption of facilities/items. The main differences between these buildings were the number of people working, which affects the number of other elements present in the buildings such as printers, and the presence of laboratories.

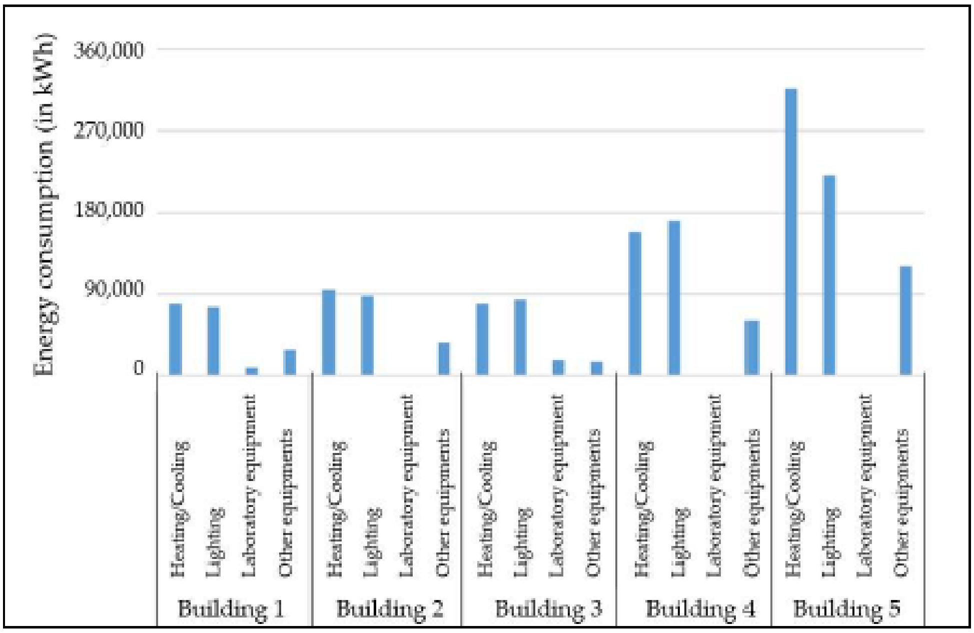

Figure 13. Energy consumption of each building.

Considering the results shown in Tables 2–4, the energy to be used for V2G technology is assessed. However, V2G must be also compatible with V2H technology. Logically, the drivers will be willing to save this available energy for their own homes rather than injecting it into the grid. This topic will be discussed in the result discussion in Section 4.3.

Table 6 depicts the main results obtained in this research. An additional gain of 2.89% to V2G can be obtained when considering mixed traffic conditions (with and without traffic jams). This percentage can be increased by 6.9% considering the influence of traffic jams. This percentage was obtained by dividing the total energy available per day when using and not using the algorithm

Table 6. Summary of energy saving.

Title Traffic Conditions	Total Energy Consumption (in kWh)	Total Energy Available When Using the Algorithm Per Day in kWh	Total Energy Available without Using the Algorithm Per Day in kWh	Contribution to Meet Energy Consumption When Using the Algorithm (in %)	Contribution to Meet Energy Consumption without Using the Algorithm (in %)	Delta Per Day without Using the Algorithm (in kWh)	Delta Per Year When Using the Algorithm (in kWh)
Without traffic jams	7540.1	1397.6	1384.4	18.5	18.4	13.2	2904
With traffic jams	7540.1	1332.8	1239.6	17.7	16.4	93.2	20,504
Mix with and without traffic jams	7540.1	1376.9	1337.1	18.3	17.7	39.8	8756

3.3. *RE Contribution to Charge EVs*

The EVs belonging to employees should inject power into the grid when electricity consumption peaks take place. Generally, every day there are two peaks of electricity consumption which depend on the season and on the day of the week (Figure 14). Anyway, these peaks usually occur between 8 a.m. and 1:30 p.m. and from 5:30 p.m. to 8 p.m. In this research, power should be injected to reduce the first electricity consumption peak. The fact of injecting this power into the grid from EVs implies that EVs should be recharged in some cases by the user to have enough energy to come back home. Consequently, it is of paramount importance to charge them when REs are being used. In other words, the recharge process should be done when the mix is greener. The algorithm proposed by the authors allows determining when the RE contribution is higher by using Equations (1) and (2). Therefore, the charging process is greener.

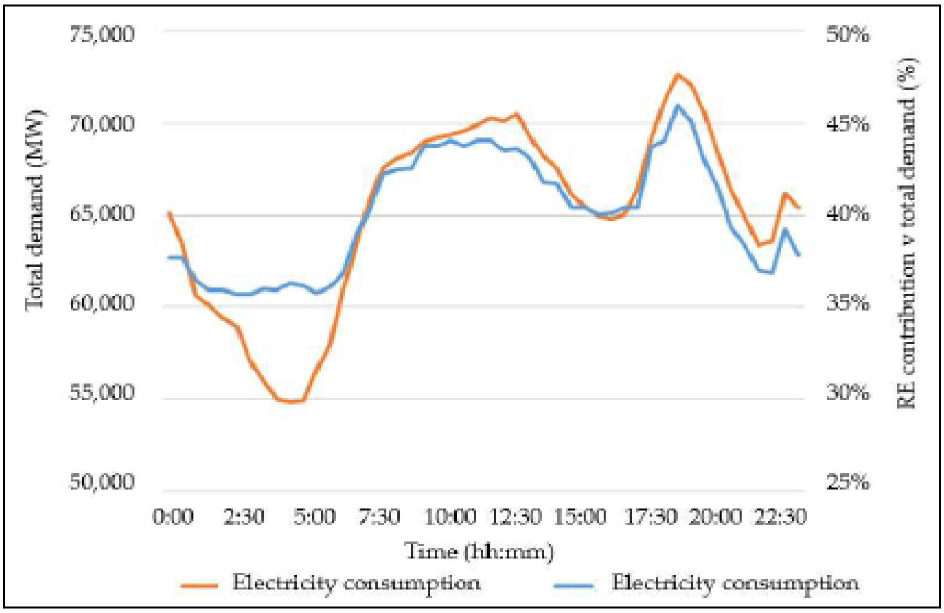

Figure 14. Renewable energy (RE) contribution for January 2018. Source: French system operator.

Table 7 shows the electricity prices offered by different suppliers in France.

Table 7. Electricity prices.

Supplier	Price for Off-Peak Periods (EUR/kWh)	Price for Peak Periods (EUR/kWh)
Supplier 1	0.1230	0.1580
Supplier 2	0.1272	0.1638
Supplier 3	0.1280	0.1660
Supplier 4	0.1161	0.1483
Supplier 5	0.1138	0.1453
Supplier 6	0.1180	0.1513

Considering the prices shown in Table 7 and Figure 14, several conclusions can be drawn: Firstly, when the RE contribution is high, charging the EV battery is expensive, and the other way around.

Secondly, drivers participating in V2G and V2H should charge their EVs between off-peak periods. Consequently, rapid or fast charging should be used. Consequently, battery life is reduced. Finally, the RE contribution vs. traditional energy sources during off-peak periods must be increased.

Policies should change to increase the RE contribution when charging EVs especially during off-peak periods. The French government announced a new plan to increase the usage of RE. This plan has new different objectives for 2023. In this new plan, two scenarios are unfolded: an optimistic and a pessimistic one. The most important figures imply that the total power installed should reach 69,980 MW in the worst-case scenario and 76,743 MW in the optimistic one. In addition to this, 150 and 167 TWh renewably sourced electricity should be delivered, respectively. It must be reminded that the current renewable capacity in France is close to 56,000 MW. Some important figures to be retained [48]:

- Primary energy consumption by RE: 10.7%;
- Gross electricity production by ER in 2017: 92.6 TWh.

3.4. *Cybersecurity*

As aforementioned in the previous sections, cybersecurity could involve a considerable amount of waste to be considered. Table 8 shows the results of this research considering 120,000 ECUs in series production and 1200 prototype units per year. Firstly, the reader can see the number of ECUs scrapped for one year due to cybersecurity reasons. The percentage of scrapped ECUs when producing prototype ECUs reaches 10.83%. Secondly, ECUs are mainly composed of plastic (housings) and electronic wastes such as microprocessors, resistors, etc. The components used in these ECUs are confidential. In addition to the data depicted in Table 8, other factors must be considered such as: varnish used in the manufacturing process, energy needed to weld and logistic transportation (emissions), among others. It must be remarked that prototype parts have a high scrap rate. Consequently, the waste produced during projects should also be considered in eco-design.

Table 8. Electronic control units (ECUs) scrapped due to cybersecurity.

Component	Quantity	Series Production	Quantity	Prototype Production
Microprocessors	190	0.16%	130	10.83%
Printed circuit board	190		130	
Housing	380		260	
Capacitors	17,100		11,700	
Resistors	21,100		14,436	
Programmable components	190		130	
Input/output connectors	190		130	
Memory RAM	280		260	

4. Discussion

This section discusses the results obtained in this research. Section 4.1 analyzes the algorithm when it comes to sustainability. Section 4.2 describes how the energy efficiency is improved. Section 4.3 explores the RE contribution. Section 4.4 discusses the number of engineers chosen for this study. Section 4.5 entitled *"threats to the validity"*, analyzes the main factors which could have an influence on the results obtained in this research.

4.1. *Sustainability of This Solution*

No matter what kind of powertrain is used in a vehicle (hybrid, electric, diesel or gasoline), CO_2 emissions are always present as analyzed by the International Council on Clean Transportation [49]. As shown in Figure 15, EVs pollute less than conventional vehicles when it comes to life-cycle emissions. Therefore, the algorithm and the solution proposed in this research are sustainable despite the process of charging and discharging that harms the battery. In addition, the EVs increase is confirmed by such a supplier as Continental®, considering the latest news concerning the recent sale of its diesel and petrol powertrain unit. Thermic engine activities are supposed to be reduced while EV activities are most likely to be increased in the year to come.

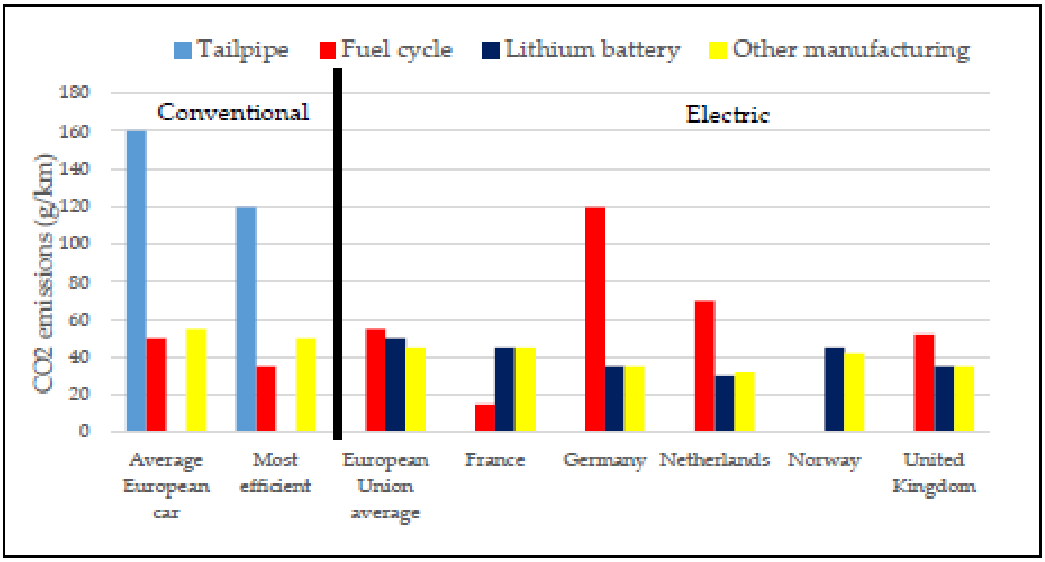

Figure 15. Life-cycle emissions from electric and conventional vehicles. Source: The International Council on Clean Transportation.

4.2. *Energy Efficiency Improvement*

Several policies are pursued with the aim of improving energy consumption based on increasing the RE usage, eco-design and building energy consumption. When it comes to eco-design, energy efficiency is a key factor and engineers try to improve energy consumption during the manufacturing process. When it comes to design processes, the eco-design process is mainly focused on the usage of recyclable raw materials and on the design of products that do not pollute much during their lives and they can also be recycled easily at the end of their lives. This research shows that the design process involves many factors that should be considered as they generate emissions in a significant way. Unfortunately, the eco-design directive does not include many topics that clearly have an influence on emissions during the design process. Investments in V2G technology allow reducing energy consumption during the design process. This reduction is increased when using the algorithm proposed in this study without any additional investment.

Several conclusions can be drawn from the data depicted in Table 5. V2G plays an essential role when it comes to eco-design as a range between 2904 and 20,504 kWh more per year is available when using depending on traffic conditions. In other words, the reduction ranges from 13.2 to 93.2 kWh per day. This figure could be increased by 61.52 kWh in mixed traffic conditions as detailed in Section 4.4. These results were obtained when using only 44 engineers.

The energy efficiency improvement allows reducing emissions. As depicted in Table 9, the emission reduction ranging from 8.96 to 23.55 kg per day was obtained when using the algorithm proposed in this study. These values were obtained taking into account the energy saving (in kWh) and the monthly emission average from January to July 2019. It must be remarked that only 44 engineers participated in this study.

Table 9. Emissions of CO_2 (in g/kWh) on a monthly basis. Source: French system operator.

Title Emissions	January	February	March	April	May	June	July
Emissions (g/kWh)	55.68	51.30	31.24	26.32	24.74	27.65	35.85
Emission reduction per day (kg/kWh). Mixed traffic	2.22	2.04	1.24	1.05	0.98	1.1	1.43
Emission reduction per day (kg/kWh). No traffic jams	5.19	4.78	2.91	2.45	2.31	2.57	3.34

Finally, the fact of reducing energy consumption by using V2G is a topic which has been subjected to research. The contribution may be significant when the smart grid will be fully deployed. However, it should be also considered that V2G must be compatible with V2H. As shown in this research, it is not always the case. Several axes are essential to make them work together. The first one is improving battery capacities in such a way that the owner can use the energy stored in the battery for both purposes (V2H and V2G). The second one is also linked to batteries as the fact of going through charging and discharging processes should not degrade batteries quickly. Finally, the RE contribution must be increased as described in Section 3.3.

4.3. *Renewable Energies*

From a theoretical point of view, it is vital to consider V2G technology to reduce the energy consumption of design buildings. In this case, two factors must be discussed. The first one is EV penetration into the market. The second one is policies. The former is essential due to the fact that the more EVs are sold, the more energy is available for V2G. Policies try to encourage drivers to choose EVs instead of traditional powertrains such as gasoline or diesel engines. Among these measures, one can find exemption from vehicle registration duties or municipal tax discounts. Despite this, the participation in V2G remains unclear for several reasons:

(a) Drivers who cover many kilometers on a daily basis will be forced to choose between V2G and V2H techniques. Considering that if drivers inject energy during the day to reduce the energy consumption in buildings, they will probably need to charge as soon as they get to their homes. Consequently, they cannot participate in V2H;

(b) The fact of reducing prices to make drivers charge their vehicles after 2 p.m. is still far from being the solution as the RE contribution is not substantial. Therefore, it is essential to promote RE facilities.

The algorithm proposed in this research allows choosing the best moment to charge the EV battery considering the electricity mix. Considering all the aforementioned facts, V2G can contribute in a significant way to the reduction of emissions during the design process and should be also a key element to be considered in eco-design. However, the percentage of improvement is completely linked to policies associated with EV recharging.

4.4. *Population Participating in This Study*

Several factors must be considered when it comes to the population participating in this research. Firstly, this research was conducted considering a small size research and development center. It must be taken into account that there are much bigger design centers in France such as the one of Renault located in Lardy (1600 workers) or the one of PSA Peugeot-Citroen located in Carrières-sous-Poissy (1300 workers). Therefore, the number of engineers who can participate when implementing the algorithm will increase. However, policies are still important to encourage people to participate in V2G [33,50].

Figure 16 shows an estimate when choosing a greater number of engineers (400 engineers) and the energy consumption calculated in Section 3.1, and the assumption shown in Table 10. When it comes to the number of engineers, the values were assigned by respecting the percentage of engineers of each location established for the test-case. When it comes to the number of times with and without traffic jams, these values were considered for the whole year. In addition, an error estimate has been added, which represents the nominal estimate with a 20% error, 30% error and so on (Table 11).

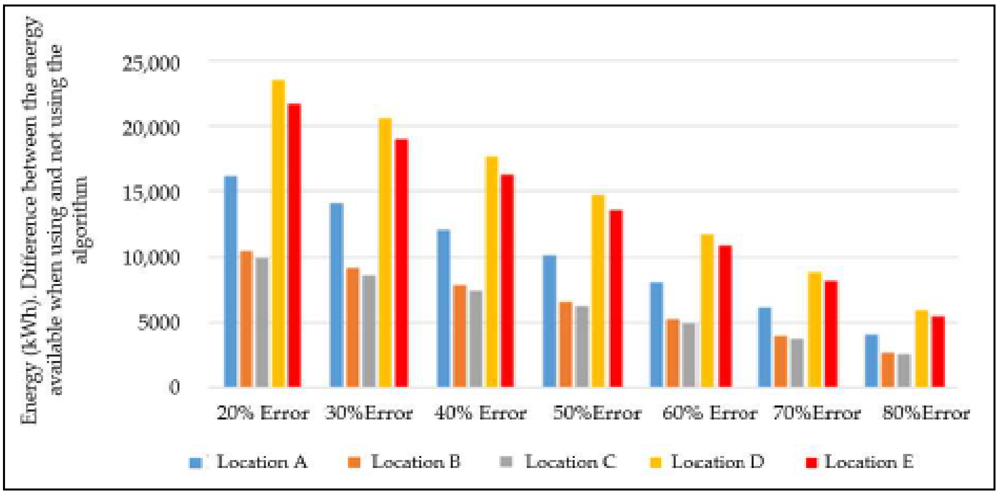

Figure 16. Energy available depending on the error in energy consumption estimate when using 400 engineers.

Table 10. Assumptions when considering a greater number of engineers.

Title Locations	Number of Engineers	Number of Times without and with Traffic Jams
Location A	91	300/60
Location B	73	320/40
Location C	73	316/44
Location D	109	180/120
Location E	54	170/140

Table 11. Gain when considering a greater number of engineers.

Title Energy and Gain Obtained	20% Error	30% Error	40% Error	50% Error	60% Error	70% Error	80% Error
Energy available per year	81,824	71,596	61,368	51,140	40,912	30,684	20,456
Energy available per day	371.93	325.44	278.95	232.45	185.96	139.47	92.98
Gain per day in EUR (0.1347 EUR/kWh)	50.09	43.84	37.57	31.31	25.05	18.79	12.52
Gain per year (220 working days)	11,021	9643.98	8266.26	6888.55	5510.84	4133.13	2755.42

Figure 16 represents the increase in energy available for V2G when using the algorithm. Location D and Location E outperform the rest of the locations when it comes to energy savings. The number of engineers (in other words the number of EVs) is not only the most relevant parameter to obtain more or less contribution to V2G and eco-design as Location E is the one which has fewer engineers/EVs participating in this case-study. Consequently, location is an important parameter.

Another important topic to be discussed is that this algorithm does not require investing in new facilities. Once the design center is adapted to use V2G, no more action is needed except for using this algorithm. As shown in Table 11, the fact of using it implies that an extra gain by EUR 11,021 could be obtained in this authors' estimate. Table 11 also shows the gain (difference between the energy available when using and not using the algorithm).

When considering the number of engineers participating in this case-study, the results are similar (Figure 17). Again, location D and E account for the biggest amount of energy available for V2G. Consequently, the V2G energy value does not only depend on the number of EVs (engineers) participating in this research but the location of the engineers.

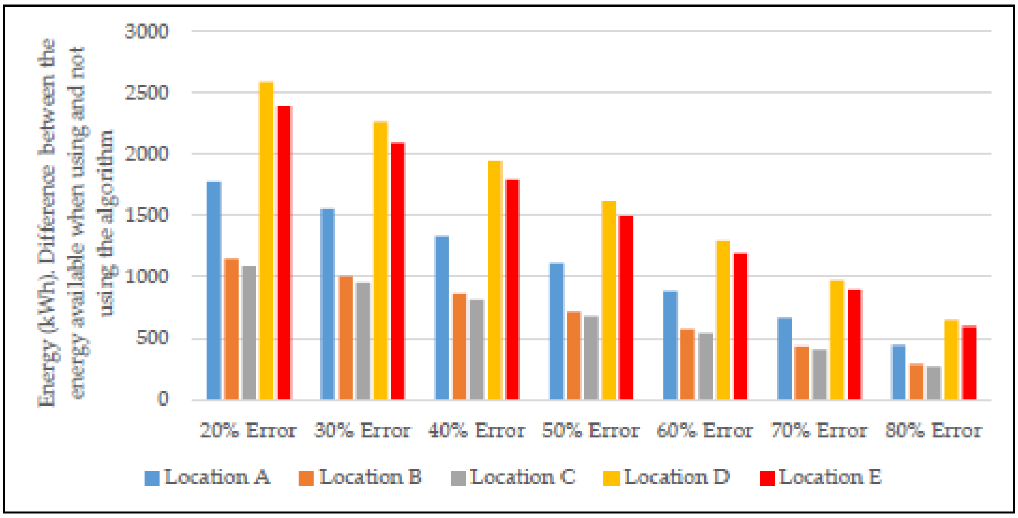

Figure 17. Energy available depending on the error in the energy consumption estimate when using 44 engineers.

Choosing the optimal location is of paramount importance. If 22 EVs had been assigned to Location D and E respectively (Figure 18), the energy available for V2G would have been increased from 39.8 to 61.52 kWh per day.

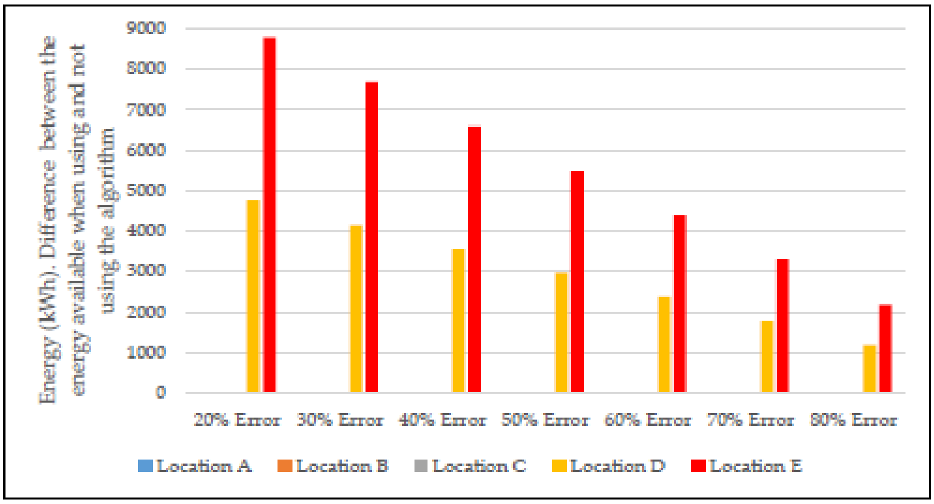

Figure 18. Energy available depending on the error in the energy consumption estimate when using 44 engineers only for destinations D and E.

Several factors such as distance and traffic state among others determine the optimal location to optimize the V2G contribution. Therefore, models which can predict the V2G contribution when determining the optimal number of engineers and location must be developed, as the fact of using more EVs does not imply that the contribution to V2G has increased in a significant way. This algorithm can be used offline to determine the optimal locations by following the procedure shown in Figure 19. Here® API can assess the routes offline to obtain the time needed and, consequently, the EV energy consumption. Thanks to this procedure, the energy consumption estimate for each driver can be obtained and, consequently, the optimal locations can be chosen.

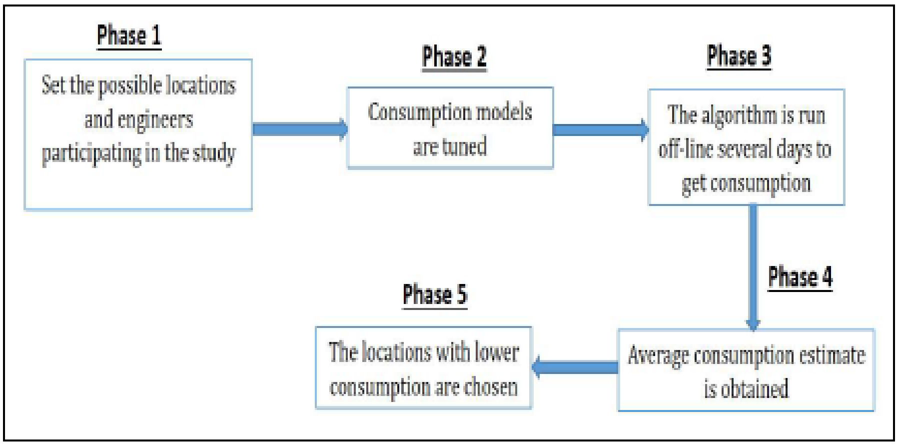

Figure 19. Method to choose the optimal locations.

4.5. Threats to Validity

In this research, internal and external threats have been analyzed. Table 12 depicts the main variables to be controlled (predictors) to check the influence on the response variables. Even though the authors considered that factors 1, 2 and 3 were chosen properly to obtain fully representative results, it is obvious that all these factors could reduce the energy available for V2G. Therefore, the energy consumption of the buildings belonging to the design center which can be supported by V2G, could be decreased. Table 12 also describes the mitigation plan (description column) to justify that the results of this research are well founded.

Table 12. Factors to be controlled in this research.

