UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Estudio de sistemas renovables avanzados para el desarrollo energético sostenible

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Study of advanced renewable energy systems for sustainable development

TESIS DOCTORAL

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Valencia, julio de 2021

Dr. D. Elías Hurtado Pérez, Profesor Titular de la Universitat Politècnica de València del Departamento de Ingeniería Eléctrica.

CERTICA que la presente memoria “Estudio de sistemas renovables avanzados para el desarrollo energético sostenible” resume el trabajo de investigación realizado, bajo su supervisión, por Dña. Paula Bastida Molina y constituye su Tesis para optar al título de Doctora.

Y para que conste, en cumplimiento de la legislación vigente, firma el presente certificado en Valencia a 7 de julio de 2021.

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Dedicado a mis padres, a mi hermana y a Juanjo.

Agradecimientos

En primer lugar, me gustaría agradecer a mi director de tesis, Elías Hurtado, toda la ayuda que me ha brindado. Me ha apoyado en cada uno de los pasos de la tesis, compartiendo conmigo sus conocimientos técnicos y enseñándome día a día. Siempre ha tenido tiempo para escucharme y darme consejo, no sólo en los buenos momentos de la tesis sino también en los más difíciles. Muchas gracias por haber apostado por mí, por tu excelente dirección y por todo tu apoyo.

También quiero agradecer a Ángel Pérez-Navarro toda la enseñanza científica que me ha proporcionado y su gran ayuda en las labores de investigación. Gracias por tu apoyo a lo largo de la tesis.

A los compañeros del grupo ARSEA, gracias por haberme acogido desde el principio en el grupo de investigación y hacerme sentir tan cómoda trabajando con vosotros/as. Gracias a todas las personas con quien he compartido etapas del doctorado en el Instituto de Ingeniería Energética y a su director y compañero de investigación Tomás Gómez.

Quiero también darles las gracias a los profesores del Departamento de Ingeniería Eléctrica. A Rubén Puche, por todas las cuestiones que me ha ayudado a resolver sobre trámites del doctorado, etapas de investigación, … también por ponerme en contacto con el grupo de investigación de la estancia y por su apoyo continuo. A Jesús Moreno y Javier Nadal, por ayudarme a preparar la docencia de Máquinas Eléctricas y respaldarme en todos los procesos que eran nuevos para mí en ese ámbito. A Bernardo Álvarez y Juan Ángel Saiz por compartir conmigo sus conocimientos técnicos y ayudarme en mi crecimiento profesional. A Antonio Fayos, Paco Rodríguez, Vicente Fort por hacerme sentir siempre una “profe” más.

Muchas gracias a Khang Huyhn, por darme la oportunidad de realizar la estancia de investigación con su grupo de investigación “Energy Systems”. No sólo se preocupó de que aprendiera y desarrollara mi labor investigadora, sino también de que mi estancia en Noruega fuera lo mejor posible. Extiendo este agradecimiento a los demás miembros del grupo de investigación Energy Systems (Rade Ciric, Immanuel, Ahmed…) y a la familia Sta que me ayudaron en todo momento y me hicieron sentir como en casa.

También darles las gracias a mis amigos de la 2ª planta del IIE: Yago, Yaisel, Iván L, Iván C, David R, David B…Desde el principio me acogieron y siempre han estado dispuestos a ayudarme. Gracias por todas las risas, almuerzos y momentos compartidos.

Por último, quiero darle las gracias a mis padres, hermana y Juanjo que siempre han estado ahí, escuchando todas mis preocupaciones, todos los nuevos planteamientos de la tesis, los papers que estaba redactando, las clases a preparar…Gracias por vuestra paciencia infinita, por ser mi apoyo día tras día y por todo vuestro amor. A mis padres, gracias por ser mi luz en el camino, recordarme siempre que todo trabajo tiene su recompensa y que tras cada caída hay que volverse a levantar. A mi hermana, por esforzarse siempre en sacarme una sonrisa y compartir conmigo tantos momentos y consejos. A Juanjo, gracias por ser mi apoyo y por todos los sacrificios que ha hecho por mí para ayudarme con el desarrollo de la tesis, anteponiendo en todo momento mi bienestar ante cualquier aspecto. También quiero darles las gracias a mi abuela y a mi tía, siempre preocupándose por mí, cuidándome y ofreciéndome su ayuda.

Resumen

La energía juega un papel fundamental en el desarrollo sostenible de las comunidades. Así, proporcionar recursos energéticos fiables, económicamente aceptables, medioambientalmente respetuosos y socialmente beneficiosos, resulta esencial para el desarrollo sostenible de las mismas. A pesar de la universalidad de dicha definición, el uso de la energía está muy vinculada al nivel de desarrollo de los países. De este modo, la problemática energética de los países desarrollados contrasta enormemente con la de los países en desarrollo.

En esta tesis doctoral se ha identificado la principal problemática energética de ambas realidades: grave impacto medioambiental de los modelos de generación del transporte tradicionales en los países desarrollados y pobreza energética en los países en desarrollo. A partir del compendio de artículos científicos de esta tesis doctoral se ha caracterizado el uso de sistemas renovables avanzados que permite solucionar dicha problemática de forma sostenible. En concreto, el principal problema energético en países desarrollados ha sido tratado mediante la planificación energética y el diseño óptimo de sistemas híbridos de energías renovables (HRES por sus siglas en inglés) en electrolineras, necesarios para la introducción de vehículos eléctricos como alternativa de movilidad sostenible. Por otro lado, el estudio de metodologías de diseño óptimas de HRES off grid y de las estufas para cocinar mejoradas mediante gasificación de biomasa se ha focalizado en la inaccesibilidad eléctrica y a sistemas de cocina limpia que sufren las comunidades en desarrollo.

Así, esta tesis aporta una serie de metodologías para optimizar y adecuar los sistemas renovables presentados para el desarrollo energético sostenible de las comunidades. Además, no sólo demuestra la idoneidad de estos sistemas para dicho fin, sino también su versatilidad de aplicación en función del nivel de crecimiento de las comunidades.

Resum

L’energia juga un paper fonamental en el desenvolupament sostenible de les comunitats. Així, proporcionar recursos energètics fiables, econòmicament acceptables, mediambientalment respectuosos i socialment beneficiosos, resulta essencial per al desenvolupament sostenibles de les mateixes. A pesar de la universalitat d’aquesta definició, l’ús de la energia està vinculada al nivell de desenvolupament dels països. D’aquesta manera, la problemàtica energètica dels països desenvolupats contrasta enormement amb la dels països en desenvolupament.

A aquesta tesis doctoral s’ha identificat la principal problemàtica energètica d’ambdues realitats: greu impacte mediambiental dels models de generació del transport tradicional en els països desenvolupats i pobresa energètica en els països en desenvolupament. A partir del compendi d’articles científics d’aquesta tesis doctoral s’ha caracteritzat l’ús de sistemes renovables avançats que permet solucionar aquesta problemàtica de manera sostenible. En concret, el principal problema energètic en països desenvolupats s’ha tractat mitjançant la planificació energètica i el disseny òptim de sistemes híbrids d’energies renovables (HRES, per les seues segles en anglès) en electrolineres, necessaris per la introducció de vehicles elèctrics com alternativa de mobilitat sostenible. D’altra banda, l’estudi de metodologies de disseny òptimes de HRES off grid i d’estufes per a cuinar millorades mitjançant gasificació de biomassa s’ha focalitzat en la inaccessibilitat elèctrica i a sistemes de cuina neta que pateixen les comunitats en desenvolupament.

Així, aquesta tesis aporta una sèrie de metodologies per optimitzar i adequar el sistemes renovables presentats per al desenvolupament energètic sostenible de les comunitats. A més, no tan sols demostra la idoneïtat d’aquests sistemes per a aqueix fi, sinó també la seua versatilitat d’aplicació en funció del nivell de creixement de les comunitats.

Abstract

Energy plays a significant role for the sustainable development of communities. Hence, supplying reliable energy resources, which result economically acceptable, environmentally friendly and socially beneficial, arises as essential for their sustainable development. Despite the universality of such definition, the energy use is highly linked to the development degree of the countries. Thus, energy problems of developed countries sharply contrast with those of developing countries.

This doctoral thesis identifies the main energy issues of both realities: severe environmental impact of energy generation models for traditional transport in developed countries and energy poverty in developing countries. The compendium of scientific papers of this doctoral dissertation characterizes the use of advanced renewable energy systems to solve such problems in a sustainable way. Namely, the main energy issue in developed countries has been addressed by means of energy planning and the optimal design of Hybrid Renewable Energy Systems (HRES) in electric vehicle charging stations, which ensure the introduction of electric vehicles as a sustainable mobility alternative. Moreover, the study of methodologies for the optimal design of off grid HRES and improved cooking stoves based on biomass gasification have approached the inaccessibility to electricity and to clean cooking systems that developing communities suffer.

Therefore, this thesis provides a number of methodologies to optimize and adapt the presented renewable energy systems for the sustainable energy development of communities. Furthermore, it demonstrates not only the suitability of these systems for such aim, but also their versatility of application regarding the growing degree of the communities.

GENERAL INDEX / ÍNDICE GENERAL

Capítulo 1. Introducción

En este capítulo se realiza una introducción a la tesis doctoral presentada. En primer lugar, se analiza la problemática energética a la que se enfrentan los diferentes países en función de su nivel de desarrollo. En segundo lugar, se revisa el estado del arte de los sistemas energéticos renovables empleados hasta la fecha para tratar la problemática identificada. A continuación, se definen los objetivos a alcanzar con este trabajo. Finalmente, se muestra la estructura general de la tesis presentada por compendio de artículos.

1.1. Problemática energética

En los últimos años, la concienciación acerca de la necesidad de llevar a cabo un desarrollo sostenible de las comunidades a nivel mundial ha aumentado de forma sustancial. De acuerdo con Instituto Internacional para el Desarrollo Sostenible, un desarrollo sostenible es aquel capaz de satisfacer las necesidades presentes de una población sin comprometer la capacidad de las futuras generaciones de conseguir satisfacer las suyas propias (IISD, 2021).

El diferente contexto político de los países ha jugado un papel fundamental en la consecución de dicho desarrollo a lo largo de los años, tal y como detallan los estudios (de Jong and Vijge, 2021; Ezbakhe and Pérez-Foguet, 2021). Con el fin de unificar ese entorno gubernamental, en la Declaración del Milenio 2000 de las Naciones Unidas se constituyó el primer marco de gobernanza para la consecución de un desarrollo sostenible a nivel mundial (Cuenca-García et al., 2019). Posteriormente, el 25 de septiembre de 2015 se creó La Agenda de Desarrollo Sostenible 2030, vigente en la actualidad. Esta agenda incluye 17 objetivos de desarrollo sostenible con 169 metas específicas a ser alcanzadas en 2030 a nivel global para erradicar la pobreza, proteger el planeta y asegurar la prosperidad. La consecución de estas metas englobaría a diferentes actores: gobiernos, sector privado, sociedad civil y personas individuales (Simsek et al., 2020; UN, 2019).

La energía resulta un factor esencial para conseguir alcanzar los objetivos de desarrollo sostenible de forma universal (Simsek et al., 2020). Vera y Langlois afirman que la provisión de servicios energéticos adecuados y fiables a un coste asumible, medioambientalmente inocuos y consecuentes con las necesidades de desarrollo sociales y económicas de la comunidad en cuestión, resulta un elemento fundamental para su desarrollo sostenible (Vera and Langlois, 2007). Arto et al. declaran que la energía, en sus diferentes formas, es esencial para proveer a los ciudadanos de los recursos básicos: educación, sanidad, alimentación, vivienda, empleo y distribución justa de ingresos, jugando un rol esencial para erradicar la pobreza (Arto et al., 2016). Además, Munasinghe presenta a la energía como el elemento central en cualquier discusión sobre desarrollo sostenible debido a su impacto directo sobre las tres dimensiones que lo caracterizan: económico, social y medioambiental (Munasinghe, 2002).

1.1.1. Relación entre el nivel de desarrollo de los países y el uso de la energía

A pesar de la universalidad de este factor, numerosos autores han investigado durante décadas la relación entre el nivel de desarrollo de los países y el uso de la energía (Alam et al., 1998; Dias et al., 2006; Lambert et al., 2014; Mazur and Rosa, 1974; Steinberger and Roberts, 2010).

El grado de desarrollo de los países se mide a partir del Índice de Desarrollo Humano (HDI, por sus siglas en inglés "Human Development Index"), que considera 3 dimensiones: la esperanza de vida, la educación y los ingresos per cápita (UNDP, 2021a). De acuerdo con la última publicación del HDI en 2019, los países con un mejor índice fueron Noruega (0.957), Irlanda (0.955) y Suiza (0.955), mientras que los tres peores fueron Chad (0.398), República Centro Africana (0.397) y por último República del Níger (0.394) (UNDP, 2021b). En la Figura 1 se puede observar también el HDI a nivel mundial. De forma global, los países de África central presentan el HDI más bajo, seguidos de algunas zonas de Sudáfrica, sudeste asiático y centro América. Por otro lado, América del Norte, Europa, el Norte de Asia, Oceanía y la zona sur de Sudamérica presentan los mayores HDI. Se identifica así a los países desarrollados y los países en desarrollo.