Id Factor	Factor	Description
1	Sample used in this research to validate the hypothesis	The number of engineers considered to assess the energy available for V2G in this research. The authors considered that this figure is significant enough as it accounts for 45% of the total number of the engineers who work in the design center.
2	Distribution of locations	Locations of engineers' homes. The authors consider that their locations are optimal as they are situated in all possible directions around the city (north, south, east and west)
3	Season considered in this research	This research was conducted during the winter, the spring and the summer. Consequently, the battery operated in cold and hot temperatures to calculate the number of kWh available for V2G.
4	Energy available for V2G	Energy available in the EV battery to be used for V2G.
5	GRU estimate	Every time a GRU neural network is built to predict a time series, a performance assessment of the network is carried out. The process is done by using Python. As shown in Figure 20, the performance assessment values were good enough to use the network (8E-07 the worst case). When it comes to NAR networks, they are automatically built by using Matlab®.

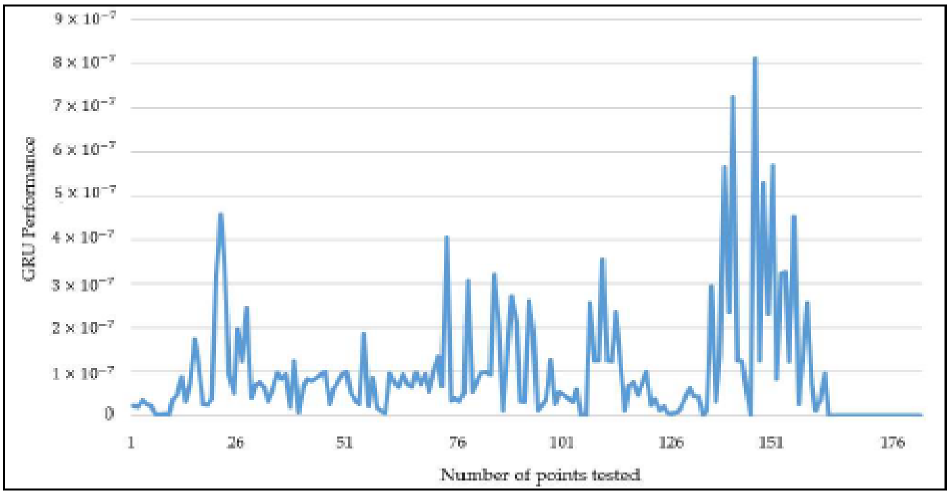

Figure 20. GRU performance evaluation.

When it comes to external variables, the authors consider that the main conclusions of this paper can be applied to other cities or design centers as:

(a) No matter how much energy is accumulated in vehicles, this energy can be used, and it can contribute to the reduction of energy consumption by buildings of design centers;
(b) V2H and V2G techniques are most unlikely to be compatible when EV energy consumption is high.

During this research, every day when the trips were going to be taken, the following tasks were carried out:

(a) New GRU and NAR networks were implemented considering the data published by the French system operator the day before;
(b) The predicted results by the GRU and NAR neural networks were compared with the results published by the French system operator considering the periods of the day when the trips were made. Figure 18 shows the performance of the GRU neural network obtained when it was implemented on a daily basis.

The aim of this procedure was to assure that the neural networks worked as expected.

5. Conclusions

Eco-design deals with several topics such as low-impact materials, energy efficiency, design for reuse and recycle, sustainable design standards and renewable energy, among others. However, energy efficiency should not only deal with manufacturing but the product design phase. This research is focused on how electric vehicles (EVs), vehicle-to-grid (V2G), eco-driving, eco-routing and eco-charging can contribute to energy savings during product design. Therefore, these factors play an essential role in eco-design. Taking into account the method and results obtained in this research, the following conclusions are drawn:

(a) Energy savings The algorithm proposed in this research which uses energy consumption models properly tuned for eco-driving, eco-routing and eco-charging allows reducing energy consumption between 2.89% and 6.9% as proved in Section 3.2. In addition to this reduction, neural networks provide drivers with useful information about when the optimal moment is to charge the battery, taking into account the renewable energy contribution.

(b) Eco-design This algorithm contributes to eco-design as:

- (*b*.1) It allows reducing emissions between 8.96 and 23.55 kg per day (Section 4.2) of CO_2 more than when EVs do not use the algorithm in this study;
- (*b*.2) This research shows that not only the number of EVs is important to increase the energy available but the way of choosing the engineers' locations. The algorithm proposed in this study allows establishing the optimal locations. Therefore, a design center could obtain more energy by using a specific number of EVs as described in Section 4.4;
- (*b*.3) The contribution of V2G to the building energy demand ranges between 0.5% and 1.3% when using the algorithm proposed in this study in a small design center (Section 3.2).

(c) V2G and Vehicle-to-home (V2H) compatibility Even though battery performance is not degraded due to charging and discharging processes, current policies keep the user from participating in V2G and V2H at the same time. The EV charging fee is higher than the savings obtained when using V2H. Consequently, V2G is not compatible with V2H. However, policies cannot be changed if the power of renewable energy installed is not increased. Therefore, renewable energy mix vs. non-renewable energy is not high enough. Consequently, the policies to promote EVs are as important as increasing the power of the renewable energy installed (Sections 3.3 and 4.2)

(d) Cybersecurity As detailed in the cybersecurity section, some policies to assure that an electronic control unit (ECU) is not violated imply that the electronic control unit is no longer available. In this present study, 190 kg of waste is generated every year taking into account the electronic control units scrapped. Consequently, some techniques used for ECU cybersecurity are not eco-friendly, and more research should be done into this topic to better integrate cybersecurity and eco-design (Section 3.4).

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/13/15/3997/s1, A beta version of the application coded in Python is provided. The full version cannot be provided as the company which has collaborated in this study has not authorized it. The measurements obtained when driving EVs are not provided as the company which has collaborated in this study has not authorized it.

Author Contributions: D.B.-D. and P.M.O.-C. were primarily responsible for creating this manuscript. D.B.-D. and P.M.O.-C. were responsible for creating the application in Python and obtained all measurements performed in this research. A.C.-S. and J.-J.B.-P. analyzed the data obtained as well as policies and collected data and information from the French System Operator. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A How to Configure the Calls to Here® API

Here® API is able to provide a great deal of information about how to go from A to B. However, the calls to the Here® API must be done properly. In this research, the API is called by using the pseudocode shown in Figure A1. The string PARAM must be built. The following parameters are indicated:

(A) apiKey. This key is generated when a user is registered on the Here® developers' website. Replace XXXX by your key;

(B) Waypoint0 and waypoint1 contain the latitude and longitude information about the origin and destination locations which are stored in the location_coor dictionary in Python. The Geopy package can be used to obtain coordinates;

(C) Mode. This parameter contains important information for the Here® API such as the type of route (the fastest, the shortest) and traffic state;

(D) As stated in Section 2, a consumption model has to be indicated by using consumptionmodel and customsonsumptiondetails.

The response variable stores the answer from the Here® server.

```
"""Routing the fastest"""
PARAM = ("apiKey = XXXX" +
"&waypoint0 = geo!" + str(location_coor [1]) + "," + str(location_coor[2]) + "&waypoint1 = geo!"+
str(location_coor[3]) + "," + str(location_coor[4]) + "&mode =
fastest;car;traffic:enabled&consumptionmodel = standard&" +
"customconsumptiondetails = " +
"speed,0,1.7,10,1.4,30,1.1,50,1.0,70,1.1100,1.2120,1.4140,1.8;" +
"ascent,30.0;descent,10.0;auxiliaryconsumption,0.8;acceleration,0.2;deceleration,0.3" +
"&legAttributes = links,trafficTime&linkAttributes = consumption,dynamicSpeedInfo")
response[1] = routing(PARAM)


"""Routing the shortest"""
PARAM = ("apiKey = XXXXXX" +
"&waypoint0 = geo!" + str(location_coor[1]) + "," + str(location_coor[2]) + "&waypoint1 = geo!"+
str(location_coor[3]) + "," + str(location_coor[4]) + "&mode = fastest;car;traffic:enabled")
response[2] = routing(PARAM)
```

Figure A1. Pseudocode to obtain the desired Here® answer.

The answer from Here® is a json file. The reader can find a great deal of information such as the speed estimation taking into account traffic conditions (*trafficSpeed* parameter), time elapsed for a specific speed and consumption, etc. The reader can easily estimate the average consumption in kWh, the average speed, etc.

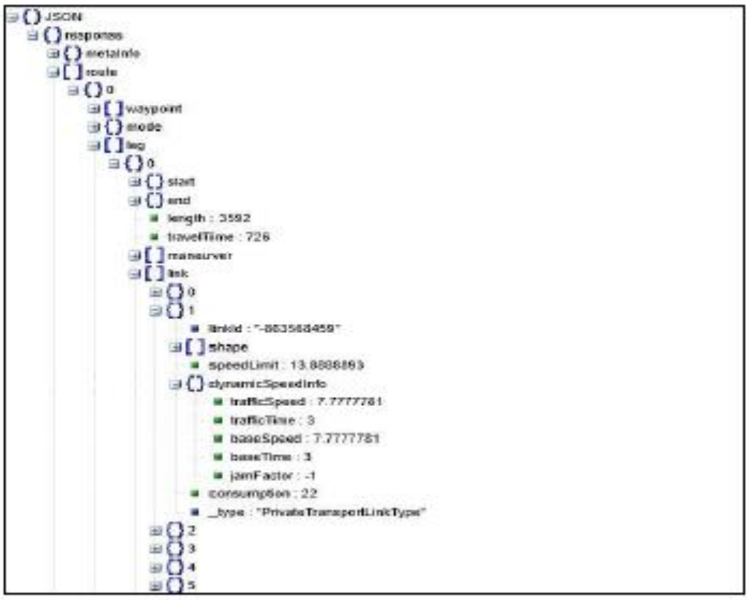

Figure A2. Here® answer. Json format.

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ANEXO VI. Factor de impacto. Energies

Journal Citation Report

Clarivate

Journal Citation Reports Browse journals

Home › Journal profile

JCR YEAR

2020

Energies

Open Access since 2008

ISSN

N/A

EISSN

1996-1073

JCR ABBREVIATION

ENERGIES

ISO ABBREVIATION

Energies

Journal information

EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

ENERGY & FUELS - SCIE

LANGUAGES	REGION	1ST ELECTRONIC JCR YEAR
English	SWITZERLAND	2010

Publisher information

PUBLISHER	ADDRESS	PUBLICATION FREQUENCY
MDPI	ST ALBAN-ANLAGE 66, CH-4052 BASEL, SWITZERLAND	24 issues/year

2020 JOURNAL IMPACT FACTOR

3.004

View calculation

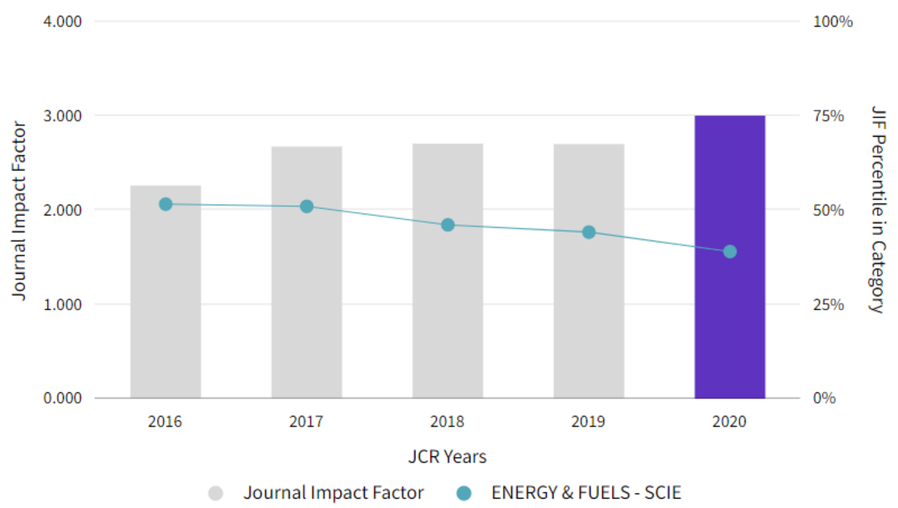
JOURNAL IMPACT FACTOR WITHOUT SELF CITATIONS

2.245

View calculation

Journal Impact Factor Trend 2020

Export

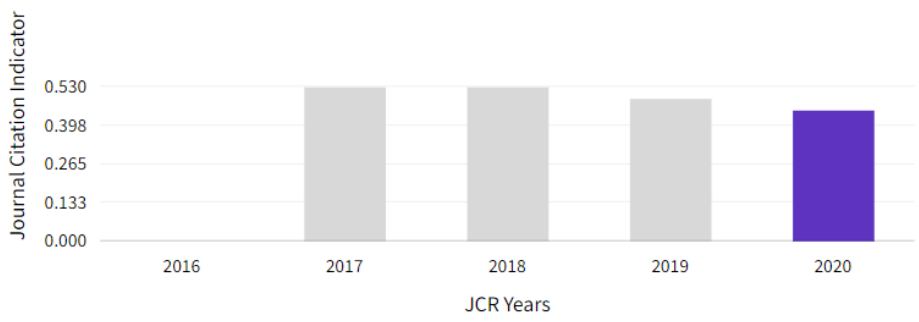


Journal Citation Indicator (JCI)

Export

0.45

The Journal Citation Indicator (JCI) is the average Category Normalized Citation Impact (CNCI) of citable items (articles & reviews) published by a journal over a recent three year period. The average JCI in a category is 1. Journals with a JCI of 1.5 have 50% more citation impact than the average in that category. It may be used alongside other metrics to help you evaluate journals. Learn more

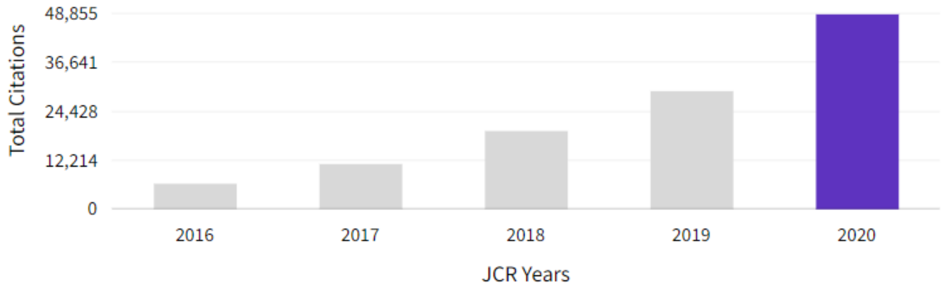


Total Citations

Export

48,855

The total number of times that a journal has been cited by all journals included in the database in the JCR year. Citations to journals listed in JCR are compiled annually from the JCR years combined database, regardless of which JCR edition lists the journal.



Rank by Journal Impact Factor

Journals within a category are sorted in descending order by Journal Impact Factor (JIF) resulting in the Category Ranking below. A separate rank is shown for each category in which the journal is listed in JCR. Data for the most recent year is presented at the top of the list, with other years shown in reverse chronological order. Learn more

EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

ENERGY & FUELS

70/114

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2020	70/114	Q3	39.04
2019	63/112	Q3	44.20
2018	56/103	Q3	46.12
2017	48/97	Q2	51.03
2016	45/92	Q2	51.63

Rank by Journal Citation Indicator (JCI)

Journals within a category are sorted in descending order by Journal Citation Indicator (JCI) resulting in the Category Ranking below. A separate rank is shown for each category in which the journal is listed in JCR. Data for the most recent year is presented at the top of the list, with other years shown in reverse chronological order. Learn more

CATEGORY

ENERGY & FUELS

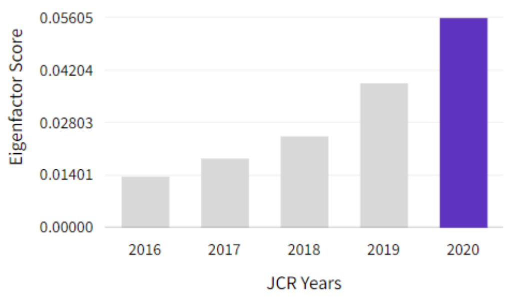
81/133

JCR YEAR	JCI RANK	JCI QUARTILE	JCI PERCENTILE
2020	81/133	Q3	39.47
2019	71/112	Q3	37.05
2018	62/103	Q3	40.29
2017	56/95	Q3	41.58

Eigenfactor Score

0.05605

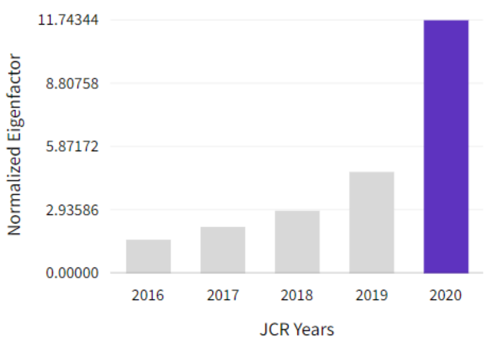
The Eigenfactor Score is a reflection of the density of the network of citations around the journal using 5 years of cited content as cited by the Current Year. It considers both the number of citations and the source of those citations, so that highly cited sources will influence the network more than less cited sources. The Eigenfactor calculation does not include journal self-citations. Learn more



Normalized Eigenfactor

11.74344

The Normalized Eigenfactor Score is the Eigenfactor score normalized, by rescaling the total number of journals in the JCR each year, so that the average journal has a score of 1. Journals can then be compared and influence measured by their score relative to 1. Learn more



Article influence score

0.444

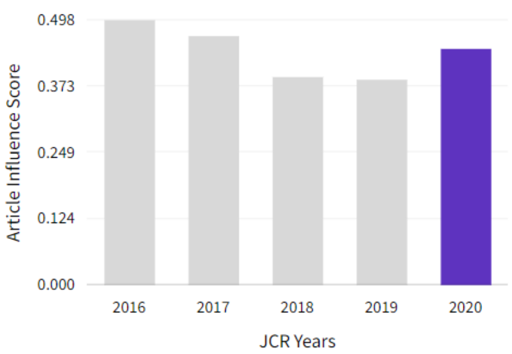
The Article Influence Score normalizes the Eigenfactor Score according to the cumulative size of the cited journal across the prior five years. The mean Article Influence Score for each article is 1.00. A score greater than 1.00 indicates that each article in the journal has above-average influence. Learn more

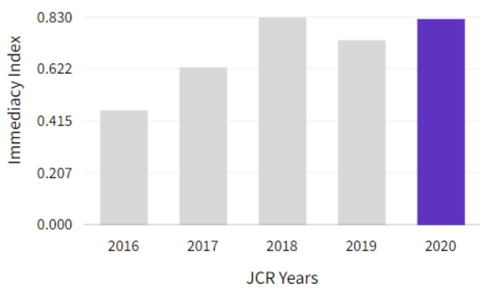
Immediacy Index

0.823

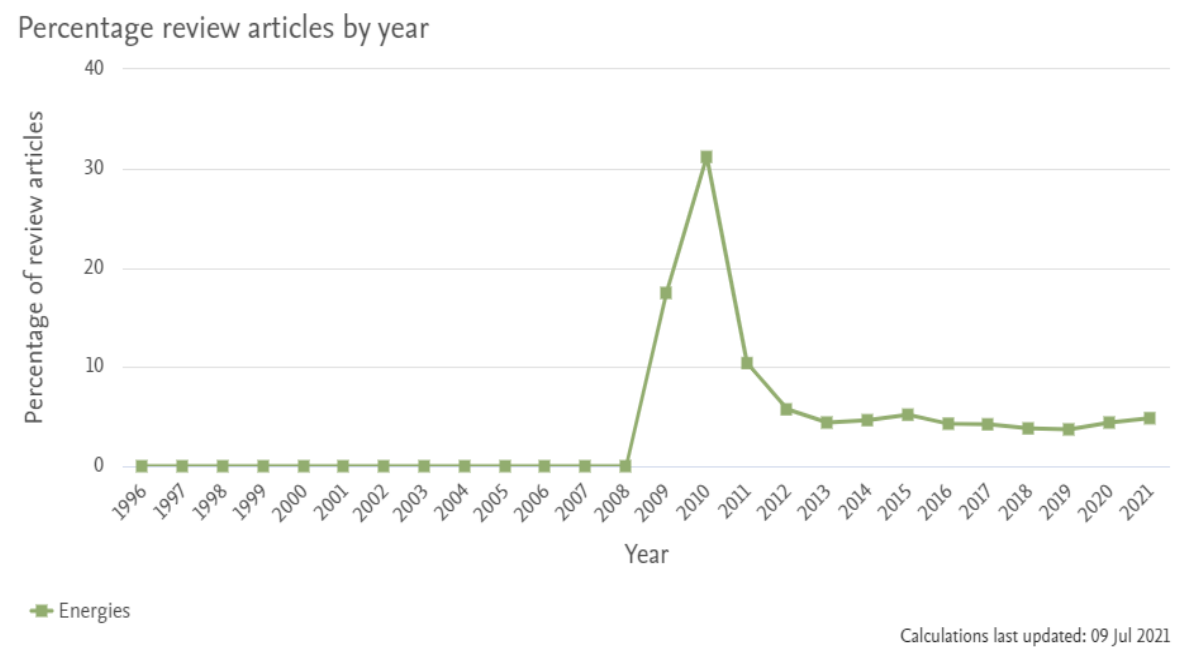
View Calculation

The Immediacy Index is the count of citations in the current year to the journal that reference content in this same year. Journals that have a consistently high Immediacy Index attract citations rapidly. Learn more





Scopus


Percentage review articles by year
Percentage of review articles
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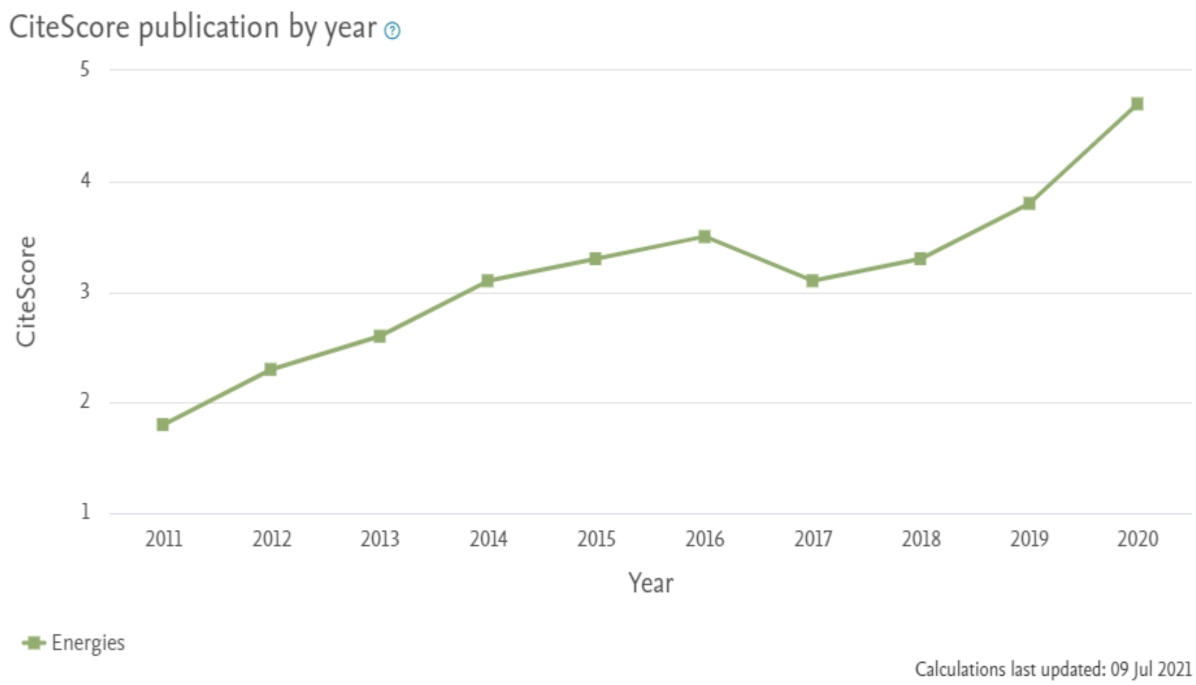
Calculations last updated: 09 Jul 2021


CiteScore publication by year
CiteScore
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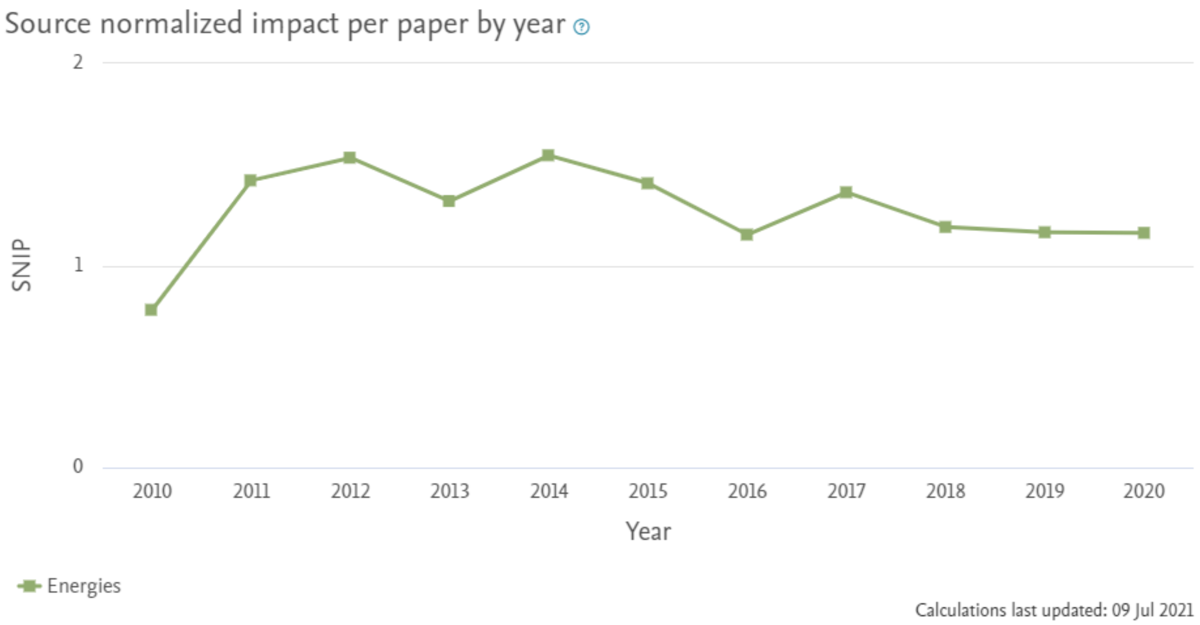
Energies
Calculations last updated: 09 Jul 2021


Source normalized impact per paper by year
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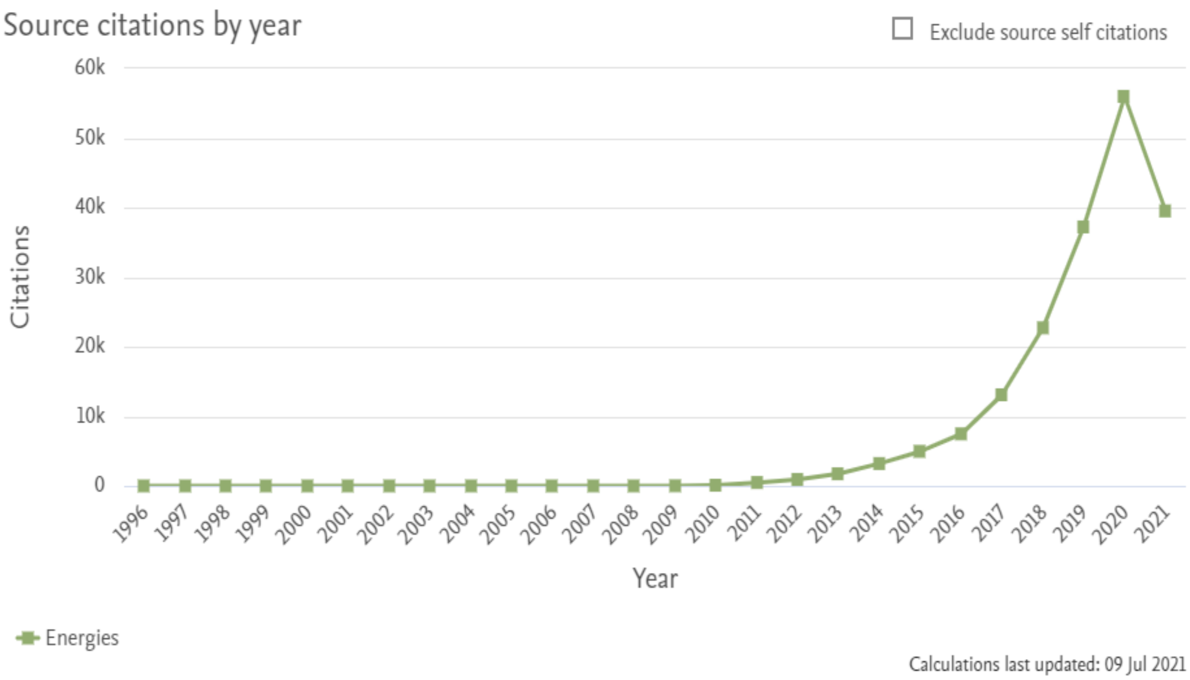
Calculations last updated: 09 Jul 2021


Source citations by year
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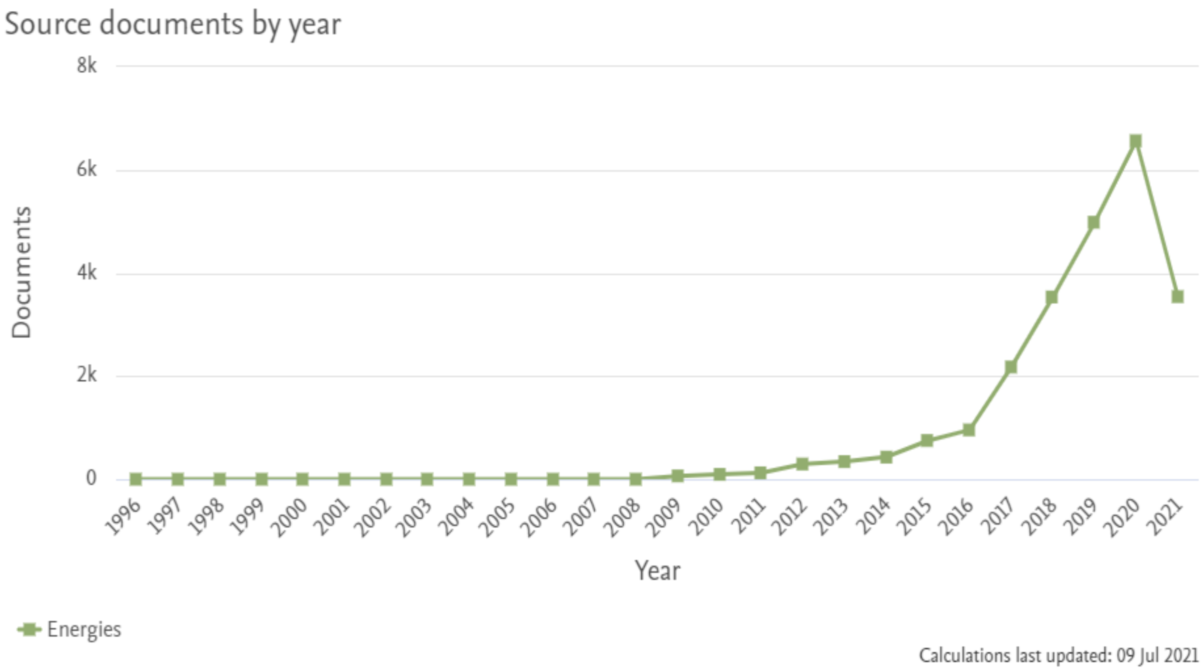

Source documents by year
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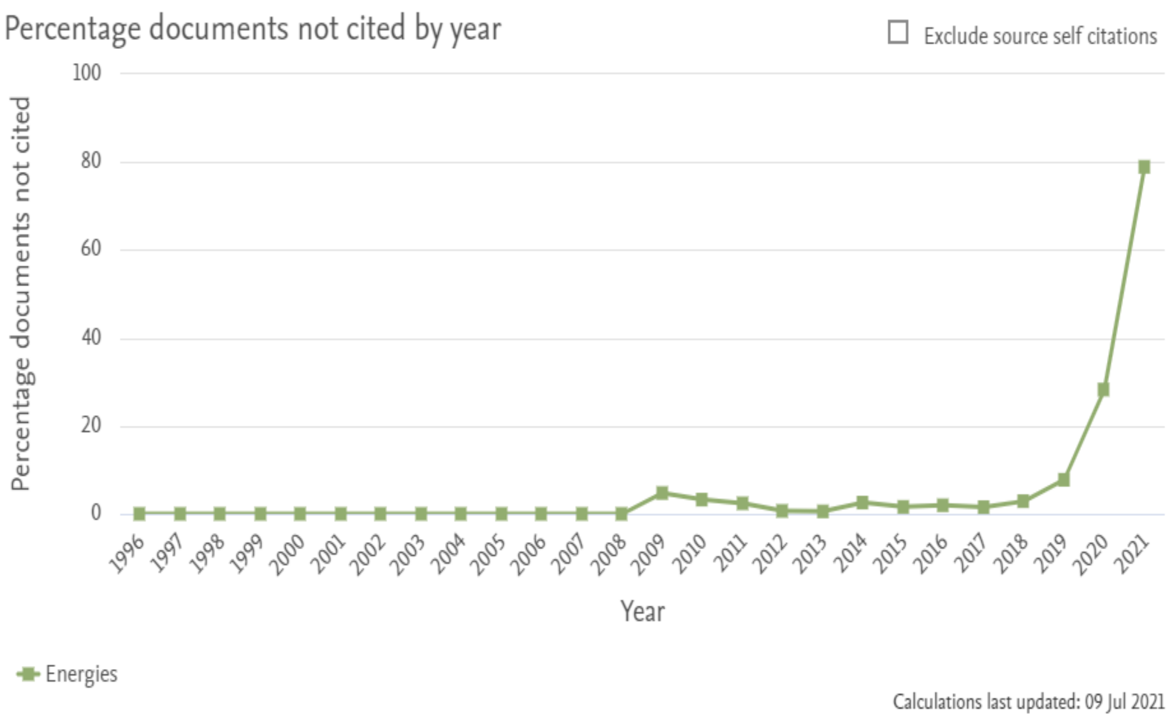
Calculations last updated: 09 Jul 2021



Percentage documents not cited by year
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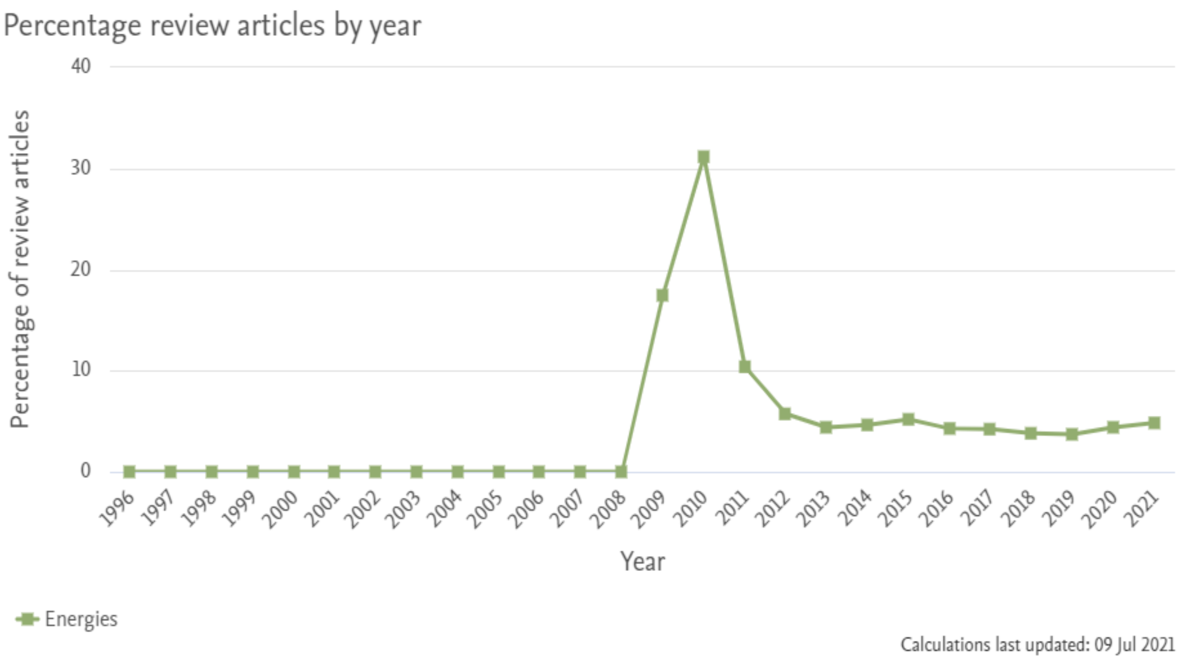
Calculations last updated: 09 Jul 2021


Percentage review articles by year
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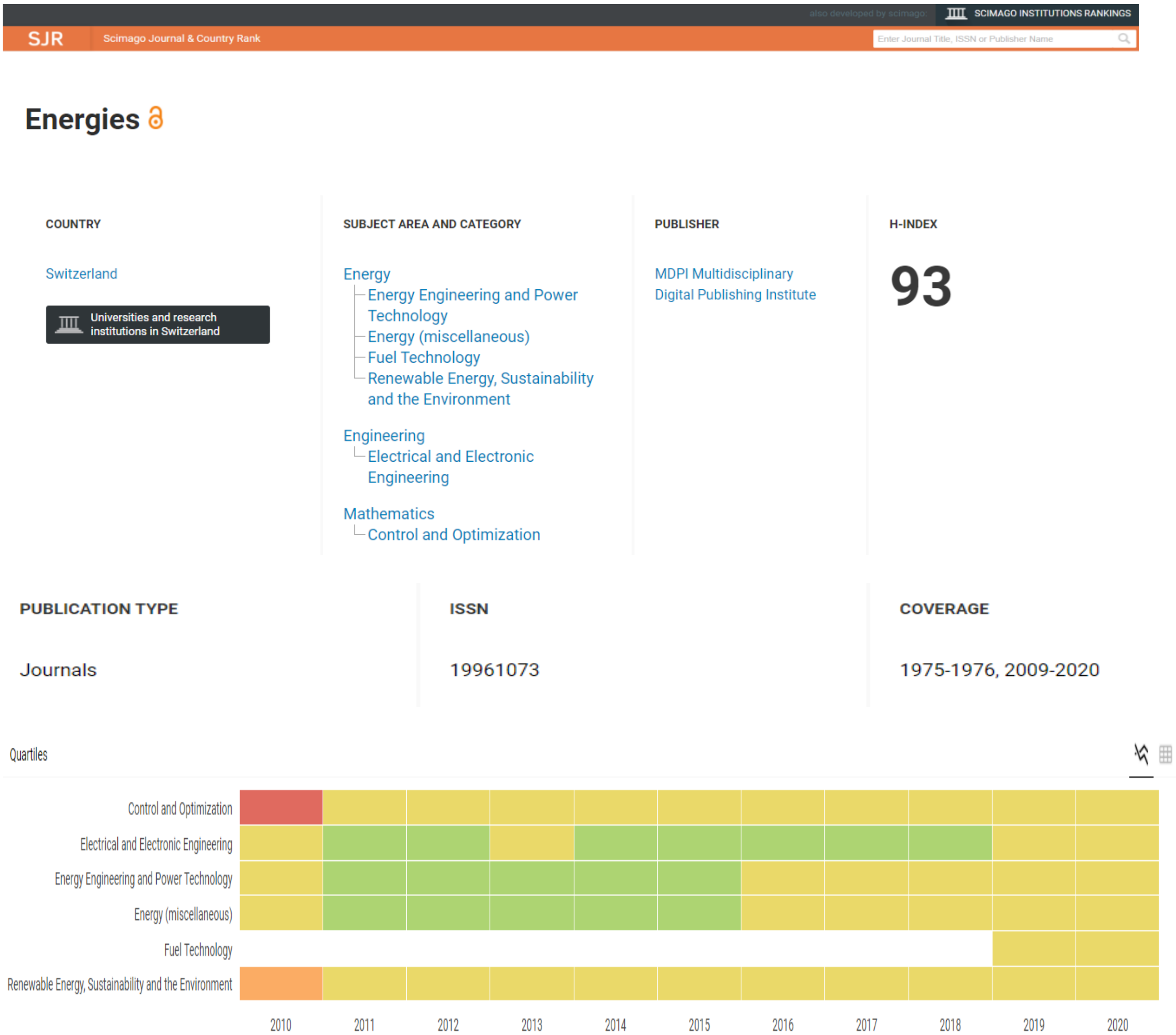
Calculations last updated: 09 Jul 2021

Scimago


SCIMAGO INSTITUTIONS RANKINGS
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Scimago Journal & Country Rank
Enter Journal Title, ISSN or Publisher Name
Energies
COUNTRY
Switzerland
Universities and research institutions in Switzerland
SUBJECT AREA AND CATEGORY
Energy
Energy Engineering and Power Technology
Energy (miscellaneous)
Fuel Technology
Renewable Energy, Sustainability and the Environment
Engineering
Electrical and Electronic Engineering
Mathematics
Control and Optimization
PUBLISHER
MDPI Multidisciplinary Digital Publishing Institute
H-INDEX
93
PUBLICATION TYPE
Journals
ISSN
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COVERAGE
1975-1976, 2009-2020
Quartiles
Control and Optimization
Electrical and Electronic Engineering
Energy Engineering and Power Technology
Energy (miscellaneous)
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Renewable Energy, Sustainability and the Environment
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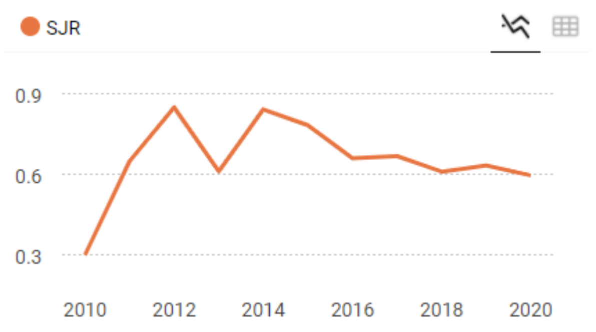

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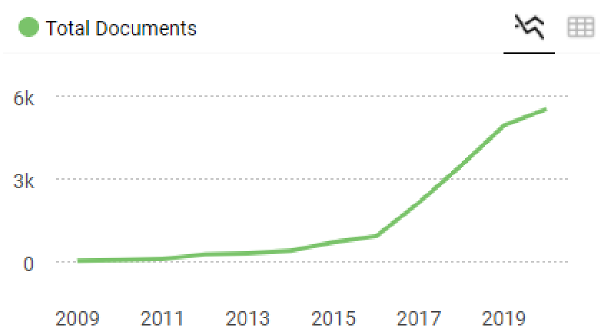

Total Documents
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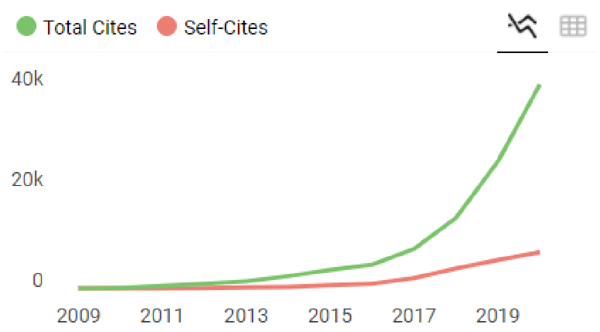

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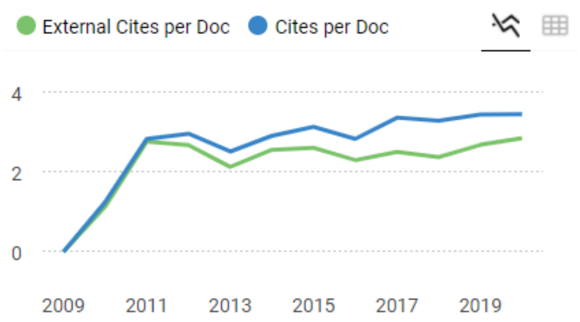

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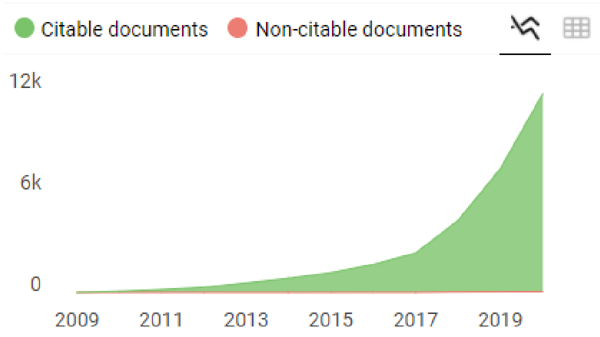

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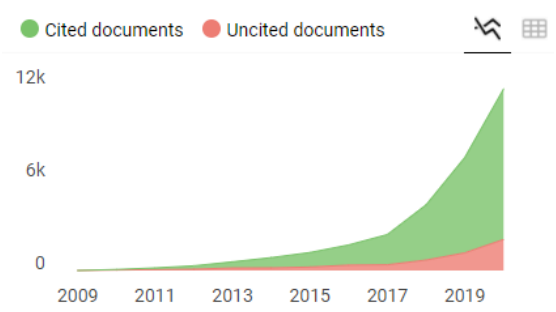

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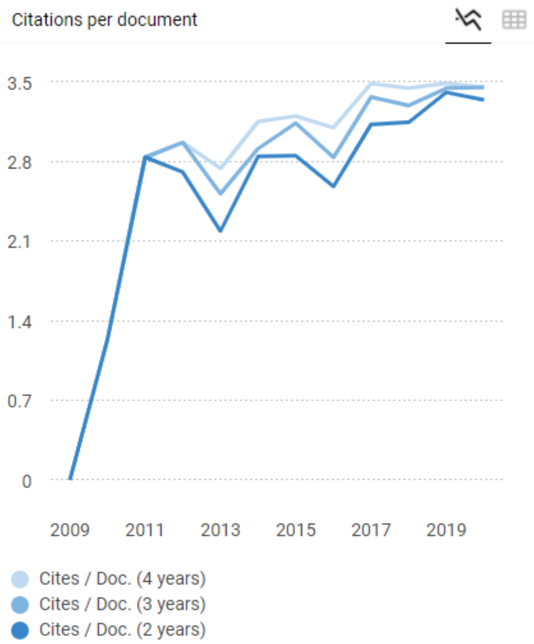
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ANEXO VII. Copia de la publicación: "Contribution of Driving Efficiency to Vehicle-to-Building"

energies

MDPI

Article

Contribution of Driving Efficiency to Vehicle-to-Building

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Abstract: Energy consumption in the transport sector and buildings are of great concern. This research aims to quantify how eco-routing, eco-driving and eco-charging can increase the amount of energy available for vehicle-to-building. To do this, the working population was broken into social groups (freelancers, local workers and commuters) who reside in two cities with different climate zones (Alcalá de Henares-Spain and Jaén-Spain) since the way of using electric vehicles is different. An algorithm based on the Here® application program interface and neural networks was implemented to acquire data of the stochastic usage of EVs of each social group. Finally, an increase in the amount of energy available for vehicle-to-building was assessed thanks to the algorithm. The results per day were as follows. Owing to the algorithm proposed a reduction ranging from 0.6 kWh to 2.2 kWh was obtained depending on social groups. The proposed algorithm facilitated an increase in energy available for vehicle-to-building ranging from 13.2 kWh to 33.6 kWh depending on social groups. The results show that current charging policies are not compatible with all social groups and do not consider the renewable energy contribution to the total electricity demand.

Keywords: vehicle-to-building; driving efficiency; renewable energy integration; vehicle-to-grid; energy consumption

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1. Introduction

When it comes to Spain, the transport sector is the main culprit for discharging pollutants into the atmosphere as well as consuming vast amounts of energy [1]. Recently, the private research center named Economics for Energy has confirmed this statement in its latest transport report as this trend will certainly continue in the year to come due to mobility needs [1]. As published by the Spanish Government, the energy consumption linked to transport has been increasing since 2013, just after the economic crisis from 1,074,714 TJ to 1,196,381 TJ in 2018 (latest data available) [2]. The same trend can be found for CO_2 emissions which accounted for 115,402,074 t in 2013 and 128,275,075 t in 2020 [2].

Electric mobility plays a key role when reducing greenhouse emissions as shown by Pillay et al. [3]. In their research, they showed how emissions could be reduced in South Africa up to 12.3% considering a specific e-car, e-truck and e-bus penetration in the market. Bastida-Molina, Hurtado-Pérez and Peñalvo-López drew similar conclusions proving that emissions can be reduced by increasing the number of electric vehicles (EVs) and boosting the number of MW of renewable energy (RE) [4]. As they stated in their research, a 100% RE generation will be needed in order to reduce up to 74 million tons per year. Zheng et al. display in their research that, *from 2011 to 2017, 682,047 plug-in EVs were sold in five provinces of China, with 18.3 billion electric vehicle kilometers traveled, 3.0 TWh of electricity consumed, a reduction in gasoline consumption of 1.6 billion liters and in CO_2 emissions by 611,824 tons* [5]. Despite these results, some research is focused on the impact of EVs on the environment and tries to evaluate whether they are more sustainable than traditional powertrains such as internal combustion engine vehicles. Helmers et al. made an interesting study comparing the environmental impacts of petrol, diesel engines and natural gas engines as well as EVs. They proved that producing battery cells with renewable electricity decreases the environmental impacts of EVs considerably [6]. In addition, EV impacts can be reduced even more by making a better use of mineral resources [6]. Messagie et al. proved that EVs are the most sustainable means of transport taking into account the whole life cycle [7].