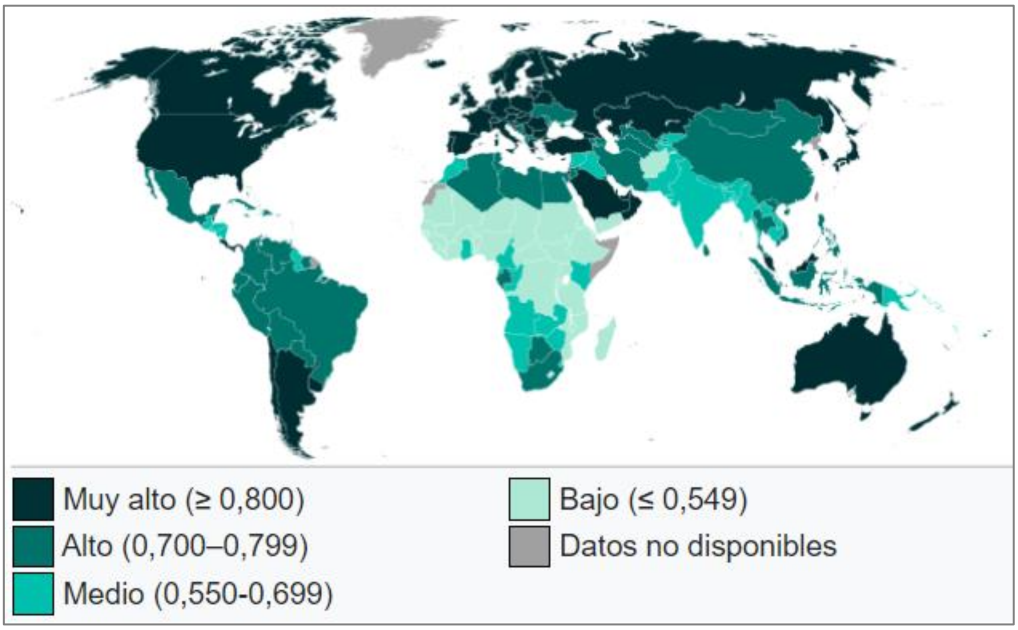


Figura 1. Índice de desarrollo humano a nivel mundial. Fuente: (PNUD, 2019).

Países desarrollados

El desarrollo económico y social de los países desarrollados ha derivado en el crecimiento de algunos sectores, especialmente el del transporte (Pérez Martínez, P. J., & Monzón de Cáceres, 2008). De acuerdo con el Banco Mundial, "el transporte es un motor fundamental del desarrollo económico y social de un país ya que genera oportunidades para los sectores empobrecidos y mejora la competitividad de la economía" (WB, 2021).

Sin embargo, su modelo de generación energética ha conllevado a un preocupante impacto medioambiental. Hoy en día, el sector transporte es responsable de cerca del 25% de las emisiones CO_2 emitidas a la atmósfera de forma global y de alrededor del 50% de las emisiones de efecto invernadero en las ciudades, propiciando el calentamiento global (Teixeira and Sodré, 2018). Esto es debido a que en torno al 93% del consumo del transporte en 2017 provino de combustibles derivados del petróleo (IEA, 2017a), cuyos recursos existen de forma limitada en la naturaleza. De este modo, el negativo impacto ambiental de los modelos de generación de energía del transporte tradicional sobre el cambio climático definen la problemática energética a afrontar por los países desarrollados.

La electrificación del transporte podría suponer una solución medioambiental a esta situación, siendo para ello necesario analizar el modelo energético de generación para recarga de estos vehículos (Zheng et al., 2019). Es cierto que, durante la etapa de conducción, los vehículos eléctricos (EVs, por sus siglas en inglés “Electric Vehicles”) no emitirían ningún contaminante. Sin embargo, durante el proceso de generación eléctrica para su recarga sí que podrían emitir contaminantes dependiendo del tipo de recursos energéticos que intervengan (Manjunath and Gross, 2017). Así, los mixes eléctricos formados por tecnologías contaminantes en alto porcentaje, como el carbón (942.33 gCO_2/kWh) o el petróleo (773.8 gCO_2/kWh), generarían grandes cantidades de CO_2 por cada unidad de energía eléctrica generada. Por ejemplo, los sistemas de generación de China y Australia se considerarían altamente contaminantes, ya que el carbón representa un 72% y un 67 % de sus respectivos mix eléctricos (Woo et al., 2017).

Por el contrario, en aquellos sistemas formados principalmente por energías limpias, como la energía solar fotovoltaica (65.05 gCO_2/kWh) o la energía eólica (17.63 gCO_2/kWh), las cantidades de dióxido de carbono por unidad de energía eléctrica generada serían muy reducidas. Noruega presenta en este sentido el sistema de generación más limpio, estando este formado en un 94% por energía hidroeléctrica (Woo et al., 2017).

A parte del problema medioambiental, numerosos estudios prevén un impacto negativo en las redes eléctricas de los países desarrollados por la introducción masiva pronosticada de EVs (Clairand et al., 2018; Deb et al., 2018; Galiveeti et al., 2018). La demanda eléctrica de estos vehículos podría traducirse en elevados picos en las curvas de consumo eléctrico si las recargas coincidieran temporalmente con las horas punta actuales de demanda. En esos momentos, el mix eléctrico depende en gran parte de tecnologías contaminantes y dependientes de los combustibles fósiles. A diferencia de los patrones de consumo tradicionales, los estudios científicos prevén que las recargas eléctricas tengan un carácter aleatorio, con mayores concentraciones hacia el final del día (Clement-Nyns et al., 2010; Dang, 2018). Así, la nueva demanda generada por los EVs podría superponerse a los actuales picos de consumo, provocando toda una serie de problemas sobre la red eléctrica (Gong et al., 2018). Clement-Nyns et al. muestran como una penetración relevante de EVs provocaría caídas y desviaciones de tensión, las cuáles alcanzaron hasta el 10.3% en su estudio (Clement-Nyns et al., 2010). J. Su et al. analizaron el impacto de la penetración de vehículos eléctricos en Nueva Zelanda, donde la demanda eléctrica iría aumentando cada año, concentrándose el consumo en las horas pico, especialmente hacia el final del día. En su estudio, se observa también como las horas pico aumentan anualmente hasta el año 2040, en el cual la máxima demanda pico excedería toda la capacidad de generación instalada en 2018 en Nueva Zelanda (Su et al., 2019). Liu et al. estiman que la penetración de vehículos eléctricos en el Norte de Europa alcanzará el 100% en 2050, pronosticándose también un incremento de la curva de consumo en las horas pico, especialmente al final del día (Liu et al., 2014).

Países en desarrollo

La problemática energética descrita para los países desarrollados contrasta con la realidad de los países en desarrollo. El estudio de la energía en estos últimos, revela su mayor problemática: la pobreza energética (González-Eguino, 2015; Kaygusuz, 2012). En este contexto, la pobreza energética se establece como un problema de acceso a fuentes de energía modernas, principalmente al gas y a la electricidad (ACA, 2021).

Los datos del Banco Mundial muestran que 1200 millones de personas carecen aún de acceso a la electricidad (Garba and Bellingham, 2021), mientras que 2700 millones de personas todavía no tienen acceso a sistemas energéticos limpios para cocinar (*in English, 1.2 and 2.7 billion people, respectively*). La mayoría de estas personas se concentra en zonas rurales de los países anteriormente indicados (Figura 1), cuya orografía dificulta en gran medida el transporte y limita la accesibilidad a los recursos energéticos (Liu et al., 2019).

Esta situación hace prácticamente imposible la conexión a la red eléctrica de dichas poblaciones (Khamis et al., 2020). Así, los habitantes se ven obligados a usar grupos electrógenos alimentados por combustibles fósiles altamente contaminantes, que generan niveles de ruidos superiores a 55 dB y cuyo uso recomendable corresponde a periodos relativamente cortos (Ali Ahmed et al., 2015). Además, la generación de energía eléctrica mediante estos equipos es cara por los altos costos del combustible, de su transporte y de las constantes operaciones de mantenimiento y reparación de los equipos (Duran and Sahinyazan, 2020).

Para la iluminación, los sistemas tradicionales empleados en estas zonas remotas son las velas o lámparas de queroseno, cuya calidad lumínica es muy baja, al igual que el área que pueden iluminar. Además, la probabilidad de que estos sistemas provoquen incendios es muy elevada, ya que las casas de estas comunidades suelen ser de madera y/o paja (Chamania et al., 2015). El humo de las lámparas de queroseno puede provocar también graves problemas de visión, respiratorios e incluso cáncer de garganta y pulmón (Bensch et al., 2017).

Por otro lado, los residentes se ven forzados también a usar los únicos recursos a su alcance para cocinar, como el carbón o la leña, empleando mucho tiempo en la recolección de dichos recursos. La recolección masiva de biomasa tradicional ha contribuido a la deforestación y degradación de la tierra en estas zonas (Barbieri et al., 2017). Además, el sistema de cocción que usan (estufas abiertas basadas en la combustión de los anteriores recursos) tiene una eficiencia térmica muy baja. Esto conlleva a un consumo excesivo de combustibles contaminantes, lo que desemboca en altas emisiones de CO_2 sobre la atmósfera (Barbieri et al., 2018). También, cuando se emplean dichas estufas abiertas en cocinas interiores, el humo que generan causa graves problemas respiratorios y oculares en los usuarios (Liu et al., 2019).

1.2. Antecedentes

Tras identificar la problemática energética para el avance sostenible de las comunidades en función de su nivel de desarrollo, se muestra la revisión de la literatura acerca de los sistemas energéticos renovables empleados hasta la fecha para su mejora.

1.2.1. Países desarrollados

Por un lado, el mayor problema energético de los países desarrollados reside sobre el negativo impacto ambiental de los modelos energéticos de generación del transporte tradicional sobre el cambio climático (apartado 1.1). La electrificación del transporte eléctrico se ha identificado como una solución a la problemática para el desarrollo sostenible, sujeta a dos nuevos condicionantes: contaminación asociada al mix eléctrico para su recarga y efectos perjudiciales en la red eléctrica vinculados a una introducción masiva de EVs.

Descarbonización del transporte electrificado

Respecto a la contaminación producida por los EVs durante la recarga, la literatura científica hace referencia a este condicionante en varios artículos científicos. Teixeira y Soldré establecen que los EVs son considerados "zero tailpipe emissions", ya que durante la conducción no emiten contaminantes. Sin embargo, anuncian que la recarga de estos vehículos puede estar sujeta a emisiones de CO_2 en función del mix eléctrico empleado (Teixeira and Sodré, 2018). Morrissey et al. también determinan la importancia de la etapa de recarga de los EVs respecto a su impacto medioambiental, así como el análisis de la intensidad de carbón de las tecnologías que componen el sistema de generación eléctrica (Morrissey et al., 2016). Weiss et al. afirman que dicha intensidad determinará la idoneidad medioambiental de la introducción de EVs respecto a la reducción neta de emisiones CO_2 sobre los vehículos tradiciones de combustión (ICEVs, por sus siglas en inglés "Internal Combustion Engine Vehicles") (Weiss et al., 2015).

La literatura científica muestra como el método Well-to-Wheel (WtW) ha sido ampliamente usado para analizar las emisiones totales netas de los EVs en función del sistema de generación y compararlas con las correspondientes a los ICEVs (Athanasopoulou et al., 2018; Ke et al., 2017; Qiao et al., 2019). Esta metodología considera el proceso completo de energía en los vehículos, desde la extracción de las materias primas hasta la conducción. Así, el análisis incluye dos etapas: Well-to-Tank (WtT) y Tank-to-Wheel (TtW) (Kosai et al., 2018).

Woo et al. analizan las emisiones provocadas por los EVs teniendo en cuenta el mix eléctrico de 70 países, así como las de los ICEVs, ambas mediante WtW. Los resultados muestran como los países con tecnologías más contaminantes son los que tendrían mayores emisiones CO_2 provocadas por EVs. En ciertos países, estas emisiones superarían incluso a las provocadas por los ICEVs (Woo et al., 2017). Moro y Lonza realizan un estudio similar, en este caso aplicando la metodología WtW a todos los países de la Unión Europea. El análisis considera también la intensidad de carbón correspondiente a los importaciones/exportaciones de energía entre países y como afectan a los mix eléctricos resultantes (Moro and Lonza, 2018). Ehrenberger et al. realizan la comparación de emisiones entre ICEVs y EVs mediante WtW para los cuatro países con mayores ventas de coches privados (Alemania, Estados Unidos, China y Japón) y para el país con mayor introducción de renovables en su mix eléctrico (Noruega) (Ehrenberger et al., 2019).

Todos los autores afirman así que la descarbonización del transporte con la penetración de los EVs sólo podrá conseguirse mediante la introducción de energías renovables, para así asegurar el desarrollo sostenible de las comunidades (Shen et al., 2019).

Diversas investigaciones han analizado como estas variaciones en los modelos energéticos afectarían a las emisiones provocadas por los EVs. Dong et al. presentan un modelo dinámico experimental para simular las emisiones de ICEVs y EVs bajo ocho ciclos de conducción teniendo en cuenta la evolución de los escenarios de generación de los lugares bajo estudio (Europa, China y Japón) (Dong et al., 2019). Van den Broek et al. usan el modelo MARKAL para simular los escenarios de generación eléctrica que permitan reducir las emisiones de CO_2 asociadas al transporte en Países Bajos en un 15% y 50% para 2020 y 2050 respectivamente sobre los niveles de 1990 y considerando la introducción prevista de EVs en dicho país (van den Broek et al., 2008). Jochem et al. utilizan el modelo PERSEUS-NET-TS para simular cuatro escenarios de generación eléctrica que permitan alcanzar los niveles de reducción de dióxido de carbono en el transporte pronosticadas en Alemania para 2030 con la penetración de EVs (Jochem et al., 2015).

Impacto sobre la red eléctrica

Respecto a la introducción de EVs, los estudios prevén que se produzca de forma exponencial a corto-medio plazo en los países desarrollados (Muneer et al., 2015). La demanda eléctrica podría verse aumentada, si las recargas de EVs coincidieran temporalmente con los actuales picos de demanda, lo cual generaría graves impactos sobre las redes eléctricas (Clairand et al., 2018; Deb et al., 2018; Galiveeti et al., 2018). De este modo, la literatura científica propone la planificación de estrategias de recarga y desarrollo de microrredes con integración de energías renovables para evitar estos aumentos en la demanda y sus negativas consecuencias sobre la red eléctrica (Gong et al., 2018; Ortega-Vazquez et al., 2013).