EVs are useful, not only for being zero-pipeline vehicles, but for being a key element in several important techniques such as vehicle-to-grid (V2G), vehicle-to-home (V2H) and, generally speaking, vehicle-to-X connections [8–11]. V2G aims to use EVs as virtual power plants in such a way that the energy stored in EV batteries could be injected into the electricity network when needed in order to reduce consumption peaks and emissions among others [12]. As detailed by Bibak and Tekiner-Mogulkoç, V2G is currently facing several barriers and obstacles such as high investments needed to apply this technology, stochastic nature of EVs (arrival and departure times, km covered, etc.), social issues and, finally, battery degradation [13]. V2G success is based on the participation of the EV owner. Consequently, the willingness to pay is an essential concept that has already been discussed in some research [14,15]. This willingness can be defined by the maximum price that can stimulate an EV owner to inject the energy available from the EV battery into the grid. Other approaches linked to social issues were introduced by Noel et al. In their dissertation, they proved how concepts such as tinkering, testing and tacit knowledge (As discussed by Noel et al., tinkering is defined as "user modification of a technology to develop new innovations and uses". Testing "deals intently with experimentation in technology, especially between the designers of a product or artifact and its users". Finally, tacit knowledge "is the embodied knowledge a user may have in learning to utilize or modify a technology") may accelerate the adoption of V2G [16]. Therefore, policies are an essential topic as discussed in several studies [17,18]. An important advantage of V2G is its capacity for better integration of the RE into the system as detailed by Mwasilu et al. [19]. At this point, it is vital to consider that the usage of V2G must be reliable; in other words, it must guarantee the system reliability, and EVs can play an important role to ensure it. To assure this, this study has proposed the usage of artificial intelligence. Rahbari et al. proposed a solution based on a neuro-fuzzy inference system in order to integrate better REs and EVs into the grid considering generation source intermittency and energy usage inconsistency [20]. Mozafar, Moradi and Amini proposed a genetic algorithm-particle swarm optimization algorithm aiming at reducing power losses, voltage fluctuations, charging and demand supplying costs as well as EV battery costs [21]. Battery degradation is an important topic to be considered when assessing the V2G participation. Recent studies show that calendar ageing is influenced by such factors as standing time, the state of charge and temperature whereas cycling ageing is affected by number of charges, the depth of discharge and charging rates [22]. Finally, regarding EVs, another important topic to be considered is aperiodic phenomena and failures in the development of the electromobility system, as they have an impact to increase or decrease the EV demand as shown by Wróblewsky et al. [23]. As shown in their research, *the impact of aperiodic failures of the economic operation of a given drive system is significant, which is closely related to the nature of the speed profile, and it mainly affects the operation of the drive system*. In addition to this, these phenomena affecting the operation of the selected drive system as well as environmental and infrastructural factors, determine the application of a given electromobility concept. Consequently, the highest frequency of such phenomena is, the worse economic justification for EVs in comparison to conventional solutions is [23]. Similar studies from Wróblewsky related to aperiodic phenomena which deal with other powertrains can be found in the literature [24].

Vehicle-to-building (V2B) is an important topic analyzed in this research. As stated by Odkhuu et al. V2B allows *bidirectional chargers and small-scale renewable energy resources, such as photovoltaic systems and small-scale with turbines* [25]. Consequently, it is possible to draw and transfer energy from/to buildings depending on the battery status. In addition to this, V2B technology offers important services to reduce the on-peak load of the building's power consumption through peak shaving, load shifting, valley filling, better integration of RE and back-up in case of electricity shortage [25]. A V2B system is mainly composed of EVs, local distributed energy generators, critical loads, a control system in charge of building energy management (BEMS) and static storage. The aim of the BEMS is to run algorithms to obtain economic revenues, such as peak reduction [26]. Some research shows that an important reduction of fossil electricity is obtained due to the RE contribution when charging EV batteries whose energy will be transferred to the building as detailed by Buonomano et al. [27]. Zhou et al. describe in their research the main advantages of integrating EVs with RE such as cutting energy consumption of buildings, reducing the import/export pressure on the electric grid and shifting peak-loads to sub-peak or off-peak periods [28]. There are technical issues linked to V2B technology, such as the stochastic characteristic of driving schedule of EVs [29,30], which our research is focused on. Other topics are related to infrastructure and lifetime of EV batteries [31]. Ghaderi showed in his research that V2B offers significant profit even considering the battery degradation based on a scenario composed of six EVs and a V2B system [32]. Gagne et al. proved in their research that V2B is economically viable in regulated markets [33]. Similar studies linked to economic viability for similar technologies such V2G can be found in the literature [34].

All aforementioned techniques are based on EVs and, if their energy efficiency was improved, the amount of energy available to be used would be increased. Eco-driving (EDR) and eco-routing (ER) are key elements to improve energy efficiency. ER consists of finding the most energy-efficient route for a vehicle to travel between two points in such a way that an optimal way to reduce energy consumption is offered to drivers. Thibault and Sciaretta proposed an energy consumption model which considers speed fluctuations and road infrastructure to reduce consumption [35]. Some elements such as slopes have a significant influence on energy consumption and are considered in some ER algorithms [36]. Other authors have proposed the usage of evolutionary algorithms [37]. When it comes to EDR and pollutants, research is focused on this topic no matter what types of powertrains are used. Orfila, Saint-Pierre and Messias proposed an Android application based on EDR assistance for internal combustion engines [38]. Similar research can be found for hybrid cars and EVs [39,40].

Emission reduction is of great concern in the European Union (EU) and EDR and ER claim to play a key role. From 2010 to 2013 the ECOWILL (Widespread Implementation for Learner Drivers and Licensed Drivers) project which was supported by the Intelligence energy Europe Program of the European Commission was conducted. This project was linked to qualify and certify driver instructors and roll-out EDR short-duration trainings for licensed drivers [41]. Due to this project, many European countries had a strong commitment to boost EDR in driving schools. As stated by Botte et al., *cooperative-intelligent transportation systems (C-ITS) represent the set of technological and functional elements that allow specific communication tasks identified as V2X* [42]. C-ITS should ensure environment-friendly driving through in-vehicle technologies such as EDR as stated in the JRC Science for Policy Report published by the European Commission [43]. In addition to this, the EU offers the opportunity to manufactures to consider CO_2 saving from innovative technologies which cannot prove their CO_2 reduction effects under the test procedure used for vehicle type approval [44,45]. Among these innovative techniques, one can find EDR. In addition to this, one can find initiatives and projects which consider ER and EDR at the same time such as a project called REDUCTION performed in the EU [46]. This project developed state-of-art methodologies for ecological routing, ecological driving, multi-modal ecological routing, in addition to cutting edge onboard communication devices [46]. Finally, eco-charging (EC), and generally speaking, smart charging is relevant to many topics such as RE, electricity market, etc. In 2019, the EU signed the EU's Paris Agreement commitments for reducing greenhouse emissions focused on energy performance in buildings, RE, energy efficiency and electricity market design among others [47]. In addition to this, currently, one of the most important initiatives in the EU is the European Green Deal (EGD) which aims to make Europe the first climate-neutral continent. The EGD rests on three pillars: reduction in greenhouse emissions by 2050, stimulation of economic growth without linking it to the use of resources, and the involvement of all members of society in the implementation of this new strategy [48]. To achieve the goals of the EGD, many actions need to be undertaken in all sectors of the economy, such as: *investing in environmentally friendly technologies, supporting industry to innovate, rolling out cleaner, cheaper and healthier forms of private and public transport, decarbonizing the energy sector, ensuring buildings are more energy efficient and working with international partners to improve global environmental standards* [49,50]. Additionally, EGD aims to improve and promote the integration of RE into the transport and electricity sectors by drawing on several research studies that exist on this subject [51–54]. As suggested by Gil-García et al., it is imperative to consider the initiatives focused on EVs if the objective is to reduce emissions and increase RE's penetration. They have concluded that renewable penetration of at least 82% is necessary to fulfil the emissions-reduction target by 2050 [51]. According to Keller et al., large-scale deployment of RE generators and EVs is expected to reduce emissions in the electricity and transport sectors [54]. Their research shows that electrifying all of the existing EVs will require a 60% increase in the generation capacity, and the levelized cost of electricity would increase only by 9%. Consequently, emissions reduction in transport, as well as RE integration, is a topic of great concern. Research shows how EDR, ER, and EC can contribute to sustainable mobility emissions reduction in transport and better integration of RE, reduction in the energy consumption of buildings, and clean energy.

Based on aforementioned policies, research which assesses the impact of EDR, ER and EC on several techniques such as V2G, V2B and V2X should be conducted. In this current research, the authors have studied this topic in depth by taking into account several important topics. Firstly, the stochastic usage of EVs according to social groups (freelancers, local workers and commuters) as their way of using EVs is different. Consequently, the results shown in this research will be highly valuable for policymakers. Secondly, the impact of EDR, ER and EC is assessed considering climate zones in Spain. Finally, the compatibility between V2X techniques has been analyzed in Spain based on the already installed RE power. This research aims to:

(a) Analyze how EDR, ER and EC based on EVs can improve the amount of energy available in a V2B system. An algorithm coded in Python based on the Here® application program interface (API) and neural networks is presented to enhance the amount of energy available for V2B [55].
(b) Assess how important is to consider social groups (freelancers, local workers, commuters) to calculate the energy available for V2B as the way of using EVs is different.
(c) Quantify the reduction of energy consumption of buildings.
(d) Analyze if current charging policies are coherent considering the social groups representing the working population and RE contribution in the Spanish electric system.

This paper is structured like this. Section 2 describes the method, including the cities chosen for this research and the description of the algorithm used. Sections 3 and 4 detail the results and discuss the main findings. In addition, a validity section including a sensitivity analysis and threats to validity analysis is displayed in this Section 4. Section 5 analyzes the conclusions of this study. A beta version of the application coded in Python is available in Supplementary Materials.

2. Methods

2.1. Description

The method followed in this research is depicted in Figure 1. The main idea behind this method is to choose two representative cities, buildings and residents of those buildings in order to assess the improvements introduced by EDR, ER and EC based on an algorithm implemented on Python and neural networks. Firstly, the cities subjected to this study are chosen as detailed in Section 2.2 considering climatic zones, traffic conditions and population among others. Secondly, the buildings used to measure improvements in energy consumption when using EDR and ER are selected (Section 2.3). In Section 2.4 the participants, who are residents in the chosen buildings, are determined. In Section 2.5, the algorithm based on EDR, EC and ER concepts is described in detail. In Section 2.6 the energy consumption estimates of the buildings are made, and, owing to the algorithm, the improvements are assessed. Section 2.7 displays how statistical analysis of data coming from EV consumption is made. Section 2.8 describes the equipment used in this study. Finally, EC, EDR and EC contribution is assessed.

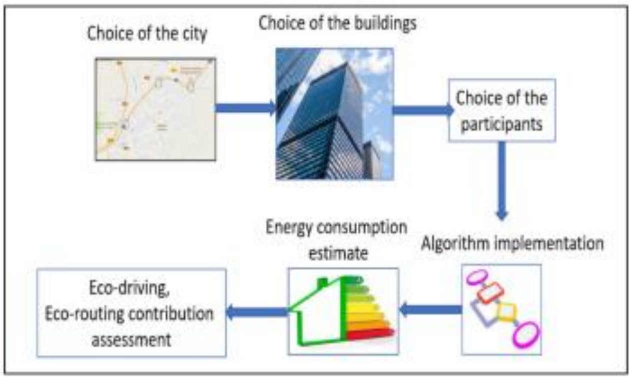

Figure 1. Methodology used in this research.

2.2. *Choice of the City*

Spain has different climatic zones but, as shown in Figure 2, two of them prevail in the country: the Mediterranean and Continental ones. The former is characterized by hot dry summers and mild winters. This climate can be broken down into three subtypes. The latter is characterized by wide diurnal and seasonal variations in temperature and by low, irregular rainfall with high rates of evaporation that make the land arid. To do this study more representative, two cities belonging to different climatic zones were chosen: Alcalá de Henares and Jaén (Figure 2). Due to the differences, the consumption patterns are different.

Figure 2. Spanish climate.

Alcalá de Henares belongs to the Community of Madrid (Spain), 32 km away from the Spanish capital. To be more specific, this city is the second biggest one in this Community. Its population is 197,345 inhabitants in 2020 based on the data provided by the Spanish National Institute of Statistics. Generally, traffic jams are often reported in the city. Aiming at monitoring the traffic state, the townhall has installed 17 cameras mainly located downtown. This city is also interesting as it is connected to one of the most important roads to enter Madrid.

The population of Jaén which is located in the south of Spain is 112,757 in 2020 according to the data provided by the Spanish National Institute of Statistics. This city has installed cameras in strategic points aiming to improve the traffic in the city due to its high intensity.

Taking into account all the data mentioned above, a comparison between two similar cities located in different climatic zones can be made.

2.3. Choice of the Buildings

Several factors influence energy consumption when it comes to buildings. As detailed by Huebner et al., different variables such as building factors, socio-demographics, attitudes and self-reported behavior in their research affect energy consumption in different buildings [56]. To be more specific, 39% of the variability in energy consumption is linked to buildings, 24% to social-demographic variables, 14% is linked to heating behavior and only 5% is linked to attitudes and other behaviors [56]. This study was based on a sample of 924 English households.

Hueber et al. did also research about the aforementioned topic focused on electricity consumption instead of energy consumption by using an 845 English household sample [57]. In their research, they showed that 34% of variability in electric consumption came from appliance use and lighting while 21% was linked to social-demographic variables. Harputlugil and de Wilde analyzed in-depth the interaction between buildings and humans when it comes to energy consumption. In this case, one important conclusion is that lifestyle is an essential factor to be considered to understand energy consumption profiles and occupants' patterns [58]. Pan et al. concluded the importance of having a good understanding of how occupants use the appliances of buildings in order to improve energy efficiency [59]. Moreover, like this the occupants' behavior could be addressed to a more sustainable one. Finally, Yousefi, Gholipour et Yan proved that occupants' behavior and envelope materials play a key role when choosing the envelop material types [60].

Considering this, the conclusions that can be drawn when choosing buildings for this study are:

a. Orientation of buildings is a key factor when it comes to electricity consumption and energy in general.
b. Based on the previous studies, a different occupation rate for each flat must be considered.
c. As EVs will be used to assess the energy available for V2B technology, different social sectors must be considered.
d. Finally, different work timetables should be considered in this study.

2.4. Choice of the Participants in This Research

In this study, the authors have proceeded to choose participants according to their professions and the number of kilometers covered. This is a key point to be taken into account in order to obtain more accurate results. Based on this, one can distinguish:

(a) Freelancers. They cover a considerable number of kilometers on a daily basis according to statistical data published by different institutions [61]. Consequently, they are supposed not to inject a large amount of energy when using the V2B technology.
(b) Commuters. Commuters can choose between using the public transport and their own vehicles to get to work. In this study, commuters are supposed to drive to work by using EVs. Thanks to statistical methods described in Section 2.8, the daily mileage and energy consumption will be assessed.
(c) Local workers. Again, local workers can use the public transport or their vehicles to get to work. In this study, local workers who use their vehicles to go to work have

been considered. In this case, the number of kilometers covered is supposed to be low. Consequently, they can contribute in a very important way when using the V2B technology.

All assumptions made about kilometers covered on a daily basis have to be confirmed based on statistical methods. Consequently, the reduction of emissions and energy consumption is influenced by the type of workers mix living in a building. The number of participants is shown in Table 1: freelancers, local workers, commuters and other occupants of the household who do not belong to these social groups (mainly students and the unemployed). Potential deviations in the assumptions earlier described are considered in the sensitivity analysis displayed in Section 4.5. In this research, we have proceeded to choose medium size or big apartments which consume vast amount of energy. It is true that houses could have been chosen, but it was not done as almost all occupants were freelancers or commuters. Consequently, we were unable to draw a conclusion in regard to other social sectors. Finally, the aim of the authors was to choose buildings with a different mix of freelancers and commuters as they are supposed to be willing to invest in EVs taking into account that local workers cover a small number of kilometers, but they could be forced to invest a large amount of money in EVs.

Table 1. Number of participants in this research.

Building	Location	Orientation	Average Surface (m^2)	Occupants	Total Participants	Commuters	Local Workers	Freelancers	Rest of Occupants
A	Alcalá	South	90	35	15	5	2	8	20
B	Alcalá	North	85	45	20	8	3	9	25
C	Alcalá	West	100	32	15	6	2	7	17
D	Jaén	South	75	42	20	10	2	8	22
E	Jaén	North	80	45	20	11	2	7	25
F	Jaén	West	90	12	10	5	1	4	2

2.5. *Algorithm*

The algorithm proposed in this study is based on ER, EDR and EC concepts. It was coded by using the Here® API which offers several location services with customization of navigation maps, current traffic conditions and historical traffic data patterns among others. One of the most important features of the Here® API is the energy consumption models. Due to them, when they are properly set up, the energy consumption for a specific trip can be easily assessed, which this research does.

To better understand what the algorithm does, seven different stages can be distinguished:

1. Phase 1. Consumption models are tuned. As shown later, energy consumption models must be tuned by using real time driving data of the specific driver. This factor is of great significance in order to apply the EDR concept properly.
2. Phase 2. The destination is chosen by the driver. This algorithm offers a web interface that the driver can use in order to type the destination.
3. Phase 3. The Here® API is in charge of determining the best route available. It must be stated that the way how the algorithm plans the best routes belongs to the Here® competence. The Here® API is called by using the python code.
4. Phase 4. Here® proposes different routes based on the energy consumption models already tuned. This topic makes Here® consider EDR and ER concepts. Here® can propose three types of routes. The first one is called the fastest, which is the one that requires less time. The second one is known as the shortest, which attempts to find the one which requires that less distance is covered. The last one is the balanced one which tries to find a compromise solution between distance and time. It is only use for trucks.

5. Phase 5. Once the Python code obtains the three routes and the energy consumption, the algorithm can easily determine the final energy available of the battery and if a charging process will be needed. It must be stated that the initial autonomy of the EV before starting the trip must be specified by the driver before leaving.
6. Phase 6. The algorithm chooses the route which implies that energy consumption is the lowest based on the data obtained in phase 4.
7. Phase 7. The python code runs a block known as the EC block. Its aim is to determine the RE contribution as well as the energy structure generation (wind energy, photovoltaic, etc.) by using different types of neural networks. Thanks to this, the drivers obtain information about when the charging process is greener and less pollutant.

The Here® API includes energy consumption models that aim to estimate energy consumption based on several parameters, such as speed and auxiliary energy consumption (heating and cooling systems, for instance). When tuning the consumption models, each parameter has to be specified in kWh and based on its dependence with the EV speed (when possible, as some of them, such as radio consumption, are not dependant on speed). These values were calculated by acquiring the data after the drivers participating in the study drove the EVs for several months. Data were collected using laptops equipped with Inca® software and input/output from the ETAS® supplier (Figure 3) [62,63]. After having analyzed the data acquisition, the consumption models can be tuned (Appendix A). Figure 4 shows how this was performed. The process consists of specifying energy losses depending on acceleration, decelerations, slopes, etc. whose values were obtained by analyzing the data acquisitions thanks to MDA software [64]. Once this is done the experiment can be reproduced easily. The Here® API can assess and return an estimate of energy consumption for the fastest, the shortest and the balanced routes. The algorithm chooses the one with less energy consumption. Finally, based on the battery capacity before the trip, the algorithm can determine if the EV will have to be charged during the trip.

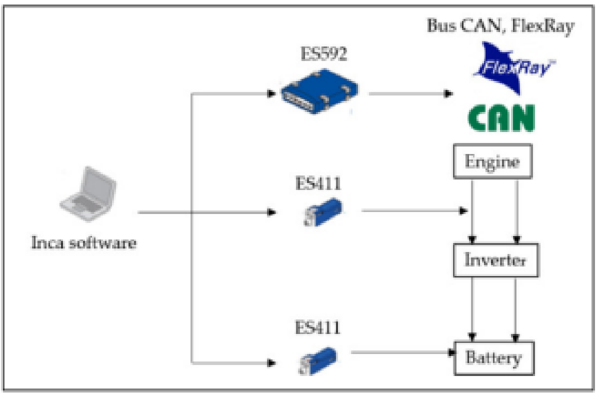

Figure 3. ETAS® input/output modules connection.

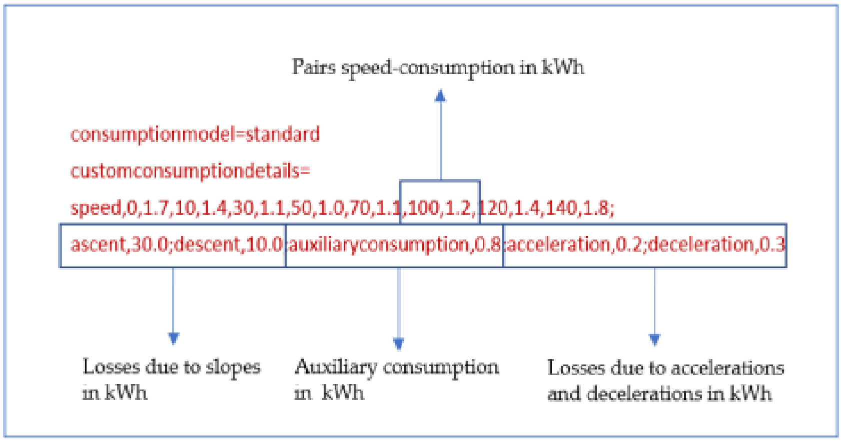

Figure 4. How to configure the consumption model.

Finally, the assessment of how green the charging process is must be determined by using the EC block. This part of the Python code is responsible for predicting when the charging process should be done based on the RE contribution. Owing to this, the driver will be informed about the best moment to charge EV to reduce greenhouse emissions during charging. One of the main characteristics of this block is that it can predict the energy structure (solar energy power, wind power energy, nuclear energy, and so on). The main tasks of this EC block are as follows:

(a) Based on the consumption models already tuned, analyze in-depth information regarding the battery capacity and energy consumption to cover a journey set by the driver.
(b) Estimate when the charging process should be done according to the analysis obtained in a.
(c) Assess the RE contribution calculated using the Gated Recurrent Units (GRU) networks and nonlinear autoregressive (NAR) networks as shown later [65–68].

After executing the *EC* block, a score is calculated based on the RE contribution following Equation (1). The higher this score, the more the contribution of RE in charging EVs.

$$EC = \frac{RE_{c,t}}{RE_{max,d}} \quad (1)$$

$RE_{c,t}$ is the *RE* contribution to the total electricity demand at *t* (in MW), and $RE_{max,d}$ is the maximal *RE* contribution (in MW) during the day when the charging process takes place. $RE_{c,t}$ and $RE_{max,d}$ are calculated using the GRU neural networks. The *RE* contribution is assessed as follows (2):

$$RE_c = \frac{RE}{RE + NRE} \quad (2)$$

RE_c is the *RE* contribution (in %), *RE* is the total electricity generated by *RE* sources (in MW), and *NRE* is the total electricity generated by not RE, such as coal (in MW).

$RE_{c,t}$ and $RE_{max,d}$ are estimated using the Spanish system operator data published daily, where one can find the CO_2 generation structure and the day's total electricity demand [69]. The electricity demand and total RE generation usually follow the same pattern. Generally speaking, only weekends and seasons are the relevant parameters to be considered. Consequently, recurrent neural networks play a key role in predicting the electricity demand for a desired period of the day to midnight in the algorithm proposed in this study. The Python code analyzes the data provided by the neural networks and assesses the maximum RE contribution of that specific day by following Equations (1) and (2).

Recurrent networks face technical issues when predicting long-term series due to the vanishing gradient problem when the recurrent neural networks are trained with gradient-based learning methods and backpropagation. These methods imply that neural network weights are updated proportionally to the partial derivative of the error function with respect to the current weight in each training iteration. The gradient may be vanishingly small. Consequently, the weight may not change, and the training process might be stopped. Long short-term memory (LSTM) or GRU networks are used to make more accurate long-term predictions. In this research, the authors chose the GRU networks since they are more computationally efficient than LSTM networks. GRU is a recurrent neural network composed of update and reset gates. Basically, these are two vectors that decide what information should be passed to the output. The special characteristic about them is that they can be trained to keep information from long ago without washing it through time or remove information irrelevant to the prediction [66–68].

Figure 5 shows the pseudocode of the GRU networks employed in this study. The data used to implement the GRU network were provided by the Spanish system operator for the last four years. The first three-year data are used to train the network, and the last-year data are employed to test the network performance. As usual, when implementing a neuronal network, all the input and output data must be processed to make them range between 0 and 1 to assure optimum network performance. The GRU networks were implemented using the keras package of Python. To do this, some parameters must be configured. The Sequential parameter specifies that the model is sequential, and the output of each layer is the input for the next layer. In this study, the Dropout function was employed. Dropout is a technique in which randomly selected neurons are ignored during training to temporally remove their contribution to the activation of the downstream neurons on the forward pass and ensure that weight updates are not applied to the neuron on the backward pass. This technique renders the network less sensitive to the specific weights of neurons. To analyze the error loss, the mean squared error, since it is highly recommended for regression problems, was chosen. To optimize the model using an optimization algorithm, the Adam method, due to its computational efficiency, was used.

The algorithm proposed in this study integrates a code in Python that is able to estimate the structure generation for the next two hours based on the data provided by the Spanish system operator. This estimate is made by using NAR networks, which are widely used to manipulate and predict time series [66–70]. NAR networks are described mathematically as follows (3):

$$\hat{y}(t) = f(y(t-1) + y(t-2) + \ldots + y(t-d)) + \varepsilon(t) \tag{3}$$

f is the network output for a specific set of input data, $\varepsilon(t)$ represents the error between the prediction values $\hat{y}(t)$ and the actual ones y. Finally, d is the number of delays involved in prediction. When designing neural networks, some parameters can be chosen flexibly by the designer. These parameters, it should be noted, exert a significant impact on prediction accuracy. Some of them are the number of hidden layers and the number of neurons used in each layer. Despite this flexibility, these numbers must be chosen to achieve two goals: the first is to obtain a good prediction accuracy, and the second is to avoid the network from becoming too complex. Figure 6 shows how the accuracy of the network varies depending on the delay parameter. When a high value is chosen for d, the predicted value changes very slowly. However, if d is too low, the network cannot properly follow the trend. Consequently, d must be specified empirically to take the optimal value since d determines how important the past values are for the prediction. When generating electricity using RE, sudden changes in the RE generation structure can happen due to weather conditions. These changes may not be predicted using the past values. Consequently, in some cases, NAR may not be as accurate as it should be. Therefore, in the algorithm proposed in this study, the accuracy remains on the GRU networks and not on the NAR ones. Even if it has not been implemented in the current version of the algorithm, there is a technical solution:

MATLAB® can update the network and correct predictions continuously for $t + 1$, $t + 2$, $t + 3$, and so on, if the real value of t is known. As the Spanish system operator provides data every hour in real-time, this solution can be applied. In this research, the optimal value for d was 3. The pseudocode used for coding the NAR networks is shown in Figure 7. The trainlm function was employed to train the network to update bias and weights using the Levenberg-Marquardt optimisation. This choice was based on the fact that it is the fastest backpropagation algorithm despite its major usage of memory.

```
Import packages: numpy, pandas, keras, tensorflow, sklearn

#import data provided by the Spanish System Operator
pd. read_csv_file (data_2016, 2017, 2018, 2019)

#Preparation of the data used as inputs of the GRU network
X=reshape_data_inputs

#rescale data to 0-1 scale
minimum = amin(X, axis=-1).reshape
maximum = np.amax(X, axis=-1).reshape()
X = (X-minimum) / (maximum-minimum)
Y = (Y-minimum) / (maximum-minimum)

#network parameters. A model is a stack of layers
model = Sequential ()

#Adding layer with the number of inputs specified
model.add (GRU (128, input_shape=(data), return_sequences=True))
model.add(Dropout(0.1)) # Dropout = 10%

# Whether to return the last output in the output sequence, or the full sequence.
model.add (GRU (64, return_sequences=True) #Adding layer with the number of inputs specified
model.add(Dropout(0.1)) # Dropout = 10%

model.add(GRU(32, return_sequences=True)) ) #Adding layer with the number of inputs specified
model.add(Dropout(0.3)) # Dropout = 30%

#Optimizer choice and error measurement
model.compile(loss='mean_squared_error', optimizer='adam')

#Training
his = model.fit(X, Y, batch_size=2, nb_epoch=5, verbose=1)# ,
callbacks=[TQDMNotebookCallback()])
```

Figure 5. GRU network code.

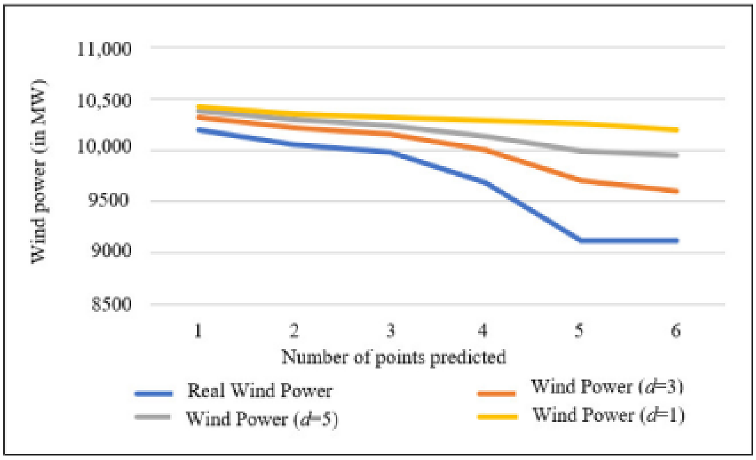

Figure 6. Inaccuracy in predictions when using different *d* values.

```
data = Spanish_system_operator_data; % loading data

net = narnet(1:3,10); % three delays and 10 hidden layer size.

[Xs,Xi,Ai,datas] = preparets(net,{},{},T); % preparing data to train

net = train(net,Xs,datas,Xi,Ai);  %train the network

[Y,Xf,Af] = net(Xs,Xi,Ai); %network performance assessment

[netc, Xic,Aic] = closeloop(net,Xf,Af); %predicting results in close loop
```

Figure 7. NAR network code in MATLAB®.

2.6. Energy Consumption of EVs

The participants were driving EVs during the winter from December 2020 to January 2021 and during the summer from June 2020 to July 2020. These dates were chosen to consider the temperature effect. The trips were randomly chosen according to the participants' professional and personal needs. This is a key element to consider the stochastic usage of EVs.

2.7. Statistical Analysis

To establish the average consumption of EVs for each social group, a statistical analysis must be done. Owing to this, the energy available for V2B is assessed for freelancers, local workers and commuters. As per the first analysis of the data collected, these data were closed to a normal distribution. The R software, and more specifically the PASSWR package, was used to confirm this assumption [71]. The main advantage of this package is that the data can be explored in depth thanks to the statistical parameters such as kurtosis, skewness and *p*-value. Kurtosis is a measure of relative peakedness of distribution. It is a shape parameter that characterises the degree of the peakedness. A distribution is said to be leptokurtic when the degree of peakedness is higher than 3; it is mesokurtic when the degree of peakedness is equal to 3, and it is platykurtic when the degree of peakedness is less than 3 [72–74]. Skewness refers to a distortion or asymmetry that deviates from the symmetrical bell curve or normal distribution in a set of data. When the data under analysis are close to a normal distribution, the skewness is close to 0. Symmetry, it is vital to note, does not infer that the data follow a normal distribution. Consequently, the aforementioned analysis must be carefully conducted. The *p*-value is the probability of finding the observed, or more extreme, results when the null hypothesis (H_0) of a study question is true.

In addition to the statistical parameters described earlier, several plots were used to confirm that the data analyzed follow a normal distribution: histograms, Q-Q plots and boxplot. The histogram represents the frequency of occurrence of specific phenomena that lie within a specific range of values, which are arranged in consecutive and fixed intervals. The quantile-quantile or Q-Q plot is an exploratory graphical device used to check the validity of a distributional assumption for a data set. A boxplot, sometimes called a box and whisker plot, is a type of graph used to display patterns of quantitative data [73,74].

Finally, it is essential to describe how statistical outliers were assessed. These points are the ones whose values differ significantly from the rest of the observations. This difference is linked to variability. In order to detect them, the following tools have been used: histograms, z-scores and interquartile range [74]. The z-scores method measures how many standard deviations an element is from the mean. The interquartile range is a measure of statistical dispersion, being equal to the difference between 75th and 25th percentiles, or between upper and lower quartiles. As the data were analyzed on a daily basis, statistical outliers were mainly linked to unusual traffic conditions such as traffic accidents.

2.8. Equipment Used

The means employed were the following:

1. Vehicle control units (VCU) designed by important European suppliers.
2. EVs provided with a 40 kWh were employed. Their autonomy was 250 km with a maximum speed of 144 km/h.
3. The INCA® software was used since it was necessary to read the memory positions of the VCU [62].
4. The MDA software was employed to visualize the dat file and analyze the trend of the software variables [64].
5. Here® and Open Charge Map® APIs [55,75].
6. The ES411 and ES592 modules from ETAS® were used since they allowed connecting the laptop to EVs to record all the software variables specified using Inca®.
7. Power meters. Manufacturer Gafild. Operating voltage 230 AC. Max. current 16 A.

3. Results

3.1. EV Consumption

The algorithm proposed in this research aims to improve energy efficiency by considering the stochastic usage of EVs. To do this, many measurements were performed on social groups such as freelancers, local workers and commuters. To assess each social group's average energy consumption when using and not using the algorithm, the collected data were statistically analyzed as described in Section 2.8. The results obtained after this analysis are depicted in Table 2 for Alcalá de Henares and in Table 3 for Jaén. First of all, it must be taken into account that all these data are close to a normal distribution. This assumption was confirmed by assessing different parameters such as skewness, kurtosis and *p*-value. When it comes to freelancers, skewness is close to zero. Consequently, the distribution is symmetric. Kurtosis aims to prove that the data distribution tails are not dissimilar from normal distribution ones. The *p*-value represents the null hypothesis: the data follow a normal distribution. When the *p*-value is greater than 0.05, the null hypothesis is confirmed. One important characteristic of skewness and kurtosis is that they are sensitive to the sample size. Therefore, the Q-Q plots and histograms were used to confirm that the data collected followed a normal distribution. Based on this statistical analysis, the hypothesis H_0 was confirmed. In addition to energy consumption, it is essential to establish the number of kilometers by following the same statistical method. Regarding freelancers, the number of kilometers was found to range from 95 km to 110 km per day. When it comes to local workers and commuters, the number of kilometers covered varies from 57 km to 70 km per day. Finally, commuters cover between 4 km and 6 km per day. When it comes to Jaén, the number of kilometers travelled by freelancers ranges between 78 km and 90 km a day. Regarding commuters, they drive between 3.5 km and 5.5 km daily. Finally, local workers cover between 3.2 km and 5.3 km a day. The main differences between both cities are analyzed in Section 4.1. These results are complementary to other studies. Zhang et al. detailed how large-scale EV development impacts the stability of electric grid as well as decisions linked to the construction of new facilities (charging facilities). They conducted a depth-study of stochastic usage of EVs based on several factors such as daily distance travelled, energy consumption, etc. [76]. Similar research was done by Shi et al. showing interesting data about the average speed and consumption based on stochastic usage of EVs [77]. The impact on the electricity grid can also be stochastic as shown by Schey, Scoffield and Smart [78]. All this research did not consider social groups which are a key element for future energy policies due to the fact that their usage of EVs is different as proved in this study.

Table 2. EV consumption in kWh in Alcalá de Henares.

Factor	Freelancers		Commuters		Local Workers	
	A.U. [(1)]	N.A. [(2)]	A.U. [(1)]	N.A. [(2)]	A.U. [(1)]	N.A. [(2)]
Mean	24	26.2	9	10.5	3.3	3.9
Std deviation	0.6	0.4	0.3	0.32	0.32	0.29
Kurtosis	3.7	4.0	3.7	4.5	4.1	4.2
Skewness	−0.135	−0.121	−0.041	−0.032	−0.025	−0.015
p-value	0.395	0.401	0.401	0.415	0.396	0.399

[(1)] N.A. means no algorithm is used; [(2)] A.U. means the algorithm is used.

Table 3. EV consumption i kWh in Jaén.

Factor	Freelancers		Commuters		Local Workers	
	A.U. [(1)]	N.A. [(2)]	A.U. [(1)]	N.A. [(2)]	A.U. [(1)]	N.A. [(2)]
Mean	21	22.9	8.5	9.5	4.3	4.9
Std deviation	0.7	0.3	0.4	0.36	0.36	0.31
Kurtosis	3.6	4.1	3.5	4.3	4.0	4.1
Skewness	−0.145	−0.111	−0.045	−0.03	−0.02	−0.013
p-value	0.385	0.301	0.411	0.405	0.356	0.349

[(1)] N.A. means no algorithm is used; [(2)] A.U. means the algorithm is used.

3.2. Energy Consumption of Buildings

In order to verify the improvements introduced by the algorithm based on EC, ER and EDR, it is essential to measure energy consumption of the buildings chosen for this case-study. To do this, smart counters and power meters were installed in each participant's apartment. Consequently, it was possible to measure the energy consumption of all facilities of the apartments such as: electric heating, air conditioning, lighting, TV sets, fridges, microwave ovens, vitroceramic hobs, washing machines and dishwashers. All these measurements were performed in the climatic areas described in Section 2.

When analyzing the Spanish electricity demand curve, there are two main consumption peaks. The first one is usually between 12 a.m. and 1 p.m. and the other one from 8 p.m. to 10 p.m. depending on the season. There are two main differences between the summer and the winter curves. Firstly, the electricity demand is lower in the summer. Secondly, the peak between 12 a.m. and 1 p.m. is higher than the other one in the summer. Therefore, it is important to check the energy consumption pattern of the buildings chosen in this case study. Figure 8 shows the winter energy consumption for buildings A, B and C which are located in Alcalá de Henares. As one can see, the energy consumption trend is similar to the Spanish one as there are two peaks present. However, there are important differences. Firstly, from 4 p.m. to 6 p.m. the energy consumption decreases as the energy consumption patterns of buildings A and C follow the Spanish one. Nevertheless, it is not the case for building B. Secondly, the trend followed by buildings A and C has similarities comparing to the Spanish trend, but this first energy consumption peak lasts less time than expected. Figure 9 shows results during summertime. As expected, two consumption peaks are present and the first one is the most important. Again, in this case, building B has a different behavior in comparison with buildings A and C as its consumption is higher during the off-peak periods. As explained in the discussion section, these particularities of electricity demand curves can be analyzed considering the number of occupants of the apartments as well as the diversity of social groups they belong to. The reader can find the curves for the second climatic zone in the Supplementary Data as the conclusions are similar except for the fact that total energy consumption changes slightly. This variation is totally normal as in Jaén the consumption is slightly lower as stated by the Institute of Diversification and Energy Saving of Spain. This analysis was done in the winter and in the summer when temperatures are the coldest and the hottest, respectively. The conditions of the electricity system cannot affect the results of the experiment.

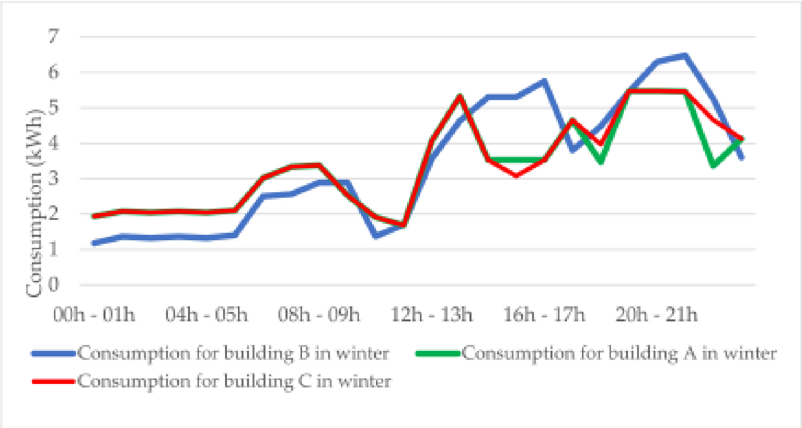

Figure 8. Winter consumption curves for the buildings located in Alcalá.

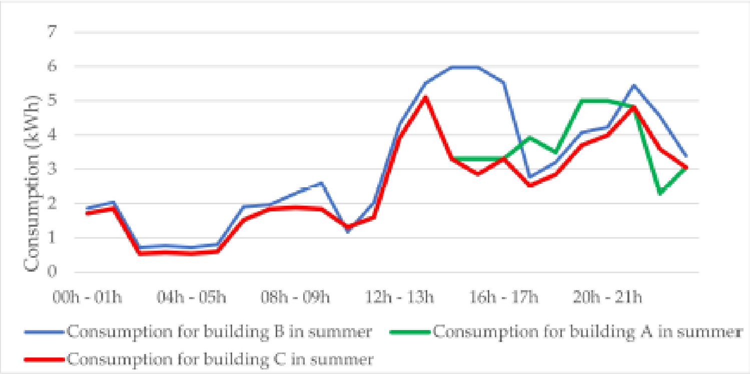

Figure 9. Summer consumption curves for the buildings located in Alcalá.

Variations of energy consumption depending on climatic zones have been studied widely in the scientific literature [79–82]. Energy consumption profile is an essential topic to be considered as shown in a lot of research. Csoknyai et al. analyzed in detail energy consumption and household composition (couple with children, couples without children, single, single with children and other) [83]. Kavousian, Rajagopal and Fisher focused their efforts on analyzing pattern energy consumptions of buildings based on classifying the occupants into age groups [84]. Laaroussi et al. conducted research into how occupant presence and behavior influence energy consumption [85]. However, the research does not take into account social groups, occupants present, EDR, EC and ER at the same time. Table 4 quantifies how energy consumption of the building can be reduced when all these factors are considered at the same time. As one can see, the contribution to V2B is different for each building due to the number of freelancers, local workers and commuters. Consequently, it is essential to discuss this topic in the next section. Although the results depicted in these two tables imply that all participants in this research contribute to V2B, this assumption might be false. Therefore, a sensitivity analysis is done in Section 4.5.

Table 4. Energy available for each building in Alcalá de Henares and Jaén on a daily basis.

	Freelancers			Local Workers			Commuters			Energy Available for V2B A.U.	Energy Available for V2B NA
	Number	kWh Available A.U.	kWh Available N.A.	Number	kWh Available A.U.	kWh Available N.A.	Number	kWh Available A.U.	kWh Available N.A.		
Building A	8	128	110.4	2	73.4	72.2	5	155	147.5	356.4	330.1
Building B	9	144	124.2	3	110.1	108.3	8	248	236	502.1	468.5
Building C	7	112	96.6	2	73.4	72.2	6	186	177	371.4	345.8
Building D	8	152	136.8	2	71.4	70.2	10	315	305	538.4	512
Building E	7	133	119.7	2	71.4	70.2	11	346.5	335.5	550.9	525.4
Building F	4	76	68.4	1	35.7	35.1	5	157.5	152.5	269.2	256

N.A. means no algorithm is used; A.U. means the algorithm is used.

4. Discussion

4.1. EV Consumption

The energy consumption of EVs is stochastic as already proved in the professional literature [76,77]. This research aims to show that social groups are so important that they should be considered when analysing the stochastic usage of EVs. As described in Section 3.1, freelancers covered many kilometers on a daily basis. Firstly, the results for Alcalá de Henares show that even though freelancers' contribution to V2G and V2B may not be important, ER and EDR can improve energy efficiency up to 8.4%. Due to the fact that freelancers are a much consuming energy social group when it comes to EV usage, they are forced to participate in V2G or V2B, but not in both of them as discussed in Section 4.3. Regarding commuters, the energy efficiency enhancement can reach 14.3% owing to the algorithm proposed in this study. In addition, the amount of energy available for V2B participation is high and owing to ER and EDR it is even higher. Finally, local workers would be the biggest contributors to V2B if they had an intention to buy EVs. However, EVs high prices can pose a serious obstacle for a large number of local workers. It must also be stated that the energy efficiency gain for this social sector is low (0.6 kWh). These data are valuable for policy makers as they show the social groups which might contribute most to V2G and V2B technologies. When it comes to Jaén and using the algorithm, one can find improvements in energy efficiency up to 8.1%, 10.5% and 12.2% for freelancers, commuters and local workers, respectively. It is important to remark that the number of kilometers covered in both cities for each social sector are similar. After having analyzed the data collected during the trips, two conclusions are drawn. Firstly, people are more likely to get caught in traffic jams in Alcalá de Henares than in Jaén. Consequently, a higher consumption is expected. Secondly, the difference between both cities is more remarkable in the winter. As Alcalá is colder than Jaén, EV performance is affected by temperature. This conclusion is aligned with other research. Sagaria, Neto and Baptista proved that energy consumption can vary between 25% and 30% depending on the location where the EV is used- in the northern or southern countries [86]. On the other hand, the difference between both cities is not big enough in order to find significant distinctions in EV charging patterns contrary to the conclusions drawn by Yan et al. [87].

4.2. Energy Available for V2B

The number of kWh available for V2B purposes depends on three factors. The first one is the share of EVs in the market. The second one is energy efficiency linked to EVs. This parameter should be improved by means of EDR and ER in order to increase the amount of energy available to be used for V2B. Finally, the third one is the social groups to which the participants belong to, as the way of using EVs is completely different. This research is focused on the two last concepts. As shown in Figure 10, in the buildings chosen for this case-study, most of the people belong to the social groups of freelancers and commuters. Buildings D and E are the ones which achieve more significant savings in energy due to the enhancement in terms of EV energy consumption discussed in the previous section. As detailed earlier, freelancers fail to contribute in a significant way owing to the number of kilometers covered. However, even if local workers are the less important group, on some occasions such as the case of building B, they can contribute in a very important way as the number of kilometers covered is very low and, consequently, the energy available for V2B is high. When it comes to the usage of the algorithm proposed in this research, improvements which range from 13.2 kWh to 33.6 kWh can be obtained on a daily basis based on the results depicted in Figure 11.

Figure 10. Contribution to V2B based on social groups.

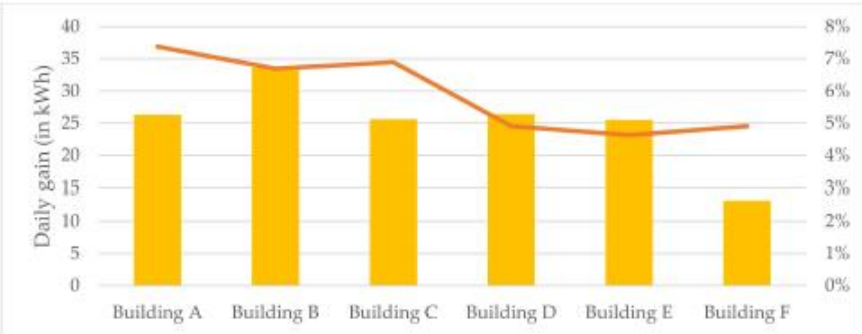

Figure 11. V2B improvement owing to ER and EDR.

Considering Figures 10 and 11, commuters and local workers are the most important contributors to V2B. Consequently, policies should be addressed in order to increase the EV presence in these two social groups. Of course, freelancers are an important group to be considered based on an environmental point of view to reduce emissions but not based on their potential contribution to V2B.

The energy consumption which took place when freelancers, commuters and local workers were outside was not considered. Therefore, the household composition studied by Csoknyai et al. is not considered [83]. As shown in Figure 12, local workers make the first energy consumption peak last more time (Buildings A and B). Secondly, local workers and commuters make the second consumption peak earlier. All these consumption peaks can be reduced due to EDR and ER algorithm.

The energy self-sufficiency of the buildings subjected to this study depends on the participation of the EV owners as shown in the sensitivity analysis (Section 4.6.1).

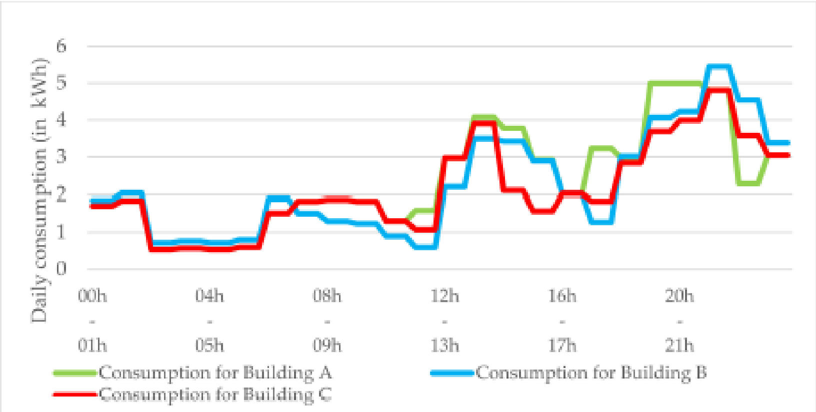

Figure 12. Electric energy consumption considering social groups.

4.3. Social Group Presence in Buildings

During this research, the authors have established which social groups contribute more to V2B. Consequently, it is of paramount importance to establish the percentage of people who belong to each social group. A binomial distribution was employed to determine the percentage of workers who belong to each social group:

(a) Set an initial hypothesis based on the number of people belonging to each social groups. To do this, a sample of five buildings for each city was chosen.

(b) A second sample was used in order to confirm or reject the hypothesis by using Equations (4) and (5):

$$H_0 \text{ is true if } \frac{|\hat{p} - p_0|}{\sqrt{\frac{p_0(1-p_0)}{n}}} \leq z_{\frac{\alpha}{2}} \quad (4)$$

$$H_0 \text{ is false if } \frac{|\hat{p} - p_0|}{\sqrt{\frac{p_0(1-p_0)}{n}}} > z_{\frac{\alpha}{2}} \quad (5)$$

n is the sample size, $\hat{p}$ is the probability of success for the sample considered, p_0 is the probability of confirmation of the hypothesis, and α is the significant level.

The results obtained are shown in Tables 5 and 6. Based on the data obtained in these tables and the consumption estimate shown in Tables 2 and 3, it is important to focus policies on these two social groups in order to increase kWh available to reduce electricity consumption in buildings.

Table 5. Percentage of occupants belonging to each social group in Alcalá de Henares.

Social Group	Sample size (Number of Households)	Probability of Success Assessed by Using the First Sample	Probability of Failure Obtained When Using the First Sample	Sample Size (Number of Households)	Probability of Success When Using the Second Sample	H_o Meaning	H_o Value ($\alpha = 0.01$)
Freelancers	150	0.15	0.85	100	0.16	The percentage of freelancers is close to 15%	Accepted
Commuters who used their vehicles		0.72	0.28		0.74	The percentage of commuters and local workers are close to 72% and 13%, respectively	Accepted
Local workers		0.13	0.87		0.14		Accepted

Table 6. Percentage of occupants belonging to each social group in Jaén.

Social Group	Sample Size (Number of Households)	Probability of Success Assessed by Using the First Sample	Probability of Failure Obtained When Using the First Sample	Sample Size (Number of Households)	Probability of Success When Using the Second Sample	H_o Meaning	H_o Value ($\alpha = 0.01$)
Freelancers	150	0.33	0.77	100	0.35	The percentage of freelancers is close to 33%	Accepted
Commuters who used their vehicles		0.45	0.55		0.49	The percentage of commuters and local workers are close to 45% and 22%, respectively	Accepted
Local workers		0.22	0.78		0.23		Accepted

4.4. RE and V2B

It is important to check the trend of electricity price, RE daily contribution and EV charging price on the Spanish market. As shown in Figures 13 and 14, the EV charging price is set by the Government and from 1 p.m. is more expensive than the electricity price in the sport market. When it comes to RE contribution, the highest value is reached between 1 p.m. and 8 p.m. During the night, when EVs are supposed to be charged, the contribution is not extremely high comparing to the rest of the day. EVs are charged when RE contribution and the price are low. This policy is contradictory as EVs contribute to the reduction of pollution because their energy may be used to reduce the peak energy consumption from 7 p.m. to 10 p.m., but to do this, EVs must be charged before 12 a.m. At that moment, the RE contribution is the lowest. The main conclusion is that promotion of RE to decarbonize the electricity system, and policy prices are as important as policies to promote EVs penetration into the market or charging points implementation. Like this, the charging process can be performed when RE contribution is high. Regarding RE in Spain, the number of MW available has been almost stable since 2012. It must be stated that establishing the optimal sizing of RE facilities under high EV integration is a relevant topic researched in several studies [87].

Figure 13. RE contribution, electricity price and EV charging price. June 2020.