La mayoría de las investigaciones están basadas en el concepto “desplazamiento de consumo”. Este método consiste en el traslado de parte de la demanda eléctrica producida durante los períodos de consumo pico hacia otros periodos con menor demanda, principalmente hacia periodos valle (López et al., 2015). Se consigue así una cobertura total de la demanda, la cual se ha aplanado, sin implicaciones negativas sobre la red eléctrica. Su et al. aplican este concepto al caso de estudio de Nueva Zelanda en 2030-2040, donde se prevé una penetración exponencial de EVs. A partir del comportamiento de recarga de los EVs, determinan una serie de estrategias de recarga basadas en restricciones de tiempo para el aplanamiento de la curva de demanda tras la introducción de EVs (Su et al., 2019). Liu et al. estudian la planificación energética de los países nórdicos europeos en 2050, donde pronostican que toda la flota de coches particulares sea eléctrica. Aplican la metodología desplazamiento de carga a partir de estrategias temporales de recarga de EVs que consideran el precio spot (Liu et al., 2014). Limmer y Rodemann analizan estrategias de recarga de EVs en electrolineras (EVCS, por sus siglas en inglés “Electric Vehicle Charging Station”) basadas en precios dinámicos. Su objetivo es doble: maximizar los beneficios de los operadores de las estaciones y reducir los picos de demanda eléctrica (Limmer and Rodemann, 2019). Otras estrategias de recarga proponen ajustar esta curva de demanda a la producción eléctrica con una alta contribución de renovables. La participación predominante de este tipo de tecnologías en el mix eléctrico se ha establecido como necesaria para asegurar una introducción sostenible de los EVs. Por ejemplo, Colmenar-Santos et al. presentan una estrategia de recarga para estos vehículos contemplando el escenario de energías renovables pronosticado para Europa en 2050 (Colmenar-Santos et al., 2019).

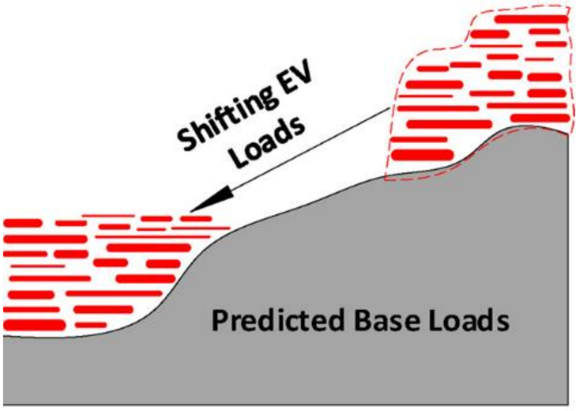


Figura 2. Desplazamiento de consumo. Fuente: (Su et al., 2019).

Por otro lado, el desarrollo de microrredes basadas en energías renovables a través de HRES permitirá también reducir la presión sobre la red eléctrica causada por la introducción prevista de EVs, contribuyendo además al desarrollo sostenible de las comunidades (Quddus et al., 2019; Wu et al., 2021). Varios artículos científicos muestran su idoneidad sobre instalaciones comunes de recarga, como es el caso de EVCS. Así, Domínguez-Navarro et al. determinan la configuración de HRES para EVCS que optimiza el coste actual neto de la instalación a partir del algoritmo de optimización genética (Domínguez-Navarro et al., 2019). Savio et al. se centran en el análisis de potencia de un HRES con recursos solares fotovoltaicos, conexión a red y apoyo de baterías para alimentar a una electrolinera de recarga rápida. Los resultados experimentales verifican los flujos de corriente y balances de potencia previamente simulados mediante MATLAB/Simulink (Savio et al., 2019). Tulpule et al. realizan una comparación económica y medioambiental entre una estrategia de recarga controlada y otra no controlada en una electrolinera con aportación de renovables y conexión a red para dos casos de estudios en Estados Unidos: Columbus (Ohio) y Los Ángeles (California) (Tulpule et al., 2013).

1.2.2. Países en desarrollo

Por otro lado, la pobreza energética se ha identificado como el mayor problema energético asociado a los países en desarrollado. Este problema queda enmarcado en la inaccesibilidad de los habitantes a la electricidad y a sistemas energéticos limpios para cocinar, especialmente en las zonas rurales (apartado 1.1).

Acceso a la energía eléctrica

En cuanto a la inaccesibilidad a la energía eléctrica, la literatura científica muestra como las energías renovables suponen una solución medioambiental al problema. Estas energías provienen de recursos naturales abundantes, ilimitados y accesibles para los habitantes de la región en cuestión, como el sol, viento, mareas, etc, a partir de los cuales es posible generar energía eléctrica de forma limpia (Ramírez Delgado et al., 2013). Respecto a las comunidades aisladas de la red eléctrica, la mayoría se ubican en África, Sudamérica y el sudeste Asiático (IEA, 2017a). En estas zonas, los niveles de irradiación anuales son muy elevados, lo que convierte a la energía solar fotovoltaica en un tipo de tecnología renovable idóneo para electrificación rural (Joshi et al., 2019). Además, el coste de este tipo de instalaciones es cada vez más económico, debido a la estandarización y reducción de coste de sus elementos, asociados a la economía de escala (Baurzhan and Jenkins, 2016) .

A partir del año 2000, numerosos estudios de electrificación rural mediante energía solar fotovoltaica fueron implementados en regiones de África (Hurtado et al., 2015; Moner-Girona et al., 2006; Njoh et al., 2019; Photovoltaics Bulletin, 2003; Wassie and Adaramola, 2021a). También en Sudamérica (Díaz et al., 2011) y sudeste asiático (Mainali and Dhital, 2015; Palit, 2013). Los recursos eólicos abundantes en algunas poblaciones de estas zonas también propiciaron el uso de pequeños aerogeneradores para electrificación de zonas aisladas (Leary et al., 2019; López-González et al., 2020). Además, se encuentran algunas instalaciones rurales basadas en sistemas aislados de biomasa (Pinheiro et al., 2011).

Sin embargo, el uso de un único tipo de energía renovable en estas instalaciones aisladas muestra su dependencia en otros sistemas (principalmente, sistemas de almacenamiento o grupos electrógenos) en los momentos en los que los recursos renovables no están disponibles. Un gran número de estudios científicos, así como la Agencia Internacional de Energía (IEA, 2017a), han demostrado la idoneidad de utilizar HRES para la electrificación de zonas aisladas de la red eléctrica (Kartite and Cherkaoui, 2019). Estos sistemas, combinan los distintos tipos de recursos renovables presentes en la región correspondiente, de forma que las limitaciones de un tipo de tecnología quedan cubiertas con el resto de fuentes. Los HRES incluyen también sistemas de respaldo propios de instalaciones renovables convencionales, como las baterías o grupos electrógenos. Sin embargo, la hibridación del sistema permite reducir en gran medida su dependencia en dichos sistemas de apoyo (Goel and Sharma, 2017).

Desde 2008 aproximadamente, se han llevado a cabo numerosos estudios de electrificación rural mediante HRES. El objetivo general de estos estudios ha tenido tradicionalmente un carácter tecno-económico: dimensionar el HRES de acuerdo con los recursos disponibles en la comunidad, asegurando la fiabilidad del sistema y al menor coste posible.

Muralikrishna and Lakshminarayan determinan que la combinación solar-eólica-baterías es la opción económica y técnicamente mejor para la electrificación de las aldeas remotas de Tamil Nadu (India), de acuerdo a una serie de condiciones: distancia a la red eléctrica superior a 50 km, energía requerida diaria menor a 75 kWh/día y coste de los paneles inferior a 1.515 $ (1.28 €). Además, anuncian también que el Coste Compensado de la Energía (LCOE, por sus siglas en inglés “Levelized Cost of Energy”) del HRES es menor que si la instalación estuviera formada únicamente por recursos solares o eólicos (Muralikrishna and Lakshminarayana, 2008). Abbas y Hassan establecen que un HRES formado también por energía solar y eólica, respaldado en este caso por un grupo electrógeno diésel, permitiría proporcionar energía eléctrica para uso doméstico y suministro de agua a 200 habitantes en la población remota de Rakhi Gaj (Pakistán) con un coste de energía menor que el de una instalación únicamente formada por recursos solares, eólicos o por grupo electrógeno (Abbas and Qadeer-Ul-Hasan, 2015).

En los estudios de Bhandari et al. (Bhandari et al., 2014) y Ma et al. (Ma et al., 2014), focalizados en la electrificación de las aldeas rurales de Thingan y Kolkhop, en Nepal y de una isla remota de Hong Kong respectivamente, señalan que el respaldo de recursos hidroeléctricos para los HRES solares y eólicos supone una solución económicamente efectiva para estos sistemas e idónea debido a su carácter totalmente renovable. Remarcan también que no todas las comunidades tienen posibilidad de incluir respaldo hidroeléctrico por sus características orográficas. Mostofi y Shayeghi añaden a esta combinación las baterías de hidrógeno para la electrificación de 12 aldeas rurales de la zona Meshkinshahr, en Irán, anunciando que el coste por unidad de energía generada por el HRES disminuye al incluir los recursos hidroeléctricos (Mostofi and Shayeghi, 2012).

El respaldo de sistemas de biomasa para HRES con recursos solares y eólicos aparece también en gran parte de la literatura científica. Dhass y Santhanam establecen que esa combinación (solar-eólica-biomasa) es la que presenta un menor LCOE para la electrificación de la población aislada de Pongalur en Tamilnadu (India). Además, los costes del ciclo de vida y unitarios resultan menores para el HRES que para un sistema renovable convencional (Dhass and Harikrishnan, 2013). Sharma y Goel determinaron que esa combinación de recursos presentaba el menor coste de energía, el menor coste actualizado neto y el menor coste de operación para las aldeas rurales de Odisha (India). En este estudio se muestra también la reducción de emisiones CO_2 respecto a la electrificación únicamente con un generador diésel: 83.04% (Sharma and Goel, 2016).

Relacionado con este último aspecto, las investigaciones sobre HRES han mostrado sus beneficios medioambientales. Azoumah et al., establecen que un HRES solar (18 kW_p)-diésel (35.5 kW) para electrificación de aldeas rurales de Burkina Faso (África) es capaz de reducir hasta 445 toneladas de CO_2 en comparación con un generador diésel convencional (38.5 kW) (Azoumah et al., 2011). El HRES solar-eólico-diésel-batería estudiado por Rohani y Nour para el área remota de Ras Musherib (Abu Dhabi) reduce las emisiones de CO_2 en un 37% en comparación con un generador diésel único (Rohani and Nour, 2014).

Además, el acceso a la electricidad conseguido mediante HRES en poblaciones remotas genera una serie de beneficios socio-económicos sobre la población: mayor acceso a la educación, generación de empleo, reducción de contaminación…(Mandal et al., 2018).

Acceso a sistemas energéticos limpios para cocinar

En cuanto a la inaccesibilidad a sistemas energéticos limpios para cocinar, las denominadas Estufas para Cocinar Mejoradas (ICS, por sus siglas en inglés "Improved Cooking Stoves") mediante Gasificación de Biomasa (ICS-G) han tratado de resolver dicha problemática (Chica and Pérez, 2019). Estas estufas son sistema de cocina cerrados cuyo diseño mejora la eficiencia térmica del proceso (mejor combustión, transferencia de calor y reducción de humos) empleando biomasa para la combustión (Mehetre et al., 2017). Esta biomasa corresponde en la gran mayoría de casos a residuos agrícolas, cuya quema tradicional era responsable del 40% de las emisiones de CO_2, 32% de CO, 20% de partículas finas suspendidas y 8% de otras emisiones enviadas hacia la atmósfera (CCA, 2014; Ministry of Agriculture, 2012). Se emplea así un combustible renovable, fácilmente accesible, con impacto climático neutro y socialmente viable.

Aunque el primer programa de desarrollo de ICS data de 1950 (Rahman, 2010), no fue hasta mediados de 1980 cuando estos planes focalizaron la investigación en las necesidades de los consumidores: reducción de humos, seguridad de los usuarios, eficiencia térmica y uso de biomasa. Entre ellos, destaca el programa indio "Programa Nacional Indio sobre Chulhas mejoradas", que concluyó con la introducción de cerca de 35 millones de ICS en India entre 1983 y 1985 (Hanbar and Karve, 2002). Por otro lado, el plan chino "Programa Nacional Chino sobre Estufas Mejoradas" introdujo cerca de 129 millones de ICS entre 1982 y 1992, principalmente en zonas rurales, siendo considerado uno de los programas más exitosos en este ámbito (Smith et al., 1993). Finalmente, en 2010 se lanzó "la Alianza Global para las Estufas de Cocina Limpias". Liderada por las Naciones Unidas, el objetivo de esta alianza fue la introducción de estos sistemas en cerca de 100 millones de hogares en la década de 2020 (Lindgren, 2020).

Estos programas quedan recopilados en los estudios (Kshirsagar and Kalamkar, 2014) y (Manoj Kumar et al., 2013). En este último, Kumar et al. muestran también el desarrollo tecnológico y de diseño que han sufrido estas estufas desde sus orígenes hasta la actualidad (Manoj Kumar et al., 2013). Mehetre et al. hacen una amplia revisión y comparación de los protocolos a nivel mundial de las ICS-G, de los diferentes modelos y de los avances que se han producido en las mismas (Mehetre et al., 2017). Patriti et al. estudian los efectos que la contaminación de las cocinas tradicionales de biomasa provoca en los usuarios y su mitigación mediante las ICS-G (Pratiti et al., 2020). Vahlne y Ahlgren muestran también la implicación política necesaria para llevar a cabo una transición ecológica hacia las ICS-G en las comunidades rurales (Vahlne and Ahlgren, 2014).

Además, numerosos estudios muestran los positivos resultados económicos, medioambientales y sociales tras introducir ICS-G en poblaciones rurales en vías de desarrollo: Etiopía (Wassie and Adaramola, 2021b), Iran (Rasoulkhani et al., 2018), India (Jeuland et al., 2020), Ghana (Dickinson et al., 2019), Pakistán (Harijan and Uqaili, 2013) o Perú (Fandiño-Del-Rio et al., 2020) entre otros.

1.3. Objetivos

El objetivo principal de esta tesis doctoral es el estudio de sistemas renovables avanzados que permitan resolver los problemas energéticos principales enmarcados en el contexto de desarrollo de las comunidades, para así favorecer su crecimiento sostenible.

Los objetivos específicos de la tesis se detallan a continuación:

- Identificación de los principales problemas energéticos de países desarrollados frente a los de países en desarrollo y revisión del estado del arte sobre soluciones renovables a la problemática identificada.

- Planificación energética renovable y de estrategias de recarga para alcanzar una descarbonización del transporte electrificado en países industrializados.
- Caracterización de HRES en EVCS para conseguir una introducción sostenible de EVs en comunidades avanzadas.
- Caracterización de HRES para permitir el acceso a la electricidad a comunidades aisladas en desarrollo.
- Caracterización de ICS-G para permitir el acceso a sistemas energéticos limpios de cocina en zonas remotas en desarrollo.

1.4. Estructura

El trabajo presentado corresponde a una tesis doctoral por compendio de artículos científicos. De este modo, cada publicación puede ser leída de forma autónoma, ya que contiene los apartados necesarios para su completa comprensión: introducción, metodología, resultados y conclusiones. Sin embargo, el conjunto de los mismos conforma un trabajo completo sobre el estudio de sistemas renovables avanzados para el desarrollo energético sostenible.

La tesis está compuesta por 5 capítulos. Al tratase de una tesis doctoral internacional, la mayor parte del trabajo se ha redactado en inglés. En concreto, los capítulos 2, 3, 4 y 5 se presentan en inglés, mientras que el capítulo 1 se presenta en castellano.

La estructura de la tesis se muestra a continuación:

Capítulo 1. Introducción.

1.1. Problemática energética.
    1.1.1. Relación entre el nivel de desarrollo de los países y el uso de la energía.
1.2. Antecedentes.
    1.2.1. Países desarrollados.
    1.2.2. Países en desarrollo.
1.3. Objetivos.
1.4. Estructura.

Chapter 2. Scientific publications.

2.1. Assessing transport emissions reduction while increasing electric vehicles and renewable generation levels.
2.2. Light electric vehicle charging strategy for low impact on the grid.
2.3. Multicriteria design and experimental verification of hybrid renewable energy systems. Application to electric vehicle charging stations.
2.4. Microrredes híbridas, una solución para países en vías de desarrollo.
2.5. Hybrid assessment for a hybrid microgrid: A novel methodology to critically analyse generation technologies for hybrid microgrids.
2.6. Sustainable Cooking Based on a 3 kW Air-Forced Multifuel Gasification Stove Using Alternative Fuels Obtained from Agricultural Wastes.

Chapter 3. General discussion of the results.

Chapter 4. Conclusions.

- 4.1. Goals fulfilment.
- 4.2. Main contributions
- 4.3. Future research lines.

Chapter 5. Bibliography

El capítulo 1 realiza una introducción a la tesis doctoral presentada. En primer lugar, se analiza la problemática energética a la que se enfrentan los diferentes países en función de su nivel de desarrollo. En segundo lugar, se revisa el estado del arte de los sistemas energéticos renovables empleados hasta la fecha para tratar la problemática identificada. A continuación, se definen los objetivos a alcanzar con este trabajo. Finalmente, se muestra la estructura general de la tesis presentada por compendio de artículos.

El capítulo 2 muestra las seis publicaciones científicas que conforman la presente tesis por compendio de artículos. A continuación, se muestra el resumen de dichas publicaciones.

Por un lado, las publicaciones científicas 1, 2 y 3 se centraron en el uso de sistemas renovables avanzados para solucionar la principal problemática identificada en los países desarrollados: el negativo impacto del transporte tradicional sobre el medioambiente.

La primera publicación "Assessing transport emissions reduction while increasing electric vehicles and renewable generation levels" (Bastida-Molina et al., 2020a) presenta una metodología nueva que permite evaluar la sostenibilidad de los EVs. Así, calcula el balance neto de emisiones CO_2 de EVs e ICEVs a través de la herramienta Well-to-Wheel (WtW). A continuación, desarrolla un proceso iterativo sobre la contribución necesaria de energías renovables en el mix eléctrico para alcanzar unos ciertos niveles de reducción de emisiones. Se aplicó al caso de estudio de España para un futuro a medio plazo.

El artículo ha sido publicado en la revista "Transportation Research Part D: Transport and Environment", del grupo Elsevier. De acuerdo con Journal Citation Reports (JCR) 2019 de Web of Science, la revista tiene un factor de impacto de 4.577 y se ubica en el cuartil Q2 de la categoría "Transportation Science and Technology" (10/36). En el ránking SCImago (SJR) 2019 de Scopus se ubica en el cuartil Q1 de las categorías "Environmental Science" y "Transportation".

La segunda publicación "Light electric vehicle charging strategy for low impact on the grid" (Bastida-Molina et al., 2020b) muestra una metodología para evitar el impacto negativo sobre la red eléctrica de una masiva introducción de EVs. El método traslada los incrementos de demanda eléctrica provocados por la introducción de EVs hacia las zonas valle, contemplando tres estrategias de recarga: en casa, en edificios públicos y en EVCS. El caso de estudio analizado corresponde a España en un futuro a medio plazo.

El artículo ha sido publicado en la revista "Environmental Science and Pollution Research", del grupo Springer. De acuerdo con JCR 2019, la revista tiene un factor de impacto de 3.056 y se ubica en el cuartil Q2 de la categoría "Environmental Sciences" (99/265). En SJR 2019 se ubica en el cuartil Q2 de la categoría "Pollution".

La tercera publicación "Multicriteria design and experimental verification of hybrid renewable energy systems. Application to electric vehicle charging stations" (Bastida-Molina et al., 2021) introduce una nueva metodología ponderada y multicriterio basada en criterios técnicos, económicos y medioambientales para el diseño de HRES en EVCS. Incluye además una etapa de validación experimental. El caso de estudio de esta publicación corresponde a la ciudad de Valencia (España).

El artículo está actualmente aceptado en la revista "Renewable Energy", del grupo Elsevier. De acuerdo con JCR 2019, la revista tiene un factor de impacto de 6.274 y se ubica en el cuartil Q1 de las categorías "Green and Sustainable Science and Technology" (9/41) y "Energy and Fuels" (19/112). En SJR 2019 se ubica en el cuartil Q1 de la categoría "Renewable Energy, Sustainability and the Environment". Durante el proceso de publicación, el trabajo está disponible en el repositorio online "arXiv", en la categoría "Electrical Engineering and Systems Science".

Por otro lado, las publicaciones científicas 4, 5 y 6 se focalizaron en el uso de sistemas renovables avanzados para solucionar la principal problemática identificada en los países en desarrollo: pobreza energética (inaccesibilidad a la electricidad y sistemas de cocina limpios).

La cuarta publicación "Microrredes híbridas, una solución para países en vías de desarrollo" (Bastida-Molina et al., 2020c) presenta una metodología de fácil aplicación en el diseño de HRES para electrificación de zonas aisladas en desarrollo por técnicos no expertos en la materia. Se aplicó al caso de estudio de la aldea Masitala (Malawi).

El artículo ha sido publicado en la revista "Técnica Industrial", del Colegio Oficial de Ingenieros Técnicos y de Grado de Valencia. Esta revista está indexada en Google Académico, EBSCO, Dialnet, Latindex, ICYT, Rebiun y Compludoc.

La quinta publicación "Hybrid assessment for a hybrid microgrid: A novel methodology to critically analyse generation technologies for hybrid microgrids" (Ribó-Pérez et al., 2020) propone una metodología novedosa para evaluar todos los criterios influyentes sobre el diseño de HRES para electrificación de zonas aisladas en desarrollo. El método incluye análisis del contexto, revisión de la literatura y la aplicación de la herramienta multicriterio (MCDM, por su siglas en inglés "Multi Criteria Decision Making) Analytic Network Process (ANP). El caso de estudio analizado corresponde a la comunidad rural "El Santuario", situada en el Corredor Seco Mesoamericano de Honduras.

El artículo ha sido publicado en la revista "Renewable Energy", del grupo Elsevier. De acuerdo con JCR 2019, la revista tiene un factor de impacto de 6.274 y se ubica en el cuartil Q1 de las categorías "Green and Sustainable Science and Technology" (9/41) y "Energy and Fuels" (19/112). En SJR 2019 se ubica en el cuartil Q1 de la categoría "Renewable Energy, Sustainability and the Environment".

Por último, la sexta publicación "Sustainable Cooking Based on a 3 kW Air-Forced Multifuel Gasification Stove Using Alternative Fuels Obtained from Agricultural Wastes"

(Hurtado Pérez et al., 2020) realiza una comparación termodinámica, económica y medioambiental entre las estufas para cocinar tradicionales (TCS, por sus siglas en inglés "Traditional Cooking Stoves") e ICS-G, así como de un combustible tradicional (carbón) y el propuesto en la publicación (briquetas). Utiliza dos métodos de testeo (Water Boiling Test y Controlled Cooking Test). Se centra en el caso de estudio de Bandudu, situada a 409 km de Kinshasa (República Democrática del Congo).

El artículo ha sido publicado en la revista "Sustainability", del grupo MDPI. De acuerdo con JCR 2019, la revista tiene un factor de impacto de 2.576 y se ubica en el cuartil Q2 de la categoría "Environmental Sciences" (120/265). En SJR 2019 se ubica en el cuartil Q2 de las categorías "Renewable Energy, Sustainability and the Environment", "Environmental Science" y "Energy Engineering and Power Technology". Este artículo ha sido también publicado en un capítulo del libro "Prime Archives in Sustainability" de la editorial Vide Leaf.

El capítulo 3 realiza una discusión general sobre los resultados obtenidos a partir de esta tesis por compendio de artículos.

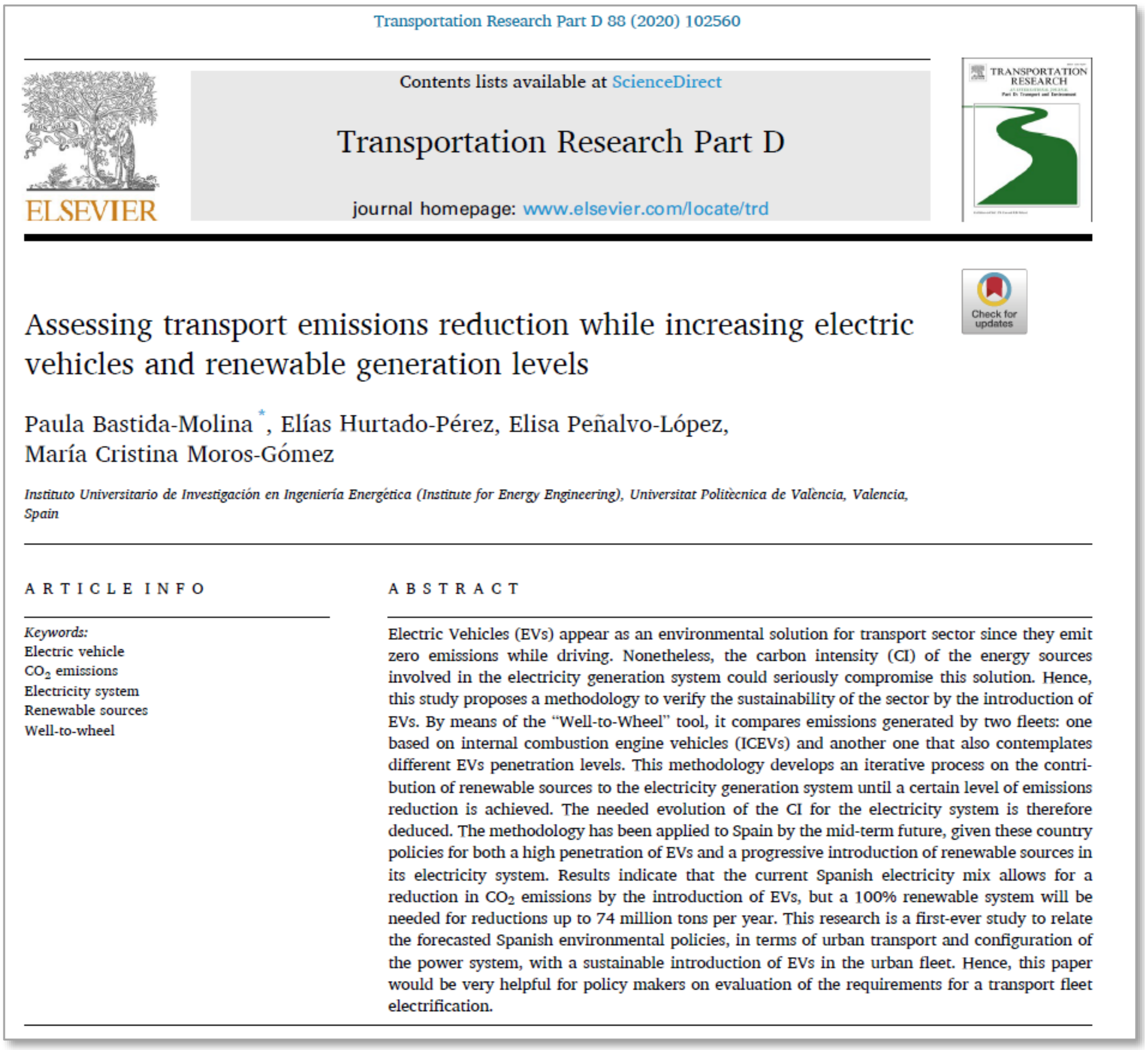
El capítulo 4 muestra las conclusiones extraídas de este trabajo científico. En primer lugar, se analiza la consecución de los objetivos planteados. Seguidamente, se presentan las principales contribuciones de esta tesis doctoral al conocimiento científico. Finalmente, se indican las futuras líneas de investigación derivadas de la tesis.

Por último, el capítulo 5 presenta la bibliografía completa de la tesis doctoral.

Chapter 2.
Scientific publications

This chapter presents the six scientific publications that compose this doctoral thesis.