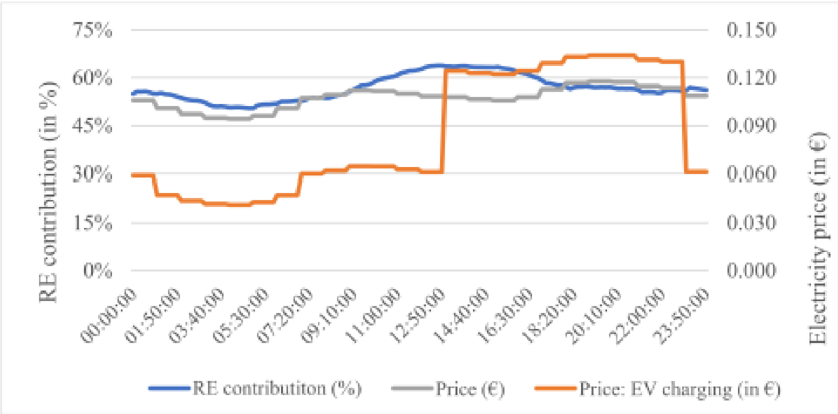

Figure 14. RE contribution, electricity price and EV charging price. December 2020.

One important point is that V2B must be compatible with other techniques, such as V2G. In this case, some important remarks must be made. Based on the total amount of energy available to be used for V2G, freelancers would tend to participate in V2B rather than in V2G, as they get more profit when using this energy to reduce their home energy consumption. When it comes to local workers, they could participate in V2G and V2B. The main issue is that they are not the most representative social sector. Finally, commuters seem to be a social sector that could also take advantage of both technologies. In order to extend the number of people who could participate in V2G and V2B, the fee to charge EVs in the second off-peak consumption should be reduced similar to Figure 15. To do this, RE should be promoted and increased in order to support energy demand to charge EVs [88]. Some research deals with the RE integration topics when using EVs. Pearre and Swan concludes that "*With a 10% adoption rate of EVs, time-of-day charging increased local renewable energy usage by 20% and enables marginal wind energy converters to upgrade*" [89]. Colmenar et al. proposed a novel grid technique in order to optimize the operation of RE and EVs to increase penetration of RE [90]. In our current research, RE, EDR, ER and EC are considered simultaneously. It is essential to highlight the importance of EC block which aim is to determine the energy structure generation as well as the RE contribution. Consequently, the EV owners know in advance, when it is the best moment to charge their vehicle based on an environmental point of view. As described in Section 2, this block can provide accurate forecasts owing to the implementation of neural networks. It must be stated that the network performance was assessed with an average value of 2.25×10^{-7}. Finally, the algorithm presented in this research uses the Open Charge Map® API which aims to inform the driver where the closest charging point is. Therefore, by using the information provided by this API, the energy consumption estimate assessed by the Here® API and the consumption models tuned properly, the driver can decide if it is possible to postpone the EV charging to a better slot in which the RE contribution is higher. Consequently, the Open Charge Map® API is also useful to make the charging process greener.

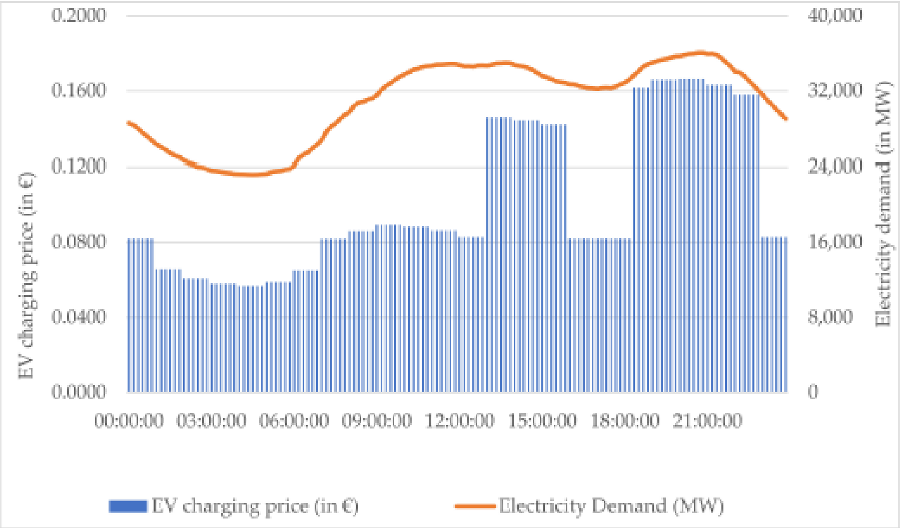

Figure 15. EV charging price proposal.

4.5. Policy Implications

As discussed earlier in this paper, EDR, ER and EC are not subject to policies in many cases. Only some recommendations have been made and a few initiatives taken as detailed in the introduction [41–43]. Taking into account the results of this research and the main goals of important initiatives such as the EGD, ER, EDR and EC must play a key role vis-à-vis addressing important issues such as the better integration of the various measures to be adopted for RE and emissions reduction. Additionally, it must be highlighted that although algorithms, such as the one described in this research, have low implementation costs, their contribution to V2B is significant. Finally, the authors recommend factoring in social groups while developing policies as the usage of EVs is different and the contribution therefore to V2B can have significant variations. Hence, it is essential to promote EVs with the help of social groups even as the needed investments continue to be made in new RE facilities.

4.6. Validity of This Research

4.6.1. Sensitivity Analysis

It is important to assess the contribution of EDR and ER to V2B taking into account the participation of EV owners. Several factors such as battery degradation and policies influence this participation. In this sensitivity analysis, several participations have been considered when the number of participants was between 25% and 75%. As Figure 16 shows similar results as Figure 11. The gain goes from 4.225 kWh (25% for Building F) to 106.775 kWh (75% for Building E) on a daily basis.

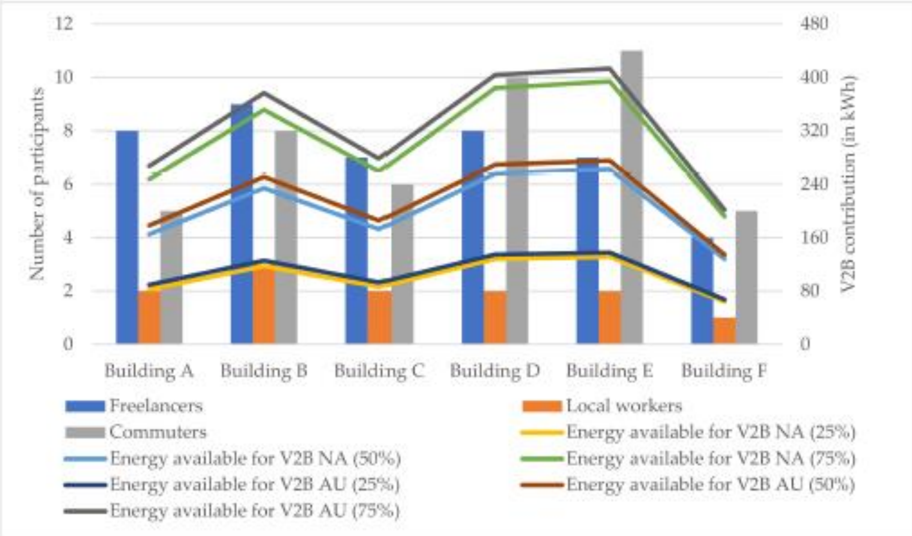

Figure 16. V2B contribution.

4.6.2. Threats to Validity

In this section, the actions taken to reduce these threats are displayed in Table 7.

Table 7. Factors chosen for validity of this research assessment.

Id Factor	Factor	Description
1	Choice of the city	When choosing the cities for this study, several factors were taken into account such as the size of the city, population, traffic analysis, distribution cameras controlling the traffic, the car park trend, etc. In addition, climactic zones were also considered to check as the battery performance may change. Taking into consideration these factors, the authors concluded that Jaén and Alcalá de Henares met the requirements for this research.
2	Choice of the social groups	Not all users have the same driving profile. It would not be accurate to estimate energy without considering this factor. The authors have considered it to be of paramount importance to give a breakdown of the population of these two cities. Firstly, freelancers as they use Evs frequently, and they are supposed not to have important amount of energy to contribute to V2B. Secondly, people who usually use public transport to commute. Therefore, their contribution to V2B will be important. Finally, other workers who work outside Alcala and Jaén or work in Alcala and Jaén.
3	Choice of the buildings	An analysis was done based on an in-depth literature review (Section 2.3) in order to determine the optimal criteria for choosing the buildings considered in this research.

5. Conclusions

Emissions linked to the transport sector and building are of great concern nowadays. Consequently, improvement in both fields must be performed. This research proposed an algorithm based on the Here® application interface (one of the most important digital maps suppliers), neural networks, electric vehicles, eco-routing, eco-driving and eco-charging concepts. By using this algorithm, the increase in energy available to be used in vehicle-to-building technology was assessed. However, there is one important topic to analyze the energy available such as the stochastic usage of electric vehicles. To be more specific, it is essential to classify the working population into social groups such as freelancers, local workers and commuters. Due to this, many data were collected in real-driving conditions from drivers who belonged to different social groups as their way of driving is different. Finally, all these data acquisitions were conducted in two cities (Alcalá de Henares—Madrid-Spain and Jaén-Spain) which are located in different climatic zones. The main conclusions that can be drawn are:

(a) Energy savings
As shown in Section 3.1, this algorithm introduces reduction in energy consumption when driving electric vehicles. As it could be expected, energy consumption is different depending on the social group. Consequently, the contribution to vehicle-to-building technology differs. Regarding Alcala de Henares, energy efficiency reaches 2.2 kWh for freelancers per day. When it comes to commuters, this gain reaches 1.5 kWh a day and, finally, 0.6 kWh and for local workers on a daily basis. Regarding Jaén, the savings are similar. The energy efficiency reaches 1.9 kWh for freelancers per day. When it comes to commuters, this gain is 1 kWh on a daily basis and, finally, 0.6 kWh for local workers a day.

(b) Contribution to vehicle-to-building
Vehicle-to-building is based on the principle that the electric vehicle owner will participate and inject energy stored in the electric vehicle battery into the building. However, it is essential to determine energy available and, again, the fact of taking into account social groups influences energy available to be used for vehicle-to-grid technique. Regarding Alcalá de Henares, energy available ranges between 112 kWh and 144 kWh a day depending on the social group mix existing in the building. In regard to Jaén, energy available ranges between 76 kWh and 152 kWh a day depending on the social group mix existing in the building. Finally, it must also be taken into account that energy consumption pattern may change depending on the social groups that occupants belong to as discussed in Section 4.2.

(c) Charging policies

In order to make the charging process greener, it is necessary to charge electric vehicles when renewable energy contribution is higher. Based on the analysis of building consumption done in this research, the energy consumption pattern can differ depending on the social group that the occupant belongs to. The algorithm provided in this research can determine when the contribution of renewable energy is higher. Due to this, when its contribution is higher, the charging price is more expensive. This paper proposes possible changes to charging fees to make vehicle-to-building and vehicle-to-grid compatible as discussed in Sections 3.2 and 4.4. In order to apply this fee, the increase in megawatt of renewable energy installed is as important as increase in the number of electric vehicles.

Supplementary Materials: A beta version of the application coded in Python is provided at https://www.mdpi.com/article/10.3390/en14123483/s1. The full version cannot be provided as the company which collaborated in this study has not authorized it. The measurements obtained when driving Evs are not provided as the company which collaborated in this study has not authorized it.

Author Contributions: D.B.-D. and P.M.O.-C. were primarily responsible for creating this manuscript. D.B.-D. and P.M.O.-C. were responsible for creating the application in Python and obtained all measurements performed in this research. A.C.-S. and J.J.B.-P. analyzed the data obtained as well as policies and collected data and information from the Spanish System Operator. All authors have read and agreed to the published version of the manuscript.

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Appendix A. How to Configure Calls to Here® API

When assessing the best route to go from A to B, Here® API is a very powerful tool as it can provide a lot of information linked to the established route. The way of calling this API when coding in Python is easy. However, some factors must be taken into account. Figure A1 depicts the pseudocode employed in this case-study in order to call the Here® API. As one can see, one important parameter is known as PARAM which is composed of several variables such as:

(a) *apiKey*. It is a key that must be generated when someone is registered in the Here® developers' web. In Figure A1, the key is represented by XXXX and, of course, the reader should type their own key.
(b) When going to A to B, waypoint0 and waypoint1 represent the latitude and longitude data of A and B. These values must be stored in Python by using a dictionary (*location_coor*). The main question is how to obtain the latitude and longitude. In this study, Geopy was used.
(c) Mode. For a more accurate assessment of the route, the reader should specify the type of route (the fastest, the shortest) and traffic state.
(d) In Section 2, the way of tuning the consumption model was explained. The Python code sends energy consumption models to Here® API by employing *consumptionmodel* and *consumptiondetails* variables.

```
"""Routing the fastest"""
PARAM=("apiKey=XXXX" +
"&waypoint0=geo!" + str(location_coor[1]) + "," + str(location_coor[2]) +
"&waypoint1=geo!"+
str(location_coor[3]) + "," + str(location_coor[4]) +
"&mode=fastest;car;traffic:enabled&consumptionmodel=standard&" +
"customconsumptiondetails=" +
"speed,0,1.7,10,1.4,30,1.1,50,1.0,70,1.1,100,1.2,120,1.4,140,1.8;" +
"ascent,30.0;descent,10.0;auxiliaryconsumption,0.8;acceleration,0.2;deceleration,0.3"
+
"&legAttributes=links,trafficTime&linkAttributes=consumption,dynamicSpeedInfo")
response[1]=routing(PARAM)

"""Routing the shortest"""
PARAM=("apiKey=XXXXXX" +
"&waypoint0=geo!" + str(location_coor[1]) + "," + str(location_coor[2]) +
"&waypoint1=geo!"+
str(location_coor[3]) + "," + str(location_coor[4]) +
"&mode=fastest;car;traffic:enabled")
response[2]=routing(PARAM)
```

Figure A1. Pseudocode to obtain the desired Here® answer.

When the Here® API determines the best route, it sends a json file to the Python code. When analyzing the structure of the file provided by Here®, a lot of important information can be collected such as traffic condition, time needed to cover the route, etc. (Figure A2). Based on these parameters, the average values of some parameters such as speed or energy consumption can be estimated easily.

Figure A2. Here® answer. Json format.

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ANEXO VIII. Copia de la publicación: “Can Eco-routing, Eco-driving and Eco-charging Contribute to the European Green Deal? Case study: Alcalá de Henares (Spain)”

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Can eco-routing, eco-driving and eco-charging contribute to the European Green Deal? Case Study: The City of Alcalá de Henares (Madrid, Spain)

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A B S T R A C T

The European Green Deal aims to make Europe the first climate-neutral continent and reduce greenhouse gas emissions by 2050.

This research offers proposals for the European Green Deal based on sustainable transport, clean energy and reduction in the energy consumption of buildings. An algorithm based on the Here® application programming interface, neural networks, data from the Spanish transmission system operator, eco-routing, eco-driving and eco-charging is proposed. Its contribution to vehicle-to-home, renewable energy integration, and vehicle-to-home and vehicle-to-grid compatibility is analysed by using data acquisitions of the trips made by drivers from different social groups.

The algorithm allows a daily energy saving of up to 2.2 kWh for freelancers, 1.5 kWh for commuters and 0.6 kWh for local workers. The vehicle-to-home contribution increases from 18 MWh to 553 MWh per year. Finally, neural networks allow better integration of renewable energy.

The contributions to the European Green Deal are as follows: energy efficiency improves when policies are addressed to the adequate social sector combined with eco-driving and eco-routing; neural networks allow for achieving a better integration of renewable energies as they can predict when its contribution is higher; and policies to make vehicle-to-grid and vehicle-to-home compatible with reduced emissions must be developed.

1. Introduction

The European Green Deal (EGD) aims to make Europe the first climate-neutral continent. The EGD rests on three pillars: a reduction in greenhouse emissions by 2050, stimulation of economic growth without linking it to the use of resources, and the involvement of all members of society in the implementation of this new strategy [1]. To achieve the goals of the EGD, many actions need to be undertaken in all sectors of the economy, such as: "*investing in environmentally-friendly technologies, supporting industry to innovate, rolling out cleaner, cheaper and healthier forms of private and public transport, decarbonizing the energy sector, ensuring buildings are more energy efficient and working with international partners to improve global environmental standards*" [2,3]. This research focuses on the concepts of sustainable mobility, reductions in the energy consumption of buildings, and clean energy. In regard to sustainable mobility, the aims of the EGD are to reduce greenhouse gas emissions by 90%, to achieve smarter traffic management, and to promote alternative modes of transport. To realise these initiatives, it will be vital to encourage the use of electric vehicles (EVs). With regard to the goal of clean energy, the EGD aims to increase the proportion of renewable energy (RE) in the electricity sector. The European Union intends to "*prioritize energy efficiency and develop a power sector based largely on renewable energy sources*" [4]. Finally, improving the energy efficiency of buildings will involve prioritising the "*design and consumption of new retrofitting of existing buildings as zero-emission/zero pollution, positive energy powerhouses with sustainable green neighborhoods*" [1]. One of the major components of this transition will be energy-positive buildings that incorporate sustainable and RE technologies.

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In 2017, road transportation accounted for 73% of the total demand from the transport sector, a value that was 34% higher than in 1990 [5]. EVs will play a key role in decarbonising the transport sector and achieving an 80% reduction in greenhouse gas emissions by 2050 [6]. Even if the entire lifecycle is considered, the sum of emissions from all activities associated with EVs (in the production, maintenance and end-of-life stages) is lower than those for traditional vehicles, despite the need for an improved battery production process [7–9]. New research also indicates that EVs are already cheaper than diesel or petrol vehicles; this was shown by Carrington [10], who analysed several factors such as cost over four years, purchase price, fuel, insurance, taxation and maintenance. Colmenar et al. [11] demonstrated that the right policies are essential to encourage the widespread use of EVs by analysing the profitability of an electric transportation model. The main problem associated with EVs is their stochastic use. Zhang et al. performed an interesting analysis of usage patterns, with a focus on important parameters such as charge consumption, the state of charge before and after charging, single-trip distances, the daily distance travelled and energy consumption [12], and found that drivers' working hours and resting routines had an important influence on energy consumption. Weldon et al. explored the usage patterns of EVs in Ireland, while Shi et al. analysed similar patterns in Shanghai, the city with the largest number of EVs, and highlighted the advantages of EVs based on their average speeds and the kilometres travelled on a daily basis [13]. Their main results indicated that EV owners tended to use their vehicles frequently and that their trips were short in terms of distance, but they did not investigate whether these patterns arose from concerns over battery life or consumer preferences [14].

Vehicle-to-grid (V2G) technology allows for better integration of RE and reductions in peak energy usage [15,16]. Hofmann et al. [17] showed that EVs cause zero pollution in the context of decarbonisation of the electricity sector in China. This conclusion was supported by Thiel et al. [18]. Vehicle-to-home (V2H) technology allows for reductions in emissions linked to buildings, as EV owners can supply their homes with the energy stored in EV batteries. Colmenar et al. [19] highlighted the benefits of V2H in terms of increasing the penetration of RE and reducing costs. Noori et al. [20] focused on how V2H contributes to achieving the energy requirements for net zero energy buildings. By combining V2H with the best design alternatives for energy-efficient buildings and solar photovoltaic sources to meet the remaining energy demand, consumption of grid electricity can be reduced by 68% compared to a conventional building design. V2H and V2G have also certain drawbacks, as the supplementary use of the battery implies that the service life of the battery will be reduced. Darcovich et al. [21] proved that the V2H technique provides useful services with acceptable levels of battery degradation under certain conditions. Lazzeroni et al. developed an approach for battery management for EVs with the aim of minimising electricity costs based on the driver's behaviour and the battery constraints [22].

Eco-driving (EDR) minimises fuel consumption and emissions, as drivers are informed about the efficiency of their driving [23]. Qi et al. [24] carried out research into EDR by quantifying the energy that was saved when this approach was applied to EVs. Sabrina et al. [25] published a study in which continuous and on-demand feedback was given on driving behaviour and a safety system was implemented. Zhan et al. [26] showed how energy efficiency can be enhanced by systems that monitor the EV battery. Eco-routing (ER) can be used to plan the most efficient route from point *A* to point *B*, taking into consideration several parameters such as the real-time traffic conditions, the types of road, the number of passengers and the cargo weight [27,28]. Nunzio et al. [29] proposed a model that considered speed fluctuations and the road network infrastructure when setting a route. Some systems have been developed based on the idea of collecting energy consumption data under real-world driving conditions to find the optimal route [30]. ER, EDR and eco-charging (EC) can reduce emissions and improve energy efficiency, as they reduce energy consumption and contribute to better integration of RE into the EV lifecycle [31,32].

In this research, we put forward several proposals for the EGD that are linked to sustainable mobility, the energy efficiency of buildings, and clean energy. Compared to previous studies, this research presents interesting and novel results in several areas, as follows:

a. We show how the usage of EDR and ER algorithms impacts energy efficiency, including the stochastic usage of EVs and social groups (freelancers, commuters and local workers). Real-world data were collected, both with and without the use of an algorithm based on the Here® application programming interface (API) [33], neural networks, data published by the Spanish transmission system operator, ER, EDR and EC. This study takes into consideration all of the social groups in the working population, such as freelancers, commuters, etc., since factors such as their modes of driving and the numbers of kilometres travelled are different. In addition, several types of vehicles were considered in order to obtain more representative data.
b. We explore the contribution of V2H to the reduction of emissions [34,35] while carrying out an in-depth analysis of the influence of EDR and ER on the stochastic usage of EVs. The energy savings and the contribution to V2H technology when using the algorithm are quantified in order to assess the reductions in the energy consumption of buildings.
c. The contribution of RE is assessed with the aim of informing the driver of the optimal time to charge the battery. Many algorithms have previously been proposed for the integration of RE by finding the optimal moment to charge an EV [36]. However, these algorithms do not take into account the tariff and regulations on EV charging established by the government and the concepts of EDR and ER at the same time. This topic is discussed in the present research.
d. Many research studies have focused on a variety of topics linked to EGD, such as the relevance of sustainable soil management, health improvements, economic aspects, etc. This study reports novel data on driving efficiency based on the usage patterns of EVs [37,38]. We identify candidate targets, the considerations that will be necessary in order to increase the presence of EVs, and their contribution to V2H and V2G when developing new policies based on the real-world data collected in this research and our algorithm based on ER, EDR and EC.
e. We carry out an analysis of the compatibility between V2G and V2H that takes into account a range of social groups (freelancers, local workers and commuters).

The remainder of this paper is organised as follows. Section 2 describes the method used in this research, including the characteristics of the city analysed in our case study, a description of our algorithm and the statistical methods used to analyse the data collected in this research. Section 3 discusses the energy consumption by EVs in all social groups and the potential contributions to V2G, among other factors. Section 4 discusses our results and proposes guidelines for the EDG. Finally, Section 5 summarises the main conclusions of this paper.

2. Method

2.1. Description

Two key aspects were considered in this research: an analysis of the working population of the city chosen for our case study, and the proposed algorithm. The former involves classifying the population into different social groups, i.e. freelancers, commuters and local workers, since the ways in which they use EVs are different. Data acquisition both with and without the proposed algorithm was carried out to record the usage of EVs by the drivers participating in this research. All of the trips analysed in this study were made according to the users' needs (aleatory trips/not previously planned). The algorithm was implemented in Python using the Here® API [33], and was designed to determine the best route based on EDR and ER models that were built by analysing data from a vehicle control unit (VCU), together with data on traffic conditions, drivers' habits, and potential recharge needs, among others [33,39]. The use of EC can tell drivers when a recharge process should be performed, i.e. when the contribution from RE is higher (see Fig. 1).

2.2. Selection criteria used for the case study

Alcalá de Henares is a city located 32 km from Madrid, the capital of Spain. According to data published by the Spanish National Institute of Statistics, it had a total of 198,750 inhabitants in 2018. Traffic was monitored using 17 cameras distributed across the whole of the city (Fig. 2) [40,41]. On the outskirts of the city (marked in black), the cameras were mainly concentrated towards the south (Fig. 2). Fig. 3 shows the main directions for road access to Madrid. They are highly conflicting points in matters of traffic density [40,41].

Considering the population, the size of the city (the second largest in the Community of Madrid), the traffic conditions and the location, this city was a good candidate for the present research.

2.3. Working population in alcalá de henares

The usage of an EV depends on the profile of the driver (the number of kilometres travelled, the mode of driving, etc.). A random sample of 100 people was used to investigate the usage of EVs. To ensure that the sample was representative, participants were drawn from different districts of the city and from various social groups. Table 1 shows the questions asked in the survey administered to this sample.

The method used to assess the number of workers belonging to each social group shown in Table 1 was as follows:

a. An in-depth analysis of all data published by the Town Hall, in order to estimate the percentage of the working population in each social group.
b. Confirmation of these estimates by using statistical methods to accept or discard the null hypothesis, H_o, whose probability is equal to the one established in a). To do this, a binomial distribution $B(1,p)$ is used, where p is the probability of success. The H_o values are analysed in the Results section using Equations (1) and (2) below [42]. For example, for the freelancer group, p is the probability of choosing a freelancer, and $1-p$ is the probability of choosing a member of the sample from another social group, such as commuters or local workers.

$$H_o \text{ is accepted if } \frac{|\hat{p}-p_0|}{\sqrt{\frac{p_0(1-p_0)}{n}}} \leq z_{\frac{\alpha}{2}} \quad (1)$$

$$H_o \text{ is rejected if } \frac{|\hat{p}-p_0|}{\sqrt{\frac{p_0(1-p_0)}{n}}} > z_{\frac{\alpha}{2}} \quad (2)$$

where n is the sample size, $\hat{\mathbf{p}}$ is the probability of success for the sample studied, $\boldsymbol{p_o}$ is the probability to be confirmed (hypothesis), and α is the significant level.