2.1. Assessing transport emissions reduction while increasing electric vehicles and renewable generation levels



Transportation Research Part D 88 (2020) 102560

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Assessing transport emissions reduction while increasing electric vehicles and renewable generation levels

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A R T I C L E I N F O

Keywords:
Electric vehicle
CO_2 emissions
Electricity system
Renewable sources
Well-to-wheel

A B S T R A C T

Electric Vehicles (EVs) appear as an environmental solution for transport sector since they emit zero emissions while driving. Nonetheless, the carbon intensity (CI) of the energy sources involved in the electricity generation system could seriously compromise this solution. Hence, this study proposes a methodology to verify the sustainability of the sector by the introduction of EVs. By means of the "Well-to-Wheel" tool, it compares emissions generated by two fleets: one based on internal combustion engine vehicles (ICEVs) and another one that also contemplates different EVs penetration levels. This methodology develops an iterative process on the contribution of renewable sources to the electricity generation system until a certain level of emissions reduction is achieved. The needed evolution of the CI for the electricity system is therefore deduced. The methodology has been applied to Spain by the mid-term future, given these country policies for both a high penetration of EVs and a progressive introduction of renewable sources in its electricity system. Results indicate that the current Spanish electricity mix allows for a reduction in CO_2 emissions by the introduction of EVs, but a 100% renewable system will be needed for reductions up to 74 million tons per year. This research is a first-ever study to relate the forecasted Spanish environmental policies, in terms of urban transport and configuration of the power system, with a sustainable introduction of EVs in the urban fleet. Hence, this paper would be very helpful for policy makers on evaluation of the requirements for a transport fleet electrification.

Assessing transport emissions reduction while increasing electric vehicles and renewable generation levels

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Abstract

Electric Vehicles (EVs) appear as an environmental solution for transport sector since they emit zero emissions while driving. Nonetheless, the carbon intensity (CI) of the energy sources involved in the electricity generation system could seriously compromise this solution. Hence, this study proposes a methodology to verify the sustainability of the sector by the introduction of EVs. By means of the "Well-to-Wheel" tool, it compares emissions generated by two fleets: one based on internal combustion engine vehicles (ICEVs) and another one that also contemplates different EVs penetration levels. This methodology develops an iterative process on the contribution of renewable sources to the electricity generation system until a certain level of emissions reduction is achieved. The needed evolution of the CI for the electricity system is therefore deduced. The methodology has been applied to Spain by the mid-term future, given these country policies for both a high penetration of EVs and a progressive introduction of renewable sources in its electricity system. Results indicate that the current Spanish electricity mix allows for a reduction in CO_2 emissions by the introduction of EVs, but a 100% renewable system will be needed for reductions up to 74 million tons per year. This research is a first-ever study to relate the forecasted Spanish environmental policies, in terms of urban transport and configuration of the power system, with a sustainable introduction of EVs in the urban fleet. Hence, this paper would be very helpful for policy makers on evaluation of the requirements for a transport fleet electrification.

Keywords

Electric vehicle, CO_2 emissions, electricity system, renewable sources, Well-to-Wheel.

Variables

$F(t)$	*Total fleet evolution.*
$r(i,t)$	*Rate of total fleet growth (%).*
$F_{ICEVs_0}(t)$	*Fleet of ICEVs without EVs penetration.*
$F_{ICEVs_F}(t)$	*Remaining fleet of ICEVs with EVs penetration.*
$f_p(i,j,t)$	*Rate of EVs penetration (%).*
$F_{EVs}(t)$	*Fleet of EVs with EVs penetration.*
$F_T(t)$	*Total fleet of ICEVs and EVs with EVs penetration.*
$g(t)$	*Emissivity of the electricity system (g CO_2/kWh).*
$P(k,t)$	*Participation of each power source in the electricity generation (%).*
$Em_{ICEVs_0}(t)$	*Emissions due to $F_{ICEVs_0}(t)$, (g CO_2).*
$d(i,t)$, $d(j,t)$	*Annual travel distances (km).*
$c_{ICEVs}(i,t)$	*Fuel consumption for ICEVs (l/km).*
$Em_{ICEVs_F}(t)$	*Emissions due to $F_{ICEVs_F}(t)$, (g CO_2).*
$Em_{EVs}(t)$	*Emissions due to $F_{EVs}(t)$, (g CO_2).*
$x_{elect}(j,t)$	*Fraction of electrical contribution for EVs (%)* [a]*.*
$c_{elect}(j,t)$	*EVs electricity consumption per kilometre (kWh/km)* [a]*.*
$x_{hyb}(j,t)$	*Fraction of hybrid contribution for EVs (%)* [b]*.*
$c_{hyb}(j,t)$	*Fuel consumption for EVs (l/km)* [b]*.*
$Em_{EVs,elect}(t)$	*Emissions generated due to the electrical behaviour of EVs (g CO_2)* [a]*.*
$Em_{EVS,hyb}(t)$	*Emissions generated due to the hybrid behaviour of EVs (g CO_2)* [b]*.*
$Em_T(t)$	*Total emissions generated by $F_T(t)$, (g CO_2).*
$g_{lim}(t)$	*Allowable maximum value of $g(t)$, (g CO_2/kWh).*
$s(t)$	*Degree of sustainability due to the substitution of ICEVs by EVs (%).*
$s_{ref}\ (t)$	*Reference value of $s(t)$, (%).*

Parameters

t	
ΔT	*Time interval for the study*
$CI\ (k)$	*Carbon intensity of each power source (g CO_2/kWh).*
$em_{WtW}(i)$	*WtW emissivity for ICEVs (g CO_2/L).*
$em_{WtW}(j)$	*WtW emissivity for EVs with hybrid behaviour (g CO_2/L)* [b]*.*
$LRSI(f)$	*Level of renewable sources introduction.*

Indices	
i	*Index for ICEVs vehicles type, i = {1, 2, 3, 4}, specifically 1: gasoline car, 2: diesel car, 3: diesel bus, 4: gasoline motorcycle.*
j	*Index for EVs vehicles type, j = {1, 2, 3, 4 }, specifically 1: BEV car, 2: HEV car, 3: PHEV car, 4: BEV bus; 5: HEV bus, 6: PHEV bus, 7: BEV motorcycle.*
f	*Index for LRSI, f = {1, 2, 3, 4, 5}*
k	*Index for the power source in electricity generation, k = {1, 2, 3, 4, 5}, specifically 1: coal, 2: nuclear, 3: oil, 4: natural gas, 5: renewable.*

[a]: Electrical behavior of EVs related to BEVs and PHEVs partly.

[b]: Hybrid behavior of EVs related to HEVs and PHEVs partly.

1. Introduction

Unlike traditional vehicles powered by internal combustion engine (ICEVs), electric vehicles (EVs) generate zero emissions while they are driven on the roads: "zero tailpipe emissions" (Driscoll et al., 2013; Morrissey et al., 2016; Teixeira and Sodré, 2018). However, a raise in the emissions due to the electricity generation system to cover the increase of electricity demand by the EVs could appear (Álvarez Fernández, 2018; Manjunath and Gross, 2017). This emission increase would mainly depend on the electricity mix structure. Therefore, the carbon intensity (CI) of the technologies involved in the electricity generation mix of every country would determine the environmental profitability degree of introducing EVs in relation to the net total CO_2 emission savings (Weiss et al., 2015).

Well-to-Wheel (WtW) analysis has been widely used to assess total carbon emissions reduction in transport sector (Athanasopoulou et al., 2018; Ke et al., 2017; Qiao et al., 2019; Woo et al., 2017). This approach considers the whole process of energy flow, from the fuel generation to the vehicle driving, dividing the whole process in two clear separate steps: Well-to-Tank (WtT) and Tank-to-Wheel (TtW) processes. An exhaustive study (Woo et al., 2017) analyses the WtW for EVs considering the generation mix of 70 different countries and compares the results with the equivalent emissions of ICEVs. Results show that countries with the highest CI power sources are also the ones with highest EVs' emissions. Even in some countries, emissions are higher than the ones generated by the corresponding ICEVs. Other study (Moro and Lonza, 2018) makes a similar analysis, applying WtW methodology to each European Union Member State. This research also considers the CI content of electricity trades between countries. Besides, it calculates how total CI of the power mix of a country decreases when importing low CI electricity from another region and the other way round. WtW method has been also applied to specific countries or regions to calculate CO_2 emissions when introducing EVs. For instance, (Onn et al., 2018) analyses the current Malaysia's case of study, (Ehrenberger et al., 2019) studies the four countries with highest passenger car sales (Germany, the United States, China and Japan) together with a highly renewable energy country (Norway). (Wu and Zhang, 2017) makes a comparison between both developed and developing countries and finally (Canals Casals et al., 2016) focuses on European countries.

All of these studies present comparisons between emissions produced by EVs with their current country electricity generation mix and the ones generated by ICEVs. They all try to determine whether the introduction of EVs is a clean solution or not, coming all to the same view: CO_2 savings when introducing EVs only happen in the cases where high CI sources are not the main representative ones in the electricity system. China emerges in this context as the global largest EVs market, with 1.2 million EVs sold in 2018 (Zheng et al., 2019) due to its appealing EVs incentive policies (Zheng et al., 2020). However, the main use of coal for electricity generation in this country (Dong et al., 2019) also foresees the highest CO_2 emissions projections for this country with EVs introduction. Study (Wang et al., 2019) specifically states that the large-scale development of EVs in China maintaining its current power structure would be equivalent to replace oil with coal in the system, which would result in carbon emissions increasing. Research (Liu et al., 2018) also forecasts the key role that fuel economy regulations will play in the short-term future of China together with the lower reliance of the power system on fossil fuel in the long-term. After China, Japan would suffer the highest CO_2 emissions for EVs, as (Dong et al., 2019) states. Japan, together with other countries such as South Korea or Taiwan, depend on the import of fuels through maritime transportation. This situation affects not only the energy mix of these countries, but also the complexity and WtW analysis (Choi and Song, 2018). So far, all the published studies claim the global necessity of moving towards a more renewable electricity system to meet decarbonization by EVs introduction (Shen et al., 2019). Particularly, (Spangher et al., 2019) equates the large effect of grid decarbonization with increasing EVs fleet. Moreover, (Hoekstra, 2019) identifies the assumption of an unchanged electricity mix over the coming years as a traditional error factor while forecasting EVs emissions reduction in a country. The study (Dong et al., 2019) addresses this traditional error. Namely, (Dong et al., 2019) presents an experimentally vehicle dynamic model to simulate ICEVs and EVs consumption under eight driving cycles to determine CO_2 emissions of both types of vehicles considering the projected emissivity evolution of the countries under study (Europe, China and Japan) until year 2040. Three main results are presented in this study. Firstly, the enhancement of both EVs and ICEVs' technologies will lead to a reduction in carbon emissions along the years, being ICEVs' emissions always higher than EVs' ones. Secondly, China is expected to produce the highest CO_2 emissions due to its power grid composition projections. Finally, the difference between CO_2 emissions from ICEVs and EVs gets smaller under highway conditions and higher under urban driving conditions.

Other methodologies have also analysed the influence of electricity structure systems regarding EVs emissions using energy models. For instance, research (van den Broek et al., 2008) uses the MARKAL model to generate a quantitative scenario for electricity and cogeneration sectors in the Netherlands, which allowed them to stablish strategies to achieve, in comparison with 1990 levels , 15% and 50% CO_2 emissions reduction in 2020 and 2050, respectively. Another study (Jochem et al., 2015) employs the energy model (PERSEUS-NET-TS) to analyse four different methods to evaluate CO_2 emissions in Germany by 2030, revealing differences up to 0.55 kg/kWh.

The existing literature only makes quantitative analyses of EVs carbon emissions and, although some studies consider the effects of a changeable electricity mix along the years, these researches lack the possibility of forecasting the detailed evolution of the power system structure needed to guarantee all the time a specific level of emissions reduction. This detailed evolution of the power system has been the focus of our investigation. Hence, our paper proposes a methodology to assess the time evolution of the renewable sources introduction in the electricity system in order to get, for a particular penetration of EVs in the fleet, a particular level of decrease in the CO_2 emission. This method also determines the limit emissivity of the power system to ensure a zero emissions introduction of EVs in a particular fleet. The methodology will evaluate the possibility to reach a sustainable transport sector by combining EVs penetration and renewable participation in the electricity system.

Other researches have also proposed methodologies to evaluate changes in the energy mix with the introduction of EVs, but they present a series of limitations that the current paper has tried to cope with. Research (Choi et al., 2018) analyses the initial consumers' preferences while selecting a vehicle and evaluates their change in preferences according to various electricity generation mix scenarios together with their environmental impact. Their results indicate that BEVs' market share could be promoted up to 10% and reduce GHG up to 5% by 2026. The evaluation period of this research represents an imminent future (2026), while our paper establishes a longer evaluation period: up to 2040. Moreover, research (Choi et al., 2018) presents four pre-established different energy mix scenarios whose composition does not depend on the level of CO_2 emissions reduction achieved with the penetration of EVs, unlike our study where the introduction of renewable sources clearly depends on two carbon emissions constrains related to the introduction of EVs. Research (Shamshirband et al., 2018) presents a methodology to optimally schedule the charging/discharging process of EVs with two main objectives: minimize costs of the system and reduce CO_2 emissions. Such methodology is applied to distributed networks that integrate renewable resources. This application differs from the one presented in this paper, since the horizon of our work extends to the configuration of all the national grid and renewable resources are introduced according to CO_2 emissions restrictions provoked by EVs. Study (Kobashi et al., 2020) proposes a techno-economic analysis of a city-scale energy system with rooftop PV, batteries and EVs with storage possibilities for Kyoto in Japan. The dimension applicability of such research focuses just on distributed networks for cities and includes only solar PV as renewable resources. Moreover, it makes an analysis of a fix temporary scenario, without including any renewable energy evolution according to the introduction of EVs. However, our study includes the configuration of the entire national grid and contemplates all different types of renewable energies, not just solar PV. Hence, our methodology is scalable to the scenario in question. Besides, our paper develops the evolution of the energy system configuration according to carbon dioxide emissions boundaries generated by the penetration of EVs. Furthermore, other studies have used the methodology Life cycle assessment (LCA) to evaluate carbon emissions impacts of the introduction of EVs. For instance, research (Burchart-Korol et al., 2020) makes a LCA of EVs battery charging in all the 28 European Union countries considering the current and the projected electricity mix structure until 2050. Despite the valuable information that could be extracted from this work, it does not indicate the total evolution that carbon dioxide emissions would suffer along this period since the work does not considered the remaining quantity of ICEVs and the projected EVs to be included in the fleet. Moreover, the introduction of renewable sources does not answer to CO_2 restrictions when introducing EVs, but to projected plans. Otherwise, our paper includes an energy model that allows a changeable introduction of renewable sources in the energy mix according to the CO_2 emissions reduction constrains due to EVs introduction. Besides, the methodology considers two different fleets to obtain the carbon dioxide emissions reduction: one formed only by ICEVs and another one formed by ICEVs and EVs. In both cases, the evolution of the quantity of such vehicles lies in forecasted data. Finally, our work employs the methodology WtW instead of LCA to assess carbon emissions reduction. Despite LCA is a more precise technique that considers more stages in the vehicles' life when analyzing its environmental suitability, WtW is the most widely used method for policy support in road transport (Moro and Helmers, 2017). According to (Moro and Helmers, 2017), WTW methodology is used for instance by the European Union for the Fuel Quality Directive and for the Renewable Energy Directive, in the USA, the Environmental Protection Agency bases its regulatory actions on the WTW approach of the GREET model, and also in China, WTW is used to assess policy options.

Having said that, we have not found any work in the literature that relates the introduction of renewable sources in the electricity mix with a double level of CO_2 constraints restriction when introducing EVs: a first level that ensures a net CO_2 emissions introduction of EVs and a second level that ensures a CO_2 emissions reduction with such introduction. Specifically, the limit electricity system emissivity (first constraint), which guarantees a net CO_2 emissions introduction of EVs, remains unexplored in the rest of the literature, to the best of our knowledge. Additionally, as far as we are concerned, no other studies include a comparison between emissions generated by two possible fleets: one completely formed by ICEVs and another one that also includes EVs. Beyond this, the method is completely scalable and true to reality since it considers the complete replacement of ICEVs cars, motorcycles and urban buses by EVs, including all the different types: BEVs, PHEVs and HEVs.

The methodology has been applied to the Spanish case study in the mid-term future, until 2040. Figure 1 (IEA, 2016) and Table 1 (DGT, 2017) provide a general caption about the electricity generation system and fleet composition of the country, respectively.

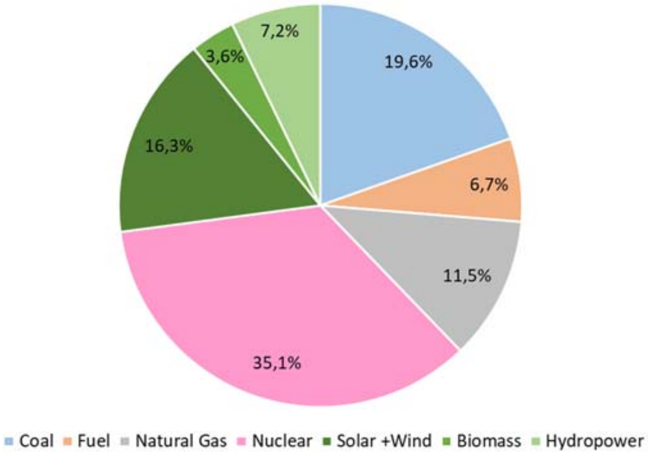


Figure 1. Current Spanish power system composition.

Table 1. Current Spanish fleet composition.

Gasoline car	Diesel car	Gasoline motorcycle	Diesel bus
9820553	13038663	3201831	14986

Spain is expected to get a large contribution to CO_2 transport emissions reduction due to the environmental policies proposed in the regulatory draft (IDAE, 2020) by the Ecological

Transition Spanish Ministry (PNIEC, 2019). This regulatory draft emerges for the first time in 2018 with three general goals: to ensure compliance with the Paris Agreement's objectives (UE, 2015), enhance the decarbonization of the Spanish economy and introduce a sustainable development model capable of mitigating climate change. In line with these three objectives, the draft presents two main fields of application: sustainable mobility and renewable electricity generation system.

Regarding the former, the draft prohibits by 2040 the sale and registration of light vehicles which produce carbon dioxide emissions, and its circulation by 2050. This measure enhances the renovation of the current aged ICEVs fleet in Spain, which has an average age of 12.4 years, whereas the European average age states at 10.8 years (ANFAC, 2018). Moreover, the Spanish regions with more than 50000 inhabitants are obliged to create spaces with low emissions before 2023, enhance the public transport and electrify urban buses. This draft also boosts the installation of recharge point for EVs, making it obligatory in the coming years for petrol stations with high shares, new construction buildings and non-residential existing buildings with more than 20 parking places. To ensure such mobility transition in a sustainable way, the Spanish Government has introduced financial aids, specifically the so called Plan Moves (ETECNIC, 2020). This Plan includes economical aids to buy EVs (only BEVs and PHEVs, together with hydrogen vehicles) and to install recharging points for such vehicles.

With reference to renewable generation, this regulation aims to achieve a 74% renewable sources introduction in the electricity generation mix by 2030 and a 100% renewable one by 2050. Moreover, the draft includes highly environmental-restrictive policies to coal power stations, which practically imply their upcoming closing (BOE, 2019). Besides, a stepped close of nuclear power plants is foreseen as another future measure for the Spanish ecological transition (Spanish Nuclear Industry Forum, 2019). Finally, the regulatory draft (PNIEC, 2019) includes a "just transition strategy" with a series of regulatory measures to reduce negative economic impacts in energy sectors that do not fit in the ecological transition.

Both effects, a large penetration of EVs and a change in the electricity mix with a growing introduction of renewable sources, make Spain an ideal case study for urban transport emissions reduction. Our study includes five different levels of renewable sources introduction (LRSI) in the Spanish power system, which reflect the previously described regulatory plans.

This research is a first-ever study to relate the forecasted Spanish environmental policies, in terms of urban transport and configuration of the power system, with a sustainable introduction of EVs in the urban fleet by using a novel methodology based on carbon emissions constraints for the electricity generation system. Hence, this paper would be very helpful for policy makers on evaluation of the requirements for a transport fleet electrification.

The paper is organized as follows: section 2 presents the methodology, section 3 describes the application to Spain by the mid-term future and section 4 provides the results and discussion of this application. Finally, the paper concludes in section 5.

2. Methodology

A methodology has been developed to determine the reduction in CO_2 emissions due to the penetration of EVs in the transportation fleet. The method establishes the needed CI factor of the electricity generation system to provide, at any time along that evolution, a specific level of emissions reduction. Figure 2 represents the flowchart of the proposed methodology, whereas Table 2 define both input and output data.

Table 2. Inputs and outputs

Inputs	**Outputs**
t_0	$F_{ICEVs_0}(t)$
t_F	$F_{ICEVs_F}(t)$
ΔT	$F_{EVs}(t)$
$F(t_0)$	$F_T(t)$
$r(i,t)$	$g(t)$
$f_p(i,j,t)$	$Em_{ICEVs_0}(t)$
$P(k,t)$	$Em_{ICEVs_F}(t)$
$CI\ (k)$	$Em_{EVs}(t)$
$g(t_0)$	$Em_{EVs,elect}(t)$
$d(i,t)\ ,\ d(j,t)$	$Em_{EVs,hyb}(t)$
$c_{ICEVs}(i,t)$	$Em_T(t)$
$em_{WtW}(i)$	$g_{lim}(t)$
$x_{elect}(j,t)$	$s(t)$
$c_{elect}(j,t)$	$LRSI(f)$
$x_{hyb}(j,t)$	
$c_{hyb}(j,t)$	
$em_{WtW}(j)$	
$s_{ref}\ (t)$	

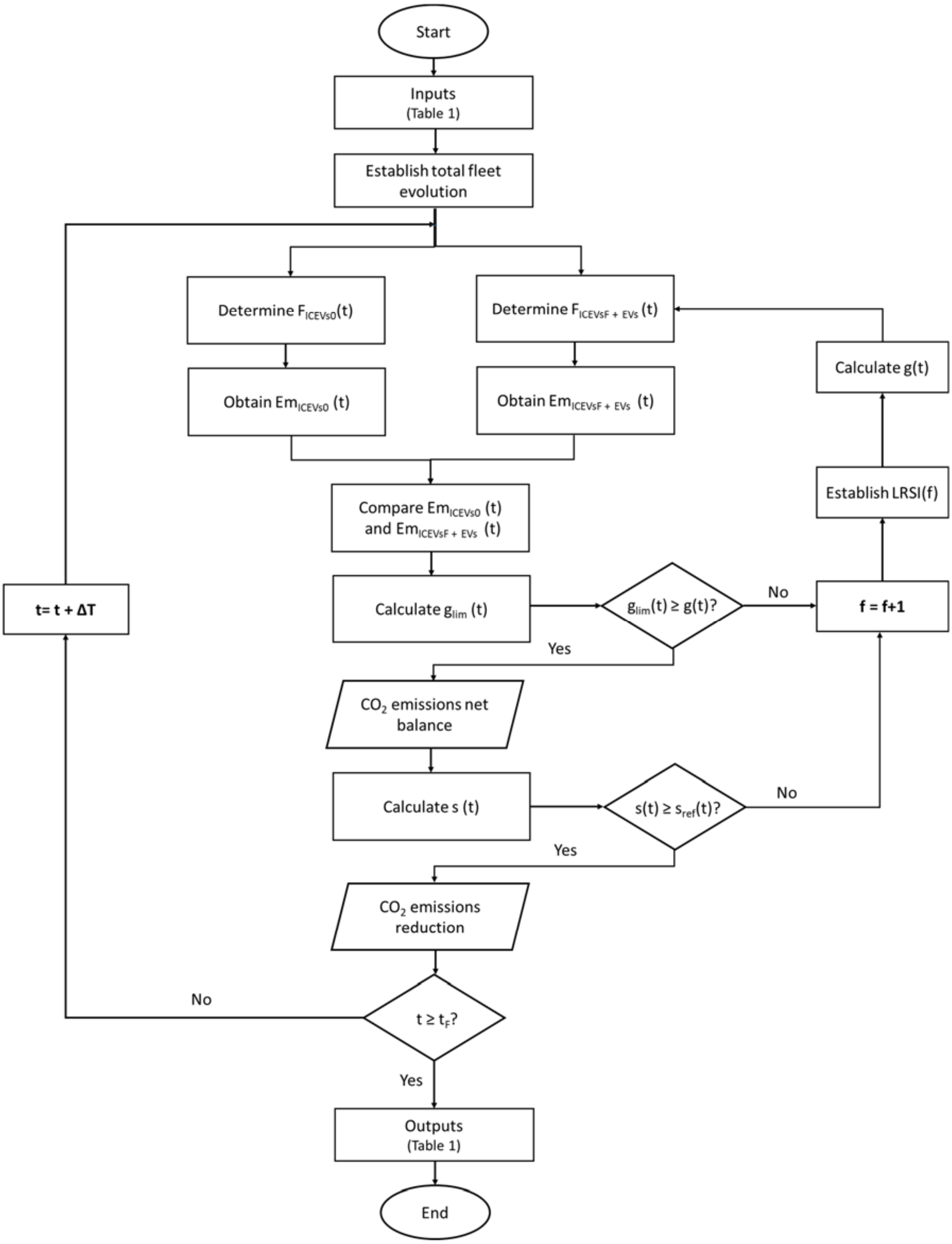


Figure 2. Flowchart of the proposed methodology.

Once the total urban fleet evolution in the considered time period is defined (eq.(1)), the methodology distinguishes two different situations. The first one is a conservative case where the fleet includes only ICEVs without any EVs penetration. This fleet is given by eq. (2)

$$F(t) = \sum_{i} F(i, t - \Delta T) \cdot r(i, t) \tag{1}$$

$$F_{ICEVs_0}(t) = F(t) \tag{2}$$

The second situation reflects the introduction of EVs in the urban fleet. Therefore, it would include the remaining quantity of ICEVs (eq. (3)) together with the different types of EVs introduced (eq. (4)): Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) (Ke et al., 2017). Finally, eq. (5) determines the total fleet in this situation:

$$F_{ICEVs_F}(t) = \sum_{j} \sum_{i} F(t) \cdot \left(1 - f_p(i, j, t)\right) \tag{3}$$

$$F_{EVs}(t) = \sum_{j} \sum_{i} F(t) \cdot f_p(i, j, t) \tag{4}$$

$$F_T(t) = F_{ICEVs_F}(t) + F_{EVs}(t) \tag{5}$$

The second stage of the methodology calculates the total CO_2 emissions generated by the two above-mentioned urban fleets in order to deduce the impact on carbon emissions due to the penetration of EVs. It results of utmost importance to clarify that CO_2 emissions calculated in this section correspond to the real emissions, not to the equivalent CO_2 emissions remaining to greenhouse gases.

The Well-to-Wheel (WtW) method is used to assess these carbon dioxide emissions (Edwards et al., 2007; Ke et al., 2017). The WtW analysis comprises two consecutive stages: the Well-to-Tank stage (WtT), where the emissions due to the processes for extraction, transportation, treatment and provision of the required fuel (electricity in the case of EVs) to be used by the fleet are calculated, and the Tank-to-Wheel stage (TtW), which determines the emissions while driving the vehicles. Table 3 reflects the flowchart of the WtW method.

Table 3. WtW method.