2.4. Description of the algorithm

The steps of the algorithm are illustrated in Fig. 4. The energy consumption models offered by the Here® API were tuned [43]. Each driver was asked to specify his or her destination using the

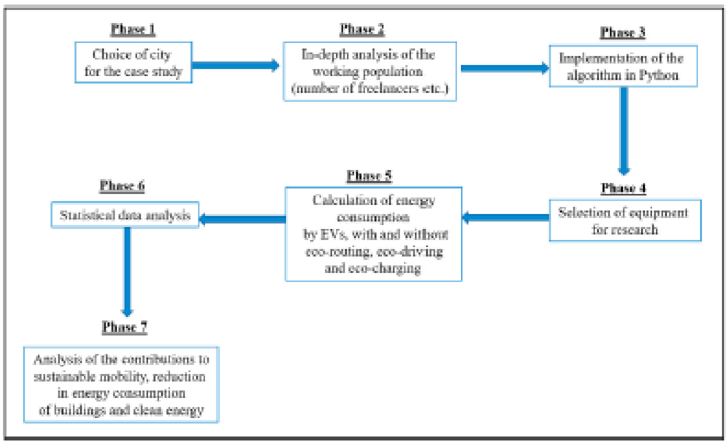

Fig. 1. Flow diagram of the method applied in this study.

Fig. 2. Distribution of cameras.

Fig. 3. Road access towards Madrid.

Table 1
Questions asked in the survey.

Questions
Profession (freelancer, commuter or local worker)
How many kilometres do you travel on a daily basis?
Do you commute?
Do you use public transport?
Are you willing to buy an EV?

web interface, and the algorithm planned the best route using the Here® API and Python. The Here® API has a parameter called *Routingmode*, which has an attribute called *Type*. *Type* can take three different values depending on the type of route: a route that minimises the travel time, a route that minimises the distance covered, and a balanced mode, which searches for an appropriate balance between distance and time (applicable only to trucks). The way in which the algorithm plans the best routes belongs to the Here® know-how. The Python code obtains the routes from the Here® API (the shortest, the fastest and a balanced route) to the destination and the energy consumption for each one. The algorithm chooses the route for which the energy consumption is the lowest. Finally, the Python code calls a block called EC, which is responsible for assessing the RE contribution and the energy structure generation (wind energy, photovoltaic, etc.) using a neural network. The driver is then given information on the times when the charging process will produce the least pollution.

The Here® API provides models that can be used to estimate the energy consumption based on multiple parameters such as the speed and the auxiliary energy consumption (from a radio, for example). To tune these models, the value of each parameter in kWh must be known for varying speeds (although some parameters are not related to speed, such as auxiliary systems). These values were assessed by acquiring data from the participating

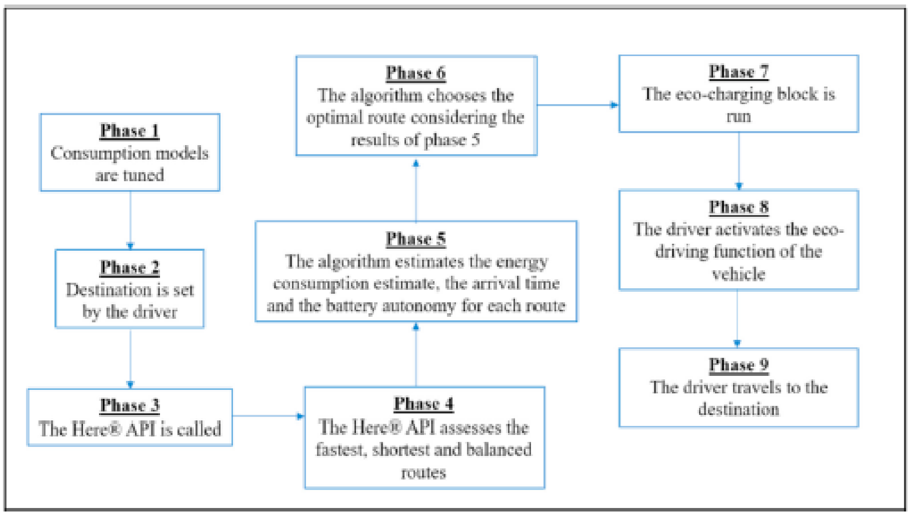

Fig. 4. Main steps of the algorithm.

drivers over the period of one month. Laptops equipped with Inca® software and input/output from ETAS® supplier modules were used for data acquisition (Fig. 5) [44,45]. The values of these factors were set by tuning engineers, who analysed the data using MDA® software [46]. Once these values were known, the energy consumption models were tuned following the official documentation from Here®. When the energy model consumption had been tuned and introduced into the Python code, Here® was able to return an energy consumption estimate for all possible routes (fastest, shortest and balanced routes). The route with the lowest consumption was chosen. Based on the capacity of the battery before the trip, the algorithm assessed whether a charge would be needed during the trip.

The last phase of the process was to run the EC block and to assess the EC score. This block was used to estimate when the charging process should take place and to measure the contribution of REs to this process. The EC block was also used to estimate the energy source (coal, gas, photovoltaic, etc.). The overall process was composed of three phases. In phase 1, several factors were assessed in depth, including the battery capacity and the energy consumption for a specific journey (the energy consumption was assessed earlier, by employing the energy consumption models). The optimum time for the charging process was then determined in phase 2. The contribution from RE and the most likely mix of energy sources (coal, gas, photovoltaic, etc.) was then obtained by using gated recurrent unit (GRU) networks and nonlinear autoregressive (NAR) neural networks in phase 3 [47–50], and this is described in more detail in a later section. At the end of the process, the EC was calculated, including the contribution from RE. The EC score can be used to estimate the level of pollution from the charging process, based on the contribution from RE. Its value is assessed using Equation (3):

$$EC = \frac{RE_{c,t}}{RE_{max,d}} \tag{3}$$

where $RE_{c,t}$ is the contribution from RE to the total electricity demand at t (in MW) and $RE_{max,d}$ is maximal contribution from RE (in MW) during the day when the charging process takes place. Both parameters are assessed by employing neural networks. The contribution from RE is given by Equation (4):

$$RE_c = \frac{RE}{RE + NRE} \tag{4}$$

where RE_c is the contribution (in %), RE is the total electricity generated by RE sources (in MW) and NRE is the total electricity generated by non-RE sources such as coal (in MW).

$RE_{c,t}$ and $RE_{max,d}$ were estimated based on data from the Spanish system operator. These are published on a daily basis, and give the CO_2 generation structure and the total electricity demand for the day [51]. Electricity demand and total RE contribution are stationary series. Only some aspects must be taken to into account, in particular weekends and seasons. The use of a recurrent neural network is therefore essential in order to predict the electricity demand for a specific day from a desired time to midnight. Our Python code was used to examine the information output by the neural network and to calculate the maximum contribution from RE for each day, using Equations (3) and (4).

Recurrent networks present problems when used for long-term predictions, due to the vanishing gradient issue that arises when they are trained with gradient-based learning methods and backpropagation. When these methods are used, each of the weights in the neural network receives an update that is proportional to the partial derivative of the error function with respect to the current weight, in each iteration of the training process. In some cases, the gradient will be vanishingly small, and the value of the weight does not vary, which may stop the training of the neural network. Long-short term memory or GRU approaches can be employed to improve long-term predictions. In this study, GRUs were used due to their computational efficiency (low memory requirements). A GRU is a recurrent neural network consisting of update and reset gates (Fig. 6) [47–50].

Mathematically, the process is as follows [47–50]:

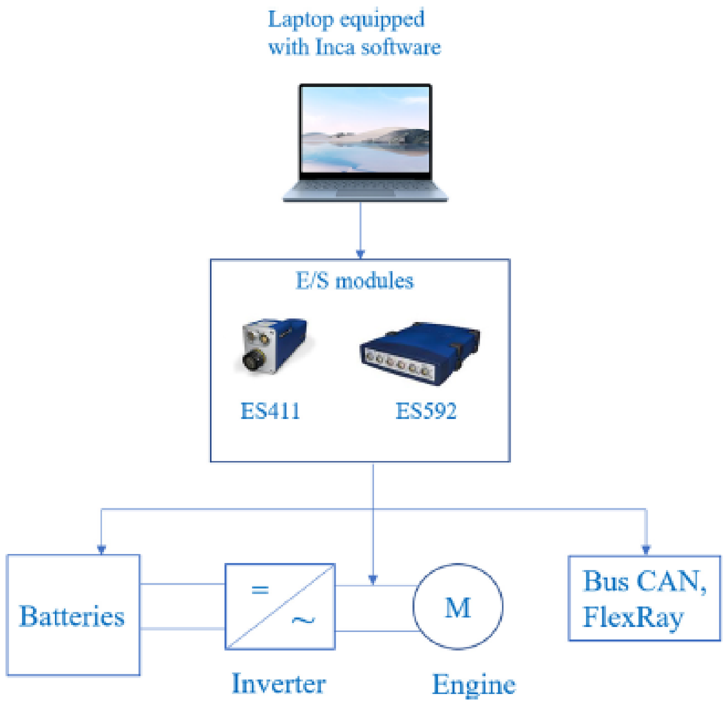

Fig. 5. Schematic showing the connection between a laptop and an EV.

a) Update gate for time step t

The update gate z_t is calculated using Equation (5):

$$z_t = \sigma \times (W^{(z)} \times x_t + U^{(z)} \times h_{t-1}) \quad (5)$$

where x_t are the inputs presented to the network, $W^{(z)}$ is the matrix of weights, h_{t-1} stores the information from the previous step t-1 and $U^{(z)}$ is its matrix of weights. Both results are added, and a sigmoid activation function is applied to normalise the result to between zero and one. The update gate allows us to determine how much of the information from previous steps should be passed along to future steps.

b) Reset gate for time step t

This calculation is given in Equation (6).

$$r_t = \sigma \times (W^{(r)} \times x_t + U^{(r)} \times h_{t-1}) \quad (6)$$

The meanings of these variables are the same as in Equation (5) except for r_t, which is the reset gate. The reset gate represents previous information which should be forgotten.

c) Current memory content

The new memory content h'_t uses the reset gate to store relevant information from the past.

$$h'_t = tanh(W \times x_t + r_t \times U \odot h_{t-1}) \quad (7)$$

The meanings of these variables are the same as in Equations (5) and (6). $\odot$ represents the Hadamard product.

d) Final memory at the current step

In this step, the vector h_t is calculated using Equation (8). This vector stores the information for the current unit and passes it down to the network. To do this, the update gate is needed.

$$h_t = z_t \odot h_{t-1} + (1 - z_t) \odot h'_t \quad (8)$$

Fig. 7 shows pseudocode for the GRU networks used in our approach. To reproduce the experiment, data from the Spanish system operator for the last four years were needed. The first three years of data were used as inputs for the network, and the last year of data was used as a target to train the network. All data were rescaled to between zero and one with the aim of ensuring network performance. The networks were parameterised using the *keras* package. The *Sequential* parameter was first applied to the code to specify that the model was sequential, and the output of each layer formed the input for the next layer. We also used a dropout function, a technique in which randomly selected neurons are ignored during training. This means that their contribution to the activation of downstream neurons is temporally removed on the forward pass, and weight updates are not applied to the neuron on the backward pass. The most important advantage of this technique is that the network becomes less sensitive to the specific weights of the neurons. From the possible methods that could be used to analyse the error loss, the mean squared error was chosen, an approach that is widely recommended for regression problems. The *Adam* optimisation algorithm was applied rather than a

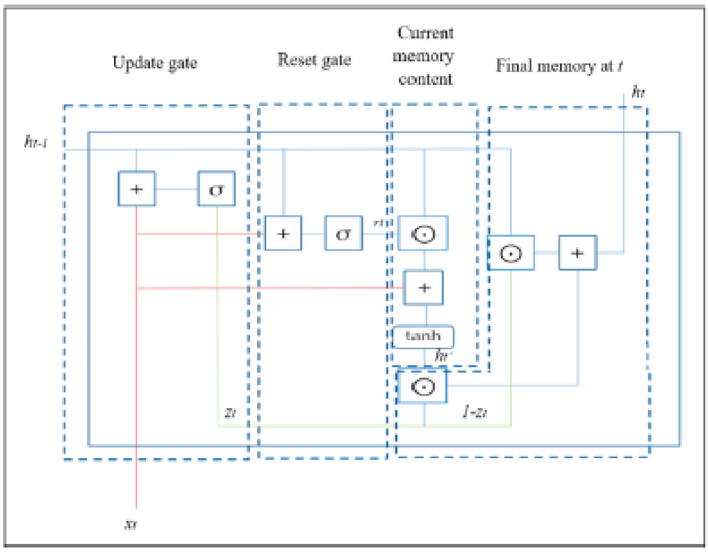

Fig. 6. Architecture of a GRU

classical stochastic gradient descent procedure to update the network weights in an iterative way, based on the training data. The main advantages of this approach are its straightforward implementation and computational efficiency. The other details used to implement the networks are shown in the pseudocode (Fig. 7).

The algorithm assesses the structure generation for the next 2 h using the data published by the Spanish system operator (CO_2 generation structure and the total electricity demand for the day) and an NAR neural network. An NAR network is helpful when manipulating time series and predictions. The network was created and trained in an open loop, and the targets are used as feedback. The networks are then checked using a closed loop [49,50,52,53]. The NAR network is expressed in Equation (9):

$$\hat{y}(t) = f(y(t-1) + y(t-2) + ... + y(t-d) + \varepsilon(t) \quad (9)$$

where f represents the network response based on the previous input data, and $\varepsilon(t)$ is the difference between the predicted value $\hat{y}(t)$ and the actual y. The number of delays establishes the d values to be considered for the prediction. The number of hidden layers and neurons per layer is flexible, in order to achieve the best performance of the neural network. This number must be carefully chosen, as the network may become highly complex. Fig. 8 illustrates the effect of choosing the value of the delay parameter when making predictions. A high value of d implies that the predicted line series changes more slowly. When d is lower, the predicted line series follows the real wind power value more accurately. If d has a very low value, then the predicted line series no longer follows the real value of the wind power. It is therefore clear that d has an important influence on the weights given to past values. Significant changes in trends are therefore not detected, which may be due to the weather conditions. Due to this, NAR networks are employed in this study as an estimation and the accuracy remains on GRU networks. However, this technical issue does not have a significant impact, as Matlab® allows for the predictions to be corrected if the predicted values are known. This is the case for this application, as it can predict $t+1$, $t+2$, $t+3$ … at a specific moment t. At time $t+1$, the neural network can be updated, since the predicted value and the real value are known in real time (since the Spanish system operator publishes the necessary data in real time). Good predictions can be obtained for the next 2 h when a value of $d=3$ is applied and when the data from 2019 supplied by the Spanish system operator are used. Fig. 9 shows pseudocode for the NAR network implemented in Matlab®. The NAR networks were trained using the *trainlm* function, in which the bias and weights are updated using Levenberg-Marquardt optimisation. This is the fastest backpropagation algorithm, although it requires more memory than other methods.

2.5. Equipment

The equipment used in this research was as follows:

1. The software and hardware for the VCU were designed by a major automotive supplier.
2. The vehicles used by freelancers had a maximum torque of 340 Nm and a maximum power of 160 kW (40 kWh capacity). The battery capacity was 40 kWh. For the local workers and commuters, all of the vehicles used were equipped with a 40-kWh battery. Their range was close to 250 km. The maximum speed was 144 km/h, and the engine torque was around 320 Nm.
3. INCA® software from ETAS® was used to read the software variables from the VCU memory [44].
4. MDA software from ETAS® was used to analyse all acquired data [46].
5. Here® and Open Charge Map® APIs were used to determine the best route and the locations of the chargers [33,39].
6. ETAS modules, including models ES411 and ES592, were used to connect the laptops to the EVs in order to acquire the data.

```
Import packages: numpy, pandas, keras, tensorflow, sklearn

#import data provided by the Spanish System Operator
pd.read_csv_file (data_2016, 2017, 2018, 2019)

#Preparation of the data used as input to the GRU network
X=reshape_data_inputs

#normalise data to a [0,1] scale
minimum = amin(X, axis=−1).reshape
maximum = np.amax(X, axis=−1).reshape()
X = (X-minimum) / (maximum-minimum)
Y = (Y-minimum) / (maximum-minimum)

#network parameters. A model is a stack of layers
model = Sequential()

#Add a layer with a specified number of inputs
model.add(GRU(128, input_shape=(data), return_sequences=True))
model.add(Dropout(0.1)) # Dropout = 10%

# Determine whether to return the last output in the output sequence, or the full sequence.
model.add(GRU(64, return_sequences=True) #Add a layer with a specified number of inputs
model.add(Dropout(0.1)) # Dropout = 10%

model.add(GRU(32, return_sequences=True)) ) #Add a layer with a specified number of inputs
model.add(Dropout(0.3)) # Dropout = 30%

# Choice of optimiser and error measurement
model.compile(loss='mean_squared_error', optimiser='adam')

#Training
his = model.fit(X, Y, batch_size=2, nb_epoch=5, verbose=1)# , callbacks=[TQDMNotebookCallback()])
```

Fig. 7. Pseudocode for the GRU network.

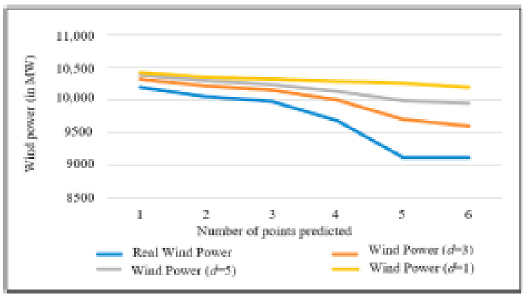

Fig. 8. Differences between predicted and real values.

2.6. Data analysis

The collected data had an approximately normal distribution, and we confirmed this assumption using the following method. The package named *PASWR* from R software was used [54] to carry our an exploratory study of the kurtosis, skewness and p-value. Kurtosis is a statistical measure that defines the extent to which the tails of a distribution differ from those of a normal distribution. Thus, kurtosis identifies whether the tails of a given distribution contain extreme values. The value representing a normal distribution is three. There are three types of kurtosis: in mesokurtosis, the value is close to three; in leptokurtosis, the value is significantly higher than three, meaning that outliers are present; and in platykurtosis, the extreme values are less than the normal distribution. Skewness essentially measures the symmetry of the distribution.; for a normal distribution, the value of the skewness should be close to zero. It is important to note that symmetry does not imply that the data correspond to a normal distribution, and the aforementioned parameters must be analysed in more depth. The p-value or probability value is the probability of obtaining test results at least as extreme as the results actually observed during the test, assuming that the null hypothesis is correct [42].

Plots are an important method of analysing data. Three types of plot were used in this research: histograms, Q-Q plots and box plots. A histogram can be defined as a graphical representation in which a group of data points are organised into user-specified ranges. A Q-Q plot allows us to assess whether data have a particular theoretical distribution, such as a normal distribution. A box plot is a graphical rendition of statistical data based on the minimum, the first

```
data = Spanish_system_operator_data; % loading data

net = narnet(1:3,10); % three delays and 10 hidden layer size.

[Xs,Xi,Ai,datas] = preparets(net,{},{},T); % prepare data for training

net = train(net,Xs,datas,Xi,Ai);  %train the network

[Y,Xf,Af] = net(Xs,Xi,Ai); %assess the network performance

[netc,Xic,Aic] = closeloop(net,Xf,Af); %predict results using a closed loop
```

Fig. 9. Pseudocode for the NAR network.

quartile, the median, the third quartile, and the maximum. The top of each rectangle shows the third quartile, a horizontal line near the middle of the rectangle shows the median, and the bottom of the rectangle represents the first quartile [42].

3. Results

3.1. Numbers of people in each social group

We determined the number of people in each social group using a statistical method that is described in a later section.

a) Freelancers

Freelancers typically travel a large number of kilometres on a daily basis. The numbers of freelancers in Alcalá are shown in Fig. 10 and Table 2, based on the data provided by the Town Hall. This trend will be essential when we establish our hypothesis H_o using the binomial distribution, as described later [55,56]. Table 2 shows the numbers of freelancers and the total numbers of workers classified by age. Most of the freelancers were between 35 and 54 years old. In the last two years, the numbers of freelancers were very close to 14.5%, and this value has followed a very stable trend (Fig. 10). The maximum percentage was slightly higher than 16% in 2015 and the minimum value was 14.2% in 2016. The last known value was 14.6%. In this research, we assumed that the percentage of freelancers was 14.6% when developing our hypothesis H_o. This value was confirmed statistically, as described in Section 2.3. A sample of 100 people was taken with the aim of assessing the number of people in each social group in the working population (freelancers, commuters and local workers). The total number of freelancers in the sample was 15, and all of these used a vehicle to get to work. Our assumption was therefore supported; the percentage of freelancers used in the remainder of this study was 14.6%, and this figure was used in Equations (1) and (2) presented in Section 2.3 [42]. In this case, only one sample was necessary, as the initial assumption was established based on the statistical data published by the Town Hall (Table 2 and Fig. 10).

Table 2
Numbers of freelancers.

Age	Total no. of workers	Total no. of freelancers
20–24	9927	1449
25–29	10,900	1591
30–34	12,514	1827
35–39	15,016	2192
40–44	17,813	2601
45–49	16,774	2449
50–54	14,550	2124
55–59	12,590	1838
60–64	11,709	1711
	121,793	17,782

b) Workers who do and do not commute

Table 3 shows the numbers of people in the different social

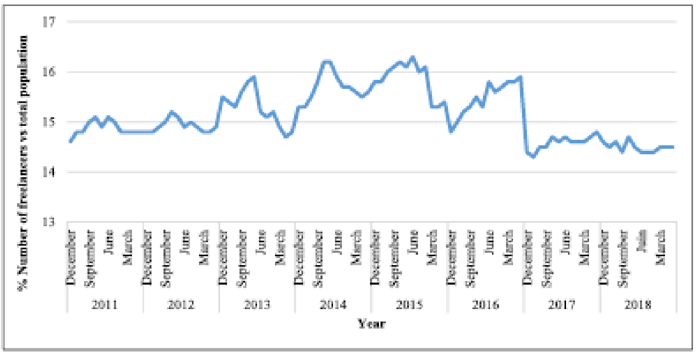

Fig. 10. Variation in numbers of freelancers in Alcalá.

groups considered as the initial hypothesis. These values were established as a baseline for the sensitivity analysis (described in Section 3.3). Commuters and local workers use their own vehicles, but no statistical data about the numbers of commuters and local workers in the city are published by the Town Hall. Consequently, the statistical method outlined in Section 2.3 was used to determine the number of commuters and local workers on a statistical basis. To do this, two samples were used:

- A sample consisting of 100 participants provided information about the numbers of people commuting (47%) and local workers (11.7%) who used their own EVs. Regarding the numbers of commuters who used public transport, estimates showed that 7,147,000 people (32,486 people on a daily basis) used trains to commute to their jobs [55,56]. It was assumed that these workers did not have EVs, as they could only have been used to reach the station. Consequently, we did not consider the ownership of EVs by this group of workers. The results from the questions shown in Table 1 indicated that only 2% of the sample of people who used public transport would be willing to buy EVs.
- A second sample of 50 individuals was used to confirm the numbers of local workers and commuters based on Equations (1) and (2). Table 4 shows how the acceptance of the percentage of each social group was conducted.

3.2. Consumption by each social group

The data collected on freelancers, commuters and local workers helped in making statistical estimates of the consumption by EVs and the improvement in energy efficiency obtained due to the algorithm. Numerous measurements were performed to assess the different driver profiles for freelancers, local workers and commuters. All of these measurements needed to be analysed statistically to estimate the average EV consumption by each group. The method described in Section 2.6 could be used, as the data appeared to have an approximately normal distribution. Table 5 shows the statistical results for each social group, obtained by analysing the consumption data for the trips performed both with and without the proposed algorithm. The most important parameters are the skewness, kurtosis and p-value. For the freelancers, the skewness was almost zero, meaning that the distribution was symmetric. The kurtosis values showed that the data distribution tails did not differ from those of a normal distribution. The p-value represents the null hypothesis: the data follow a normal distribution. The null hypothesis can be considered to be true if the p-value is less than 0.05. Since the skewness and kurtosis are sensitive to the size of the sample, a normality test was also carried out based on the Q-Q plots and histogram. The results showed that the hypothesis H_0 was confirmed. The number of kilometres travelled ranged from 95 to 110 km per day. For the local workers and commuters, the analysis was similar. The p-value confirmed the hypothesis H_0. This conclusion was supported by using the graphical method based on Q-Q plots, box plots and histograms. The number of kilometres travelled ranged from 60 to 75 km and 3–5 km per day, for the commuters and local workers, respectively.

3.3. Sensitivity analysis

One aim of the EGD is to improve energy efficiency of buildings. The impact of V2H in terms of ER, EDR and EC on the energy consumption of buildings is therefore analysed here. The trend towards EV ownership in Alcalá, which is likely to continue in the years to come, means that it is necessary to estimate the energy available for V2H. Three potential scenarios linked to the trends in car park use in Alcalá de Henares and EV sales were considered in this study, as shown in Table 6 [56]. To assess the trends in car park use in Alcalá, historical data published by the Town Hall were used, and it could be seen that:

a) Except for 2008, car park use was always less than 100,000 vehicles.
b) Over the last decade, the average rate of car park use was 95,298 vehicles.