Stages	**ICEVs**	**EVs**
Well to Tank	Extraction and processing of raw materials	Extraction and processing of raw materials
	Transportation and storage	Transportation and storage
	Gasoline / diesel refining	Electricity generation
	Power delivery system (truck, pipelines)	Power transmission and distribution (power grid)
Tank to Wheel	Driving process (fuel combustión)	Driving process

Therefore, depending on the vehicle characteristics, both WtT and TtW emissivity acquire different values (Woo et al., 2017). For vehicles depending totally on fossil fuels, like ICEVs, or partially as HEVs and PHEVs, their WtT and TtW emissivity depends on the type of fuel used: gasoline or diesel. For vehicles depending on electricity, exclusively in the case of BEVs and partially for the PHEVs, WtT emissivity depends on the emissivity of the electricity system (eq. (6)). Moreover, it is the only factor to consider: TtW emissivity acquires null value in this case since driving process involves zero-emissions (Jochem et al., 2015; Manjunath and Gross, 2017; Teixeira and Sodré, 2018).

$$g(t) = \sum_{k} P(k,t) \cdot CI\,(k) \tag{6}$$

Eq. (7) determines the emissions generated by the urban fleet transport based exclusively on ICEVs:

$$Em_{ICEVs_0}(t) = \sum_i F_{ICEVs_0}(i,t) \cdot d(i,t) \cdot c_{ICEVs}(i,t) \cdot em_{WtW}(i) \tag{7}$$

In the case of a fleet with EVs in different penetration levels, eq.(10) determines the total CO_2 emissions. It includes the emissions due to the remaining quantity of ICEVs (eq.(8)), and the corresponding to the EVs (eq.(9)) with two components: the electrical behaviour of BEVs and PHEVs partially and the hybrid behaviour of HEVs and PHEVs partially.

$$Em_{ICEVs_F}(t) = \sum_{i} F_{ICEVs_F}(i,t) \cdot d(i,t) \cdot c_{ICEVs}(i,t) \cdot em_{WtW}(i) \tag{8}$$

$$Em_{EVs}(t) = \sum_j x_{elect}(j,t) \cdot F_{EVs}(j,t) \cdot d(j,t) \cdot c_{elect}(j,t) \cdot g(t) + \sum_j x_{hyb}(j,t) \cdot F_{EVs}(j,t) \cdot d(j,t) \cdot c_{hyb}(j,t) \cdot em_{WtW}(j) = Em_{EVs,elect}(t) + Em_{EVs,hyb}(t) \tag{9}$$

$$Em_T(t) = Em_{ICEVs_F}(t) + Em_{EVs}(t) \tag{10}$$

The introduction of EVs is intended for a decarbonisation of the transport sector. However, the presence of high-CI sources in the electricity generation system could produce the opposite effect: an increase in CO_2 emissions. The methodology calculates the allowable maximum value of the electricity system emissivity (g_{lim}, eq. (12)), below which there will be a positive effect in the reduction of CO_2 emissions. This parameter indicates the upper boundary for the electricity system emissivity of the country under study that ensures a net CO_2 emissions introduction of EVs. This value is deduced by imposing a null value to the CO_2 emission balance given by eq.(11) as the difference between the emissions saved by the EVs penetration and the produced ones by the electricity consumption.

$$\left\{Em_{ICEVs_0}(t) - \left[Em_{ICEVs_F}(t) + Em_{EVs,hyb}(t)\right]\right\} - \left\{Em_{EVs,elect}(t)\right\} = 0 \tag{11}$$

$$g_{lim}(t) = \frac{Em_{ICEVs_0}(t) - Em_{ICEVs_F}(t) - Em_{EVs,hyb}(t)}{\sum_j x_{elect}(j,t) \cdot F_{EVs}(j,t) \cdot d(j,t) \cdot c_{elect}(j,t)} \tag{12}$$

The degree of sustainability due to the substitution of ICEVs by EVs can be determined by the relative reduction in CO_2 emissions, which is calculated by eq. (13):

$$s(t) = \frac{Em_{ICEVs_0}(t) - Em_{ICEVs_F}(t) - Em_{EVs,elect}(t) - Em_{EVs,hyb}(t)}{Em_{ICEVs_0}(t)} \tag{13}$$

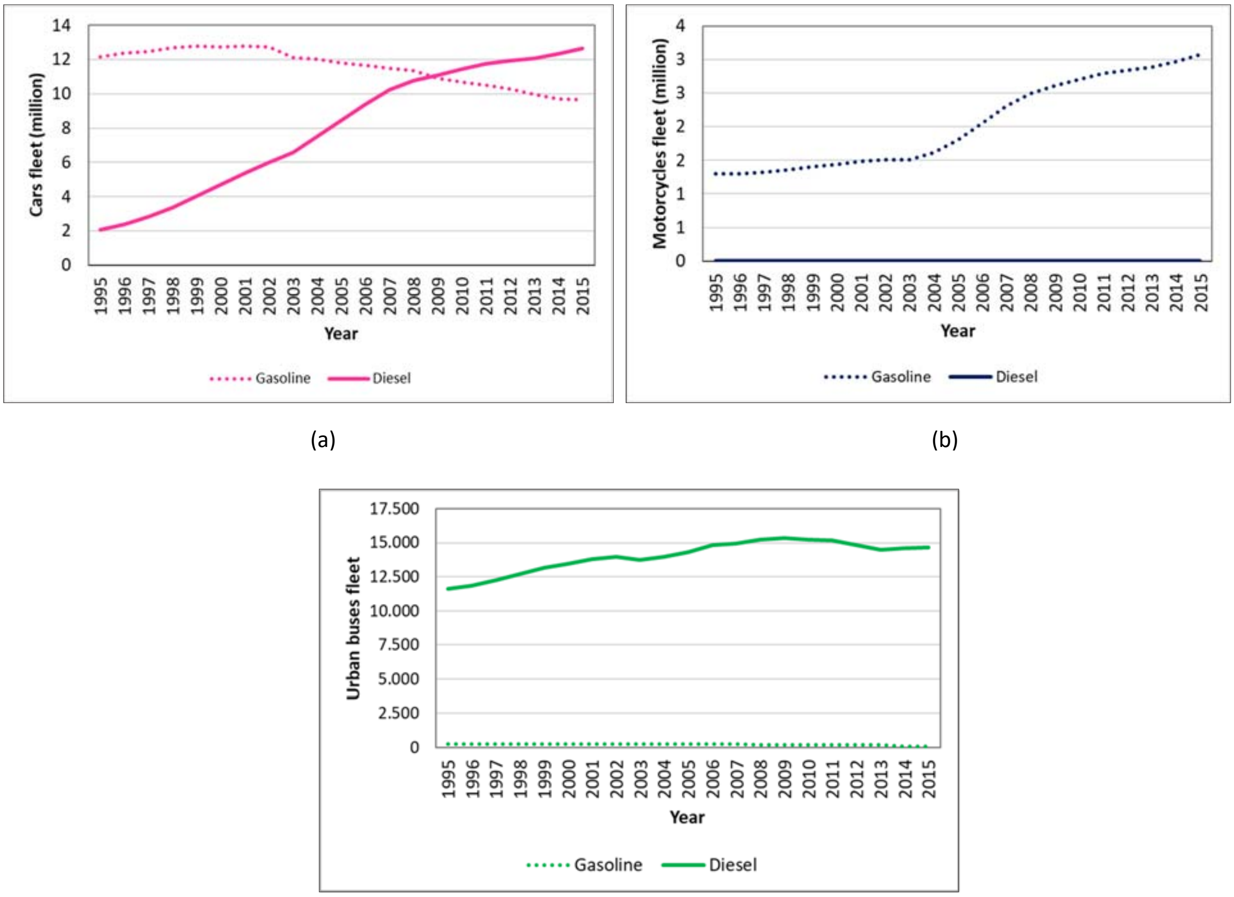
The methodology includes an iterative process in order to verify at any time two constraints: first, to determine an electricity generation system with an emissivity below the maximum value and, in the second place, given a certain level of emissions reduction, find the corresponding electricity generation system.

3. Case study: Spain by the mid-term future

This paper applies the previously explained methodology to the Spanish case study by the mid-term future: from 2016 to 2040. Spain foresees an ever-increasing electrification of the urban fleet in the medium-term, together with a stepped introduction of renewable sources in the electricity system (IDAE, 2020). This chapter describes the effect of both implications regarding EVs introduction, namely BEVs, PHEVs and HEVs.

3.1. Fleet evolution

The research focuses the methodology on the Spanish urban transport fleet, including therefore three types of vehicles: cars, motorcycles and urban buses. Although in different proportion, the three types of vehicles have traditionally used fossil fuels like gasoline or diesel (ICEVs). In 2015, 43% of the cars were gasoline cars and 57% diesel cars, whereas diesel urban buses and gasoline motorcycles had a presence of 99% each (DGT, 2017). Following historical data (DGT, 2017), shown on Figure 3, a linear extrapolation was made to estimate the expected rate of growth of these ICEVs until 2040 (Table 4). This fleet does not include the introduction of EVs and conforms the first case fleet (Case 1). According to the methodology, this fleet would also match the total urban fleet evolution and consequently, the rate of growth of ICEVS would also match the rate of growth of the total fleet. Due to the unrepresentative influence of gasoline urban buses and diesel motorcycles, they are not considered in this research.



(a)

(b)

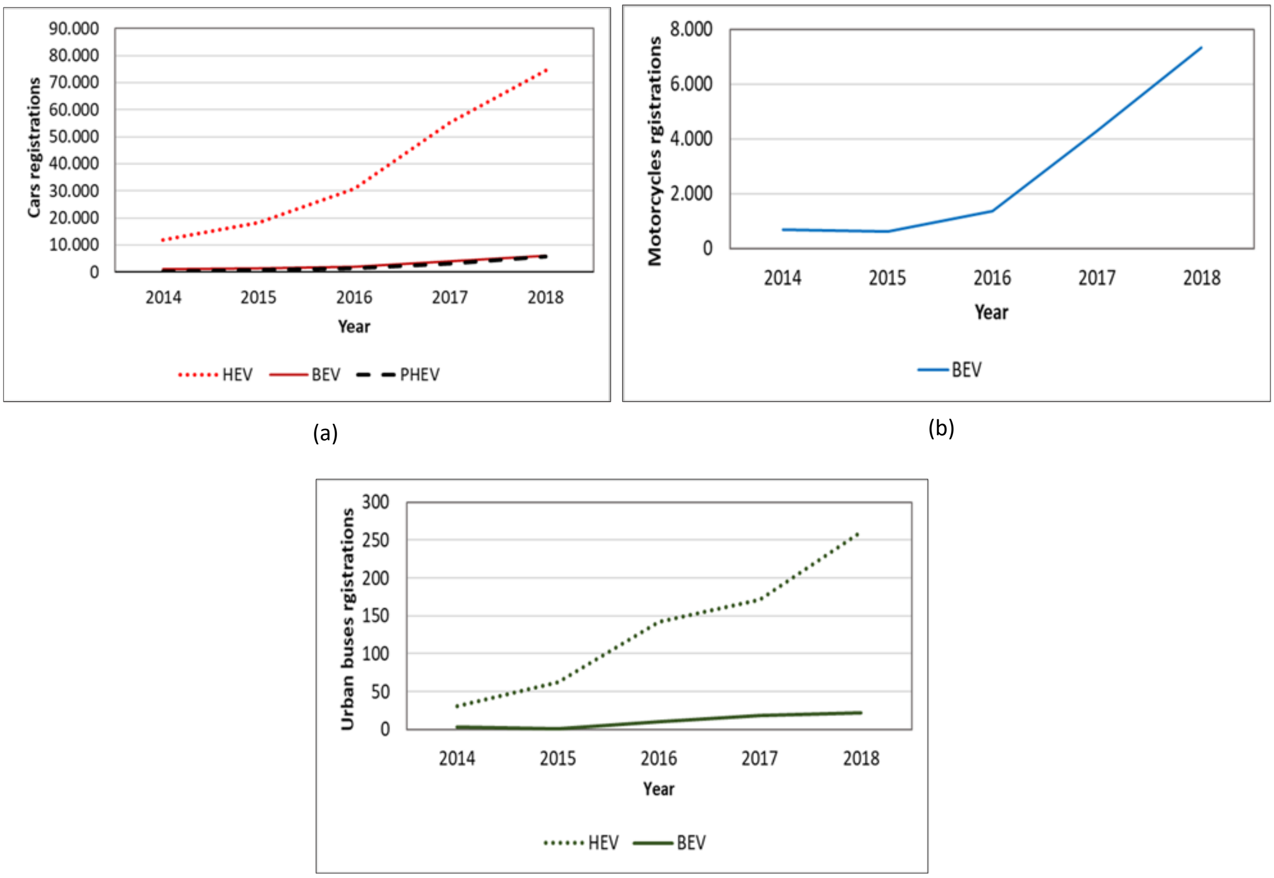
(c)

Figure 3. Spain ICEVs' historical data. (a) Cars. (b) Motorcycles. (c) Urban buses.

Table 4 . Spain ICEVs initial fleet and rate of growth. Case 1.