A 0.2% increment per year was therefore estimated. To take into account any possible errors in this prediction, several scenarios were considered. Regarding EV sales, our assumption was justified based on several international trends. EV sales have been increasing in recent years, and some institutions have forecast that this trend will continue in the future [57]. Other institutions have confirmed this trend, and have estimated that more than 18 million EVs will be on the road in 2030 [58]. These statements are also supported by the fact that the battery cost is likely to have been reduced by 2030, as highlighted by the International Council on Clean Transportation [59]. Based on this assumption and the estimates mentioned above, EV sales are forecast to increase in 2021 and 2022. In Fig. 11, the series entitled "*Sales scenario*" represents the increasing numbers of EVs in Alcalá according to Table 6. The series "*EV presence*" represents the annual ratio (in percentage) of the number of EVs using cark parks in Alcalá [56]. As we can see, this ranges from 0.87% (Scenario 3) to 3.85% (Scenario 1) in 2022.

All the scenarios shown in Fig. 11 were taken into account when assessing the energy available for V2H, both with and without the use of the proposed algorithm.

The trends in the number of freelancers, commuters and local workers are linked to the economic climate in future years. Potential scenarios will also be strongly influenced by the current pandemic. Measures such as employment regulation plans and economic aid have been introduced by governments to reduce the impact of Covid-19 and to prevent companies from cutting jobs. Unfortunately, some companies that are unable to cope with the effects of this health crisis in the short term will disappear. In the medium and longer term, an economic recovery is expected, although some disagreement has expressed regarding the speed of this recovery [60]. Three scenarios (Table 7) have been drawn up

Table 3
Numbers of workers.

	Number of workers	Percentage of workers
Freelancers	17,782	14.6
Commuters who use public transport	32,486	26.7
Commuters who use their own vehicles	57,220	47
Local workers	14,305	11.7
Total number of workers	121,793	

Table 4
Percentage of each social group.

Social group	How initial hypothesis is obtained	Probability of success as assessed based on the first sample	Probability of failure based on the first sample	Initial hypothesis in %	Second sample used to confirm the hypothesis	Probability of success based on the second sample	H_0 meaning	H_0 value ($\alpha = 0.01$)
Freelancers	Using statistical data published by the Town Hall	0.15	0.85	14.6	100	Not used	The percentage of freelancers was close to 14.6%	Accepted
Commuters who used their own vehicles	Based on the first sample of 100 individuals, as no statistical data were available	0.45	0.55	47	50	0.5	The percentages of commuters and local workers were close to 47% and 12% respectively	Accepted
Local workers		0.13	0.87	11.7		0.11		Accepted
Commuters who used public transport		0.27	0.73	26.7		0.26		Accepted

Table 5
EV consumption in kWh.

Factor	Freelancers		Commuters		Local workers	
	A.U.[a]	N.A.[b]	A.U.[a]	N.A.[b]	A.U.[a]	N.A.[b]
Mean	24	26.2	9	10.5	3.3	3.9
Std deviation	0.6	0.4	0.3	0.32	0.32	0.29
Kurtosis	3.7	4.0	3.7	4.5	4.1	4.2
Skewness	−0.135	−0.121	−0.041	−0.032	−0.025	−0.015
p-value	0.395	0.401	0.401	0.415	0.396	0.399

[a] N.A. means that no algorithm was used.
[b] A.U. means that the algorithm was used.

based on predictions made by the Spanish National Bank [60].

- *Scenario 1*

The number of EVs is represented by the series entitled "*Sales for scenario 1*" in Fig. 11. The number of working people in the city is reduced by 5% for all social groups in 2020. This percentage is based on an estimate in which the unemployment rate is increased by 21.7% in 2021 according to estimates from the Spanish National Bank [60]. In 2021 and 2022, the unemployment rate will be reduced by 2%, according to the estimates from the same institution, meaning that in 2022, the figures for freelancers, commuter and local workers will be similar to those in 2020. The percentages of workers in each social group and the numbers of EVs are shown in the baseline column in Table 7. This scenario is linked to an increase in unemployment rate and stagnation in EV sales.

- *Scenario 2*

This scenario attempts to model the impact of Covid-19 and is based on a more optimistic increase in the working population. The Spanish National Bank estimates that even if the working population is reduced in 2020, the unemployment rate will fall in 2021 and 2022. We consider a more optimistic scenario than the Spanish National Bank [60], in which the unemployment rate will fall by 4% percent for all social groups in 2021 and 2022. The number of EVs is

Table 6
Estimates used in this research.

Scenario	Estimated sales	Rate of car park use in Alcalá de Henares
Scenario 1	Estimated 35% increase in EV sales	1.002% increment
Scenario 2	Estimated 10% increase in EV sales	1.002% increment
Scenario 3	No increase in EV sales	1.002% increment

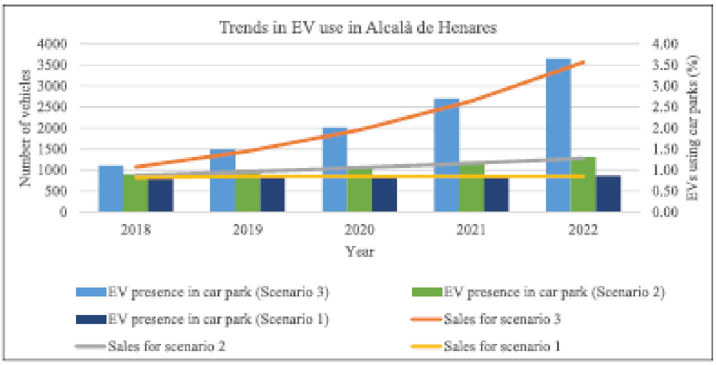

Fig. 11. Trends in EV use.

Table 7
Scenarios for assessing the energy available for V2H.

Factors	Baseline	Scenario 1			Scenario 2			Scenario 3		
		2020	2021	2022	2020	2021	2022	2020	2021	2022
Number of EVs	850	850	850	850	1058	1164	1280	1956	2641	3565
Number of freelancers	17,782	16,893	17,230	17,575	16,893	17,568	18,271	16,893	17,906	18,980
Number of commuters who use their own vehicles	57,220	54,359	55,446	56,555	54,359	56,533	58,794	54,359	57,620	61,077
Number of local workers	14,305	13,590	13,862	14,139	13,590	14,133	14,698	13,590	14,405	15,269

represented by the series entitled *"Sales for scenario 2"* in Fig. 11.

- *Scenario 3*

This scenario estimates the number of workers in each social group under the condition of a significant improvement in the economic situation (an increase of 6% in the working population). The number of EVs sold is represented by the series entitled *"Sales for scenario 3"* in Fig. 11.

The contribution to V2G from each social group is determined by two factors. Firstly, its presence in the whole working population rather than on the exact numbers of members of each social group. As mentioned above, freelancers account for 14.6%, commuters 47% and local workers 12% (these are assessed statistically in Section 3.1). Secondly, the numbers of EVs are shown in Table 7. Since 26.7% of the working population use public transport to go to work, the percentage of freelancers, commuters and local workers was increased proportionally in each scenario, as the total number of vehicles in Table 7 needs to be shared between these three social groups. As stated in Section 3.1, only 2% of the sample of people who used public transport would be willing to buy EVs. Fig. 12 shows the contribution of EDR and ED to V2H in each scenario in Table 7 for freelancers. It can be seen that the energy available for V2G is increased in all scenarios when the proposed algorithm is used. The energy gain is defined as the difference between the energy available for V2H with and without our algorithm, and this ranges between 82 and 343 MWh per year without enhancements in the battery capacity. Fig. 13 illustrates the results obtained for commuters. The energy gain ranges between 132 MWh (Scenario 1) and 553 MWh (Scenario 3) per year due to EDR and ER. The energy available is greater as commuters cover fewer kilometres than freelancers. Finally, Fig. 14 shows the results for local workers. In this case, the energy gain ranges from 18 MWh (Scenario 1) to 75 MWh (Scenario 3) per year. These results show that it is not only essential to increase the number of EVs in order to increase the energy available for V2H, but also the social group in which the presence of EVs is higher. Figs. 12–14 show that the EDR and ER algorithm can significantly contribute to increasing the energy available for freelancers and commuters to V2H. EDR and ER have a less significant impact for local workers, as the average mileage and driving times are not as high as for freelancers.

4. Discussion

4.1. Sustainable transport and energy consumption of buildings

In this research, EDR and ER are used to prove that the energy efficiency is enhanced considering social groups. Wang et al. [61] and Shi et al. [13] analysed many of the factors that influence the energy consumption of EVs, and reported that 2% of the participants travelled more than 90 km, 16% travelled between 60 and 90 km and 48% travelled between 30 and 60 km on a daily basis. Other research has examined the distribution of the numbers of trips per day [12]. However, this percentage can change in very significantly when the research sample is divided into social groups such as freelancers, local workers and commuters, as shown in the current study. The fact that energy efficiency can be improved implies that the energy consumption of buildings will be reduced thanks to V2H. As shown by Chen et al. travel distance influences V2H behaviour [62]. These authors modelled the travel behaviour (km travelled) based on a mathematical probability assessment, and showed that a range of between 20 and 60 km is most likely. However, this estimate is not accurate if social groups are considered; in other words, the energy available for V2H changes significantly depending on the numbers of freelancers, commuters, and local workers. Our results show how these different social groups

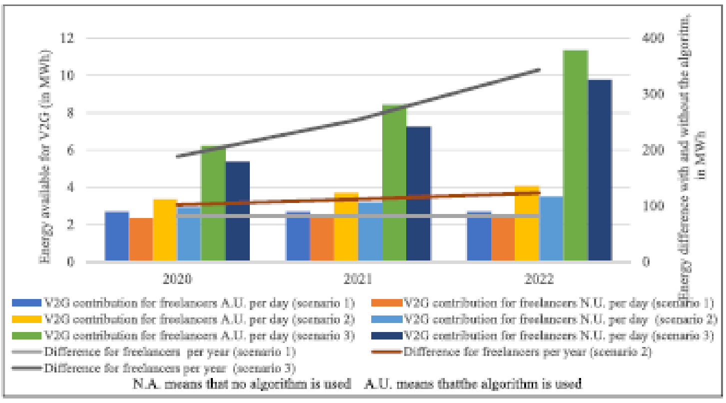

Fig. 12. V2G contribution to freelancers.

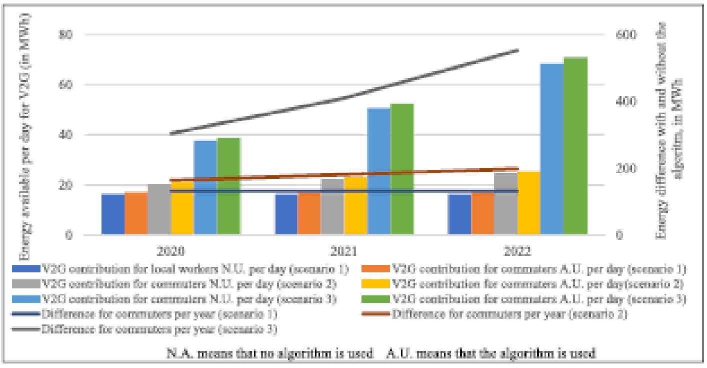

Fig. 13. V2G contribution to commuters.

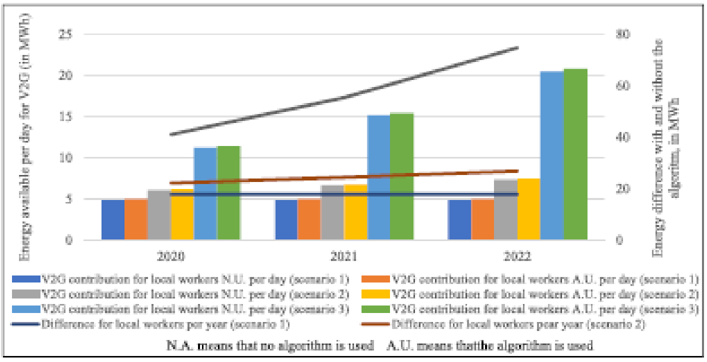

Fig. 14. V2G contribution to local workers.

contribute to V2G, as follows:

a) Commuters

Commuters frequently become stuck in traffic jams, since the traffic situation is more complicated when leaving big and medium-sized cities. The contribution to V2H when ER and EDR are used is significant for this social group (Fig. 13). Energy savings are increased when the time spent by drivers in traffic jams is reduced. An increase of between 132 and 553 MWh per year can be achieved without the need to improve battery capacity, and policies encouraging the purchase of EVs should focus on commuters in order to contribute to reductions in local emissions and to increase energy efficiency due to the use of ER and EDR (Fig. 13). In Section 4.3, we discuss whether commuters and freelancers are expected to participate in V2H and V2G at the same time.

b) Local workers

Local workers do not travel many kilometres on a daily basis. The difference between using and not using EDR and ER does not have a significant impact on energy efficiency. Without considering ER and EDR, the energy available for V2H is not high (Fig. 14) as the number of local workers is low compared to commuters and freelancers. Two conclusions can be drawn. Firstly, improvements in the energy available for V2H should focus on both increasing battery capacity and reducing harm due to charging and discharging processes, as ER and EDR do not make an important contribution to energy efficiency. Secondly, drivers can participate in both V2G and V2H, as they do not travel many kilometres.

c) Freelancers

Freelancers are a group of people who drive a relatively high number of kilometres in mixed traffic conditions, and the results for this group therefore fall between those for commuters and local workers. ER and EDR allow for increased energy savings and higher amounts of available energy for V2H.

Energy efficiency can be improved if policies designed to increase EV sales are targeted at the appropriate social groups and combined with ER, EDR and EC. If policies encourage commuters and freelancers to buy EVs, energy savings can be increased when ER and EDR are used. Hence, the use of ER and EDR, when combined with right policies, can help in achieving the goals of the EGD. This is a novel result, as in many cases, research has focused on financial incentives and subsidies to increase the penetration of EVs in the market [63–65]. Although other topics have been considered in research aiming to improve policies linked to EVs, as detailed by

Melton, Axsen and Moawed, social groups have not been considered [66].

4.2. Clean energy

The EGD aims to decarbonise the electricity sector by promoting the use of RE. The amount of RE used (in MW) must increase according to electricity consumption. Otherwise, investments in RE facilities will not be justified. Several algorithms have already been proposed to combine the contributions from RE with the EV charging process, as described by Sharifi, Banerjee and Feizollahi [67]. Much of the existing research focuses on time-of-use mechanisms that seek to transfer peak loads during rush hour [68]. However, the optimal integration of RE is not possible, as the cost of charging batteries is high when the contribution from RE is high. Figs. 15 and 16 represent the cost of charging an EV, the electricity price on the market and the contribution from RE in %. It can be seen that when the contribution from RE is high, the cost of charging an EV is highest due to the regulated price set by the government. The main conclusion that can be drawn is that the promotion of RE to decarbonise the electricity system and policies on pricing are equally as important as policies that aim to promote the penetration of EVs into the market or to implement charging points. It is only in this way that EV charging will be possible when the contribution from RE is high. In Spain, the number of MW available from RE has been almost stable since 2012, and this topic is therefore a key concern in relation to the promotion of EVs in V2H and V2G in Spain, as analysed in Section 4.3.

The EC block plays an essential role in achieving better integration of RE, as it can inform the driver of the best moment to charge the EV battery with regard to the contribution of RE. Most drivers opt to charge at night rather than at a time when the contribution from RE is high, despite the recommendations from the EC block (Fig. 17). The main reason for this is that charging at night is less expensive. The prices for charging EVs should therefore be coherent with the contribution from RE. Likewise, RE installed could be increased as the consumption between 12 a.m. and 6 p.m. (when RE contribution is higher) is also increased. The integration of RE is an important topic that should be considered when assessing the EDR in EVs, since no prior research has dealt with this in depth [69,70].

4.3. Compatibility between V2H and V2G

Some prior research has focused on policies that aim to encourage EV owners to participate in V2G, as detailed by Colmenar et al. [71,72], which can reduce energy peak consumption. The charging process usually takes place before sunset, and V2H is then used during the peak energy demand period and the EV is then charged again afterwards [19]. These policies do not guarantee the compatibility of V2G and V2H, considering the price for recharging EVs, even if EVs were promoted more widely and the sales increased. Each social group considered here is discussed below.

a) Freelancers

The contribution from this group to V2H and V2G will be low unless they charge their batteries during the day, before returning home. The relation between the electricity price on the market, special fees for charging EVs and RE contribution needs to be analysed (Figs. 15 and 16). When the contribution from RE is higher, charging EVs is expensive. This is the case after 12 a.m. as the contribution from RE is high but charging EV is expensive. The current fee established by the Spanish Government encourages recharging EVs at night (Fig. 15). In view of this, current policies are not suitable for this social group. During the first trimester of 2019 (Fig. 15), when charging EVs was cheaper, the EC will be low for EVs when using the algorithm as the contribution from RE is low. Considering the available energy for V2H, it is likely that these users will not contribute a great deal of energy to the grid, as it is more cost-effective for them to provide their own homes with electricity.

b) Commuters

These are not candidates for participating in V2G and V2H, as discussed in Section 3. The energy remaining in their batteries is likely to be used for their own homes, considering the current fees for charging EV batteries in Spain.

c) Local workers

The only candidates for participation in V2H and V2G are those who work in Alcalá. However, this social group is far from being the

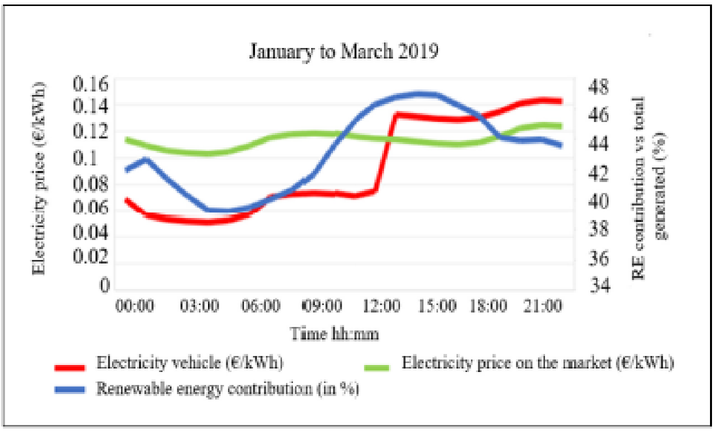

Fig. 15. Trends in electricity prices.

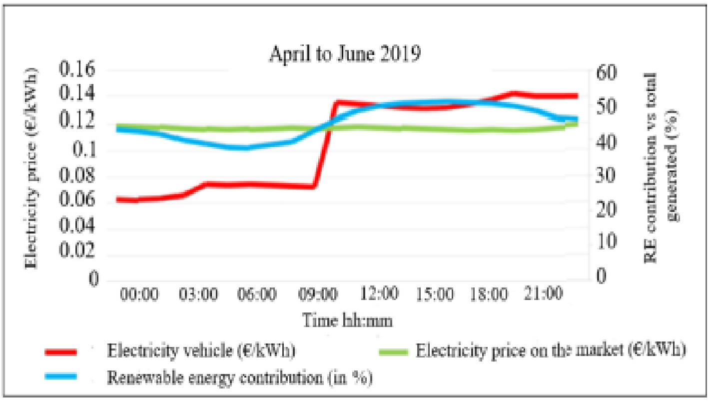

Fig. 16. Trends in electricity prices.

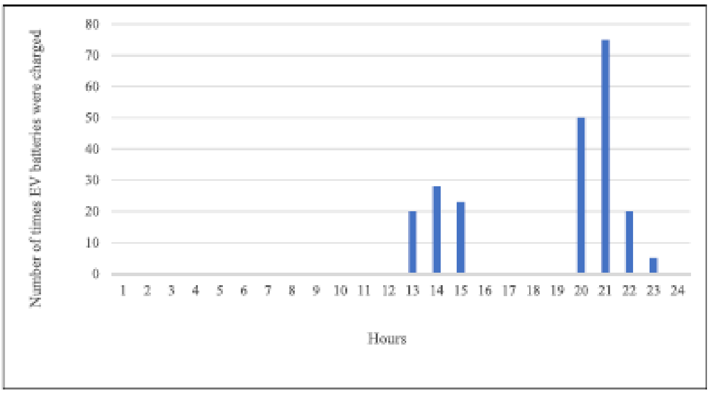

Fig. 17. Number of times EV batteries were charged in this study.

most representative one (as described in Section 3).

Assuming that Spain can achieve a high mix of REs and a high penetration of EVs in the market, the contribution from EVs in terms of V2H and V2G will only be ecologically friendly when our algorithm is used, for the following reasons:

a. The EC block can predict when the contribution from REs is higher, with the aim of reducing emissions.
b. The method of driving (EDR) and ER are used to reduce the energy consumption, as the best route is established based on the energy consumption as assessed by EDR (consumption models are tuned). Consequently, pollution will be lower and EVs will be greener and more eco-friendly.
c. The driving efficiency of EVs depends not only on EDR and ER, but also on the contribution from RE to the charging process. Our algorithm predicts this using a neural network.

4.4. Threats to validity

The actions that can be taken to reduce these threats are shown in Table 8.

Before the trips were performed, the following verifications were carried on a daily basis:

a) The results published by the transmission system operator and the those obtained from the neural network were compared. Fig. 18 shows the performance of the GRU network.
b) The neural networks were implemented based on the data from the transmission system operator for the previous day.

This procedure was applied to ensure that the neural networks operated properly.

4.5. Limitations and future research

In this research, the proposed algorithm was applied to a medium-sized city. Future research should focus on using this algorithm in larger cities in order to assess the available gain in energy for V2H. Another topic that should be considered is the stochastic usage of EVs. Although this research demonstrates the importance of considering the different social groups in the

Table 8
Factors affecting the validity of this research assessment.

No.	Factor	Description
1	City chosen for this research	The choice of Alcala de Henares (Madrid, Spain) for this case study was made by carefully considering several key factors, such as the size of the city, the population, a traffic analysis, the distribution of cameras controlling the traffic, trends in car parking, etc. After analysing these factors, it was determined that Alcalá de Henares was the best city for a trial of our approach before attempting to conduct a study in a larger city such as Madrid.
2	Market penetration of EVs	The number of vehicles in Alcalá was a key factor when assessing the available energy for V2H. Since it is not easy to accurately estimate the number of EVs that will be used in the future, several scenarios were constructed in order to consider different levels of penetration of EVs into the market.
3	Analysis of the population	Users have different driving profiles, and an accurate estimate of the energy consumed cannot be produced without considering this factor. It was considered to be of paramount importance to create a breakdown of the population of Alcalá de Henares. The first group contained freelancers, who use EVs frequently and are assumed not to have significant amounts of energy to contribute to V2H. The second group contained people who normally use public transport to commute, who make an important contribution to V2H, while the final group contains other workers who work locally or in other cities.
4	Scenarios considered in this study	All of the scenarios considered in this research took into account official estimates. In this case, an estimation from the Spanish National Bank was used to assess the energy efficiency and the contributions to V2H.

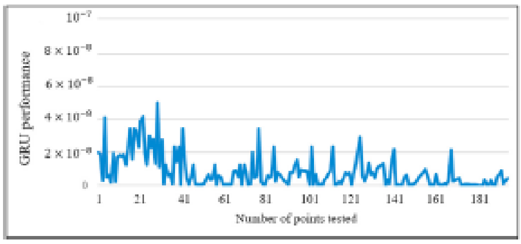

Fig. 18. Performance of the GRU network.

population, other variables should also be studied with the aim of improving the estimate of energy availability.

5. Conclusions

This research was conducted in the city of Alcalá de Henares (Madrid, Spain) with the aim of investigating the impacts of EDR, ER and EC on several factors linked to the EGD. To achieve this, a novel algorithm was implemented in Python, based on the Here® API, neural networks and data published by a Spanish system operator in order to reduce energy consumption and identify the optimal time for charging the battery. Data were acquired based on driver profiles, taking into account the most important social groups in the working population, such as freelancers, local workers and commuters. The results showed that EDR, ER and EC will be able to save significant amounts of energy in the future if policies in Spain are changed. More specifically, the results show that the energy efficiency per vehicle could reach 1.5 kWh per day for commuters, 0.6 kWh per day for local workers and 2.2 kWh per day for freelancers when our algorithm is used.

Several contributions to the EGD can be made, as follows:

a) It is vital that different policies are developed for different social groups (freelancers, commuters, etc.) since these do not contribute in the same ways (as described in Section 4.1).
b) The energy efficiency gained by using the algorithm increases the energy available for V2H technology. The amount of energy available for V2H increases by between 18 MWh and 553 MWh depending on the social group (as discussed in Section 3.3).
c) The EC block used in this research allows drivers to charge EVs when the contribution from RE is high. In this way, RE can be better integrated in order to decarbonise the electricity sector (as described in Section 4.2).
d) Freelancers and commuters who travel many kilometres on a daily basis are not likely to participate in V2H or V2G unless policies can be developed to ensure lower prices when the contribution from RE is high. In Spain, prices are currently higher when the contribution from RE is higher (as discussed in Section 4.2).
e) Policies cannot change if the power currently available from RE in Spain is not increased. As described in c), part of the demand could be moved when the contribution from RE is high, thanks to the EC block implemented in this algorithm (as set out in Sections 4.2 and 4.3).
f) Our results show that current policies for setting the cost of charging EVs in Spain are not compatible with a high contribution to V2H and V2G from the different groups in society (as described in Section 4.3)

Authors contributions

Pedro Miguel Ortega-Cabezas: were primarily responsible for creating this manuscript, were responsible for creating the application in Python and obtained all measurements performed in this research. Antonio Colmenar-Santos: analysed the data obtained as well as policies and collected data and information from the Transport System Operator. David Borge-Diez: were primarily responsible for creating this manuscript, were responsible for creating the application in Python and analysed the data obtained as well as policies and collected data and information from the Transport System Operatorobtained all measurements performed in this research. Jorge-Juan Blanes-Peiró: analysed the data obtained as well as policies and collected data and information from the Transport System Operator

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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