		Gasoline car	Diesel car	Gasoline motorcycle	Diesel bus
2016	Initial fleet	9820553	13038663	3201831	14986
2020	Rate of growth (%)	11.6	11.6	11.3	4.5
2024		6.6	6.6	11.1	4.3
2028		6.5	6.5	10	4.1
2032		5.8	5.8	9.1	4.0
2036		5.5	5.5	8.3	3.9
2040		5.2	5.2	7.7	3.7

Regarding EVs, in 2018 electric cars, electric urban buses and electric motorcycles represented just a 1%, 1.7% and 0.4% of their corresponding fleet respectively (DGT, 2017; REE, 2018). Despite this small influence, their registrations have experienced a large increase since 2014 (ANESDOR, 2019; ANFAC, 2018), like Figure 4 shows:



(a)

(b)

(c)

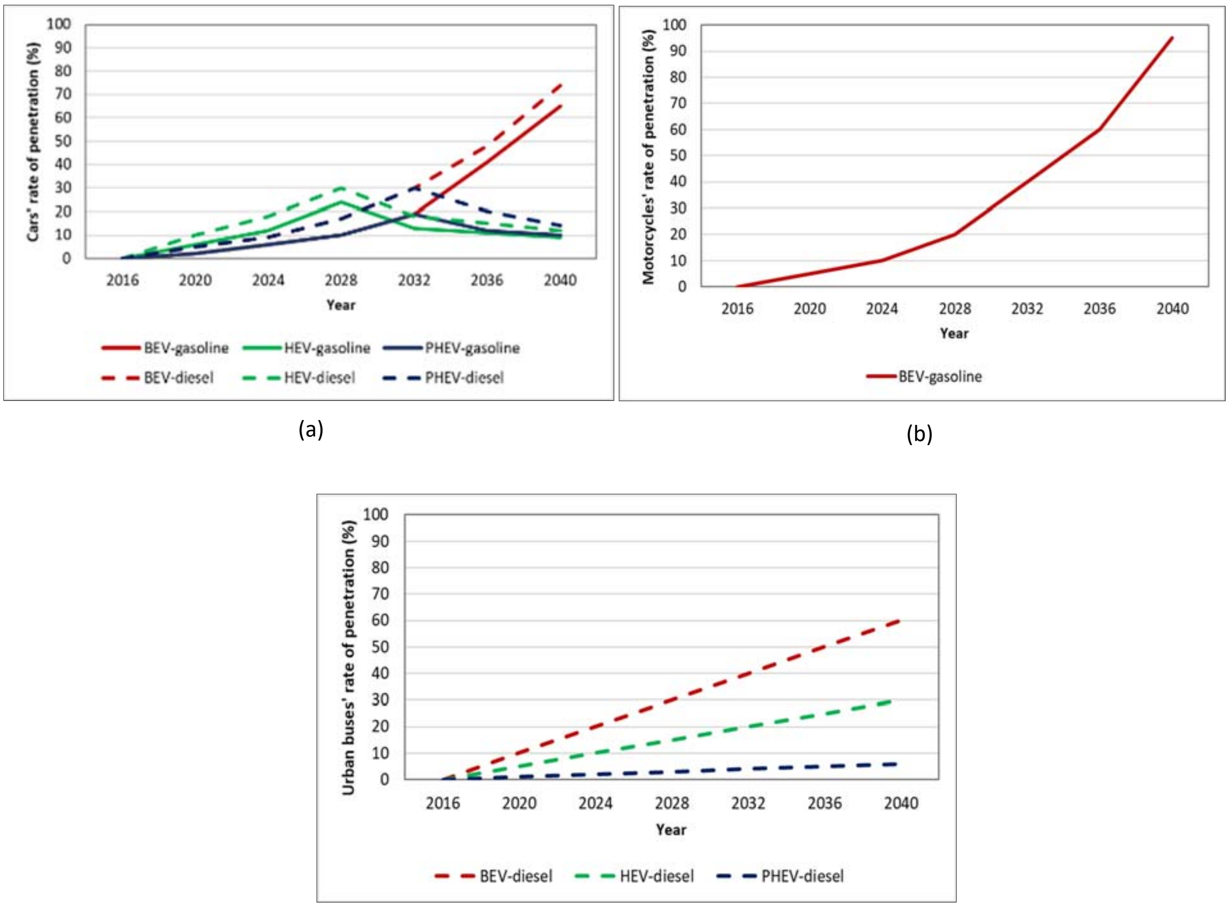
Figure 4. Registrations of EVs in Spain. (a) Cars. (b) Motorcycles. (c) Urban buses.

This trend forecasts a high penetration of EVs in the Spanish fleet for the medium-term future, also motivated by the environmental policies documented on (IDAE, 2020; PNIEC, 2019) and the aged current fleet of LEVs (12.4 years) (ANFAC, 2018) and partially urban buses (8 years) (Spanish Ministry of Development, 2016). The draft, proposed by the Ecological Transition Spanish Ministry, forbids the sale and registration of light vehicles producing CO_2 emissions by 2040, and their driving by 2050. Considering both phenomena, we propose the second case fleet (Case 2), which contemplates the introduction of EVs with different rates of penetration. These rates are now defined and Figure 5 details them.

Regarding cars, BEVs are expected to suffer an exponential growth in the coming years. Despite their slow growth of registrations during last years (Figure 4 (a)), the above mentioned prohibition would make BEVs cars the only legal ones to be sold and registered by 2040 and to be driven by 2050, so that an exponential increase of their fleet is awaited. Referring to HEVs cars, their current trend of registration (Figure 4 (a)) together with their wide proven technology forecasts a considerable and almost linear penetration of this kind of cars for the coming years. However, as they generate CO_2 emissions, their contribution to the fleet is expected to decrease in the last years of the studied period due to (IDAE, 2020; PNIEC, 2019) environmental restriction. With reference to PHEVs cars, their rate of registrations during last years is similar to the BEVs' (Figure 4 (a)), so we consider their introduction would match BEVs' one for the first period considered. Nonetheless, as PHEVs cars also generate CO_2 emissions, their sale and later driving prohibition would determine the decrease of their fleet during the last years of the period. Finally, the penetration levels of BEVs, HEVs and PHEVs cars would be higher replacing diesel ICEVs cars than gasoline ones. This consideration relates to the recent environmental policies restricting the use and registration of diesel cars (IDAE, 2020) due to the air quality damaging NOx particles that they generate.

When talking about electric motorcycles, only BEVs should be considered (ANESDOR, 2019). Their expected growth follows a similar behavior to that of BEVs cars', since they are also light vehicles and restriction (IDAE, 2020) affects them too. Therefore, an exponential introduction of BEVs motorcycles is forecasted. However, it would be stronger than BEVs cars' since this type of EVs is the only one expected for motorcycles (Figure 4 (b)).

Referring to urban buses, the above described prohibition would not affect them since they are heavy vehicles. On the one hand, this situation would make HEVs buses fleet increase in a linear way during all the period, considering their registration historical data trend. On the other hand, BEVs buses would experience a higher introduction than HEVs due to their independence on fossil fuels and the increasing environmental concerns, despite their slow registration growth in the recent years (Figure 4 (c)). With regard to PHEVs, currently there are not urban buses of this nature. Nevertheless, their good performance in the pilot project of Gothenburg (Sweden) (Hu et al., 2013) enhanced our decision on considering their slow and linear introduction in the studied period.



(a) (b)

(c)

Figure 5. Rates of EVs penetration. (a) Cars. (b) Motorcycles. (c) Urban buses.

The forecasted penetration of EVs hereby presented answers also to the European regulations in terms of electric mobility. The legislation stablishes the maximum emissions limit in 95 g CO_2/km for new vehicles from 2020 (UE, 2019). From 2025, the minimum share of EVs for manufactures will increase up to 25% and in 2035 the sale and registration of EVs will be forbidden. According to this general framework, some European countries have fixed future objectives about the penetration of EVs in their societies, for example Norway and Germany.

On the one hand, Norway stands as the first country to have stablished a 100% electric mobility plan for the coming future (Ingeborgrud and Ryghaug, 2019), where the EVs' sales represented a 52.17% of the market share in 2017. Their mobility plan stablishes that all the light vehicles and urban buses should be transformed to EVs before 2025. The hereby-presented study for Spain follows the same trend (a complete transformation of light electric vehicles and urban buses into EVs), but stablishes this objective by 2040. Authors considered this further scenario concerning the low percentage of EV's sale in 2017 (0.69% of the market share) (ANFAC, 2018).

On the other hand, Germany also stands as another European country with an ambitious plan to achieve electric mobility. The German Government initiated the National Development Plan (The German Federal Goverment, 2009) in 2009, with the target of achieving one million of EVs in 2020. This goal was finally delayed to 2023. Moreover, the German Government has recently approved a financial package of 130.000 million of euros to boost the purchase of BEVs (PHEVs and HEVs are not included). This measure drives the development of BEVs, since these EVs are the only ones to produce zero emissions while riding, unlike HEVs or even PHEVs. This aim matches the general trend of the study presented in this paper, where the introduction of BEVs increases in the highest percentage.

3.2. Fleet input parameters

The application of the methodology to the case of Spain requires the definition of the fleet input parameters: consumption data, rate of electrical and hybrid contribution, annual travel distances and WtW emissivity. Moreover, this research distinguishes between the nature of the vehicles, taking cars, motorcycles and urban buses into consideration due to their ever-increasing electrification in urban environments (Mutter, 2019; Scarinci et al., 2019; Zheng et al., 2019).

Consumption data for the vehicles were obtained after an extensive scientific review: (Huo et al., 2015, 2010; Shen et al., 2014; Wu et al., 2012) for cars and motorcycles and (Gallet et al., 2018; IDAE - UE, 2019; IDAE, 2006; Wu et al., 2019) for urban buses. Regarding ICEVs, studies (Tietge et al., 2016a) and (Tietge et al., 2016b) revealed the significant difference between certified consumption values and the real ones due to high demanding conditions of current roads, showing an increasing divergence between them along the years. Specifically, these researches showed the evolution of both certified and real consumption data of a broad range of ICEVs along these last years, also affected by the enhancement of engine technologies. Finally, a linear extrapolation made on such data allowed authors to stablish an increase of 35% in the certified fuel economy of ICEVs for 2040. Regarding EVs, studies (Huo et al., 2015; Shen et al., 2014) also reflected the higher consumption of such vehicles under real conditions in comparison with laboratory conditions. However, the improvement of the technologies for EVs is not expected to happen in a wide range due to its innovative character (Dong et al., 2019; Huo et al., 2010), which led to a final increase of 45% in the certified consumption data for EVs.

Table 5 reflects these consumption data, for both ICEVs and EVs, expressing fuel consumption in l/100 km and electrical consumption in kWh/100 km. Additionally, authors reflected these data in equivalent units (kWh_{eq}/100km) in Table 6 to enable the comparison of consumption values, according to (Academic Press, 2017).

Referring again to EVs, particularly to PHEVS, their double behaviour determines the necessity of defining the rate of electrical and hybrid contribution to the consumption of each vehicle. In this paper, we have assumed an homogenous hypothesis, where both the hybrid and electric operation have the same weight: 50% (Ke et al., 2017). Table 5 [b] shows this parameter.

The average annual travelling distances for each type of vehicles (cars, motorcycles and urban buses) corresponded to official registered data. Hence, Spanish databases (INE, 2018) and (Spanish Ministry of Development, 2016) were used to determine light EVs and urban buses' annual travel distances respectively. Lastly, Table 5 reflects these data.

Table 5. Fleet parameters. Note: l/100 km for fuel consumption and kWh/100 for electrical consumption.

	Distance (km/year)	Consumption						
		ICEV gasoline (l/100 km)	ICEV diesel (l/100km)	BEV (kWh/100 km)	HEV gasoline (l/100km)	HEV diesel (l/100km)	PHEV[b] (kWh/100 km)	(l/100km)
Cars	12500	9	5.7	20	5.1	-[a]	20.0	5.1
Motorcycles	6300	4.2	- [a]	9.1	- [a]	- [a]	-[a]	-[a]
Urban Buses	143000	-[a]	37.1	160	- [a]	27.5	160	27.5

[a]: not considered due to its irrelevant presence (ANESDOR, 2019; ANFAC, 2018).

[b]: assuming 50% for both the hybrid and electric operation (Ke et al., 2017).

Table 6. Fleet parameters. Note: kWh_{eq}/100 km for consumption data.

	Distance (km/year)	Consumption (kWh_{eq}/100 km)						
		ICEV gasoline	ICEV diesel	BEV	HEV gasoline	HEV diesel	PHEV[b] (electric)	(fuel)
Cars	12500	82.3	56.8	20	46.6	-[a]	20.0	46.6
Motorcycles	6300	38.4	- [a]	9.1	- [a]	- [a]	-[a]	-[a]
Urban Buses	143000	-[a]	370	160	- [a]	274.2	160	274.2

[a], [b]: equal to Table 5.

Emissions for vehicles dependent on fossil fuels (ICEVs, HEVs and PHEVs partly) just depend on the kind of fuel used: gasoline or diesel. Research (Woo et al., 2017) made a thoughtful study of JEC's Well-to-Wheel CO_2 emissions data (Hass et al., 2014) to determine such parameters. JEC arises as one of the most complete and updated source, since it compiles European data and researches from different European entities: EUCAR (European Council for Automotive R&D), JRC (Joint Research Center of European Comission) and CONCAWE (CONservation of Clean Air and Water in Europe). Hence, (Woo et al., 2017) establishes that WtW emissivity for gasoline is 2778.2 g CO_2/L (WtT: 2314.4 g CO_2/L and TtW: 463.8 g CO_2/L) and for diesel it rises until 3241.3 g CO_2/L (WtT: 2676.9 g CO_2/L and TtW: 564.4 g CO_2/L). Table 7 finally summarizes WtW emissivity for each kind of vehicle dependent on fuels.

Table 7. WtW emissivity for vehicles dependent on fossil fuels (g CO_2/L).

	ICEV gasoline	ICEV diesel	HEV gasoline	HEV diesel	PHEV[b]
Cars	2778.2	3241.3	2778.2	-[a]	2778.2
Motorcycles	2778.2	-[a]	-[a]	-[a]	-[a]
Urban Buses	-[a]	3241.3	-[a]	3241.3	3241.3

[a]: not considered due to its irrelevant presence (ANESDOR, 2019; ANFAC, 2018).

[b]: partly dependent on fossil fuels.

Conversely, WtW emissivity for vehicles dependent on the power system (BEVs and PHEVs partly) vary with the structure of the electricity generation system. Hence, section 3.3 describes different configurations for the system depending on the degree of renewable sources introduction.

3.3. Levels of renewable sources introduction in the electricity mix

Unlike vehicles dependent on fossil fuels, the configuration of the power system directly affects emissions for vehicles dependent on electricity: BEVs and PHEVs partly. In this research, we propose five different levels of renewable sources introduction (LRSI) in the Spanish power system to achieve a net decrease in CO_2 emissions by the introduction of EVs. Hence, the configuration of the system moves from the current one to a total renewable configuration. This evolution answers to the forecasted composition of the power system considering the environmental policies proposed by the Spanish Government (PNIEC, 2019). This plan aims to achieve a 74% renewable sources introduction in the electricity generation mix by 2030 and a 100% renewable one by 2050. Moreover, the decision making process for each LRSI lies not only in the just mentioned draft, but also in the historical evolution of electricity generation and primary sources contributions to the Spanish electricity system (IEA, 2016), represented by Figure 6 and Figure 7 respectively.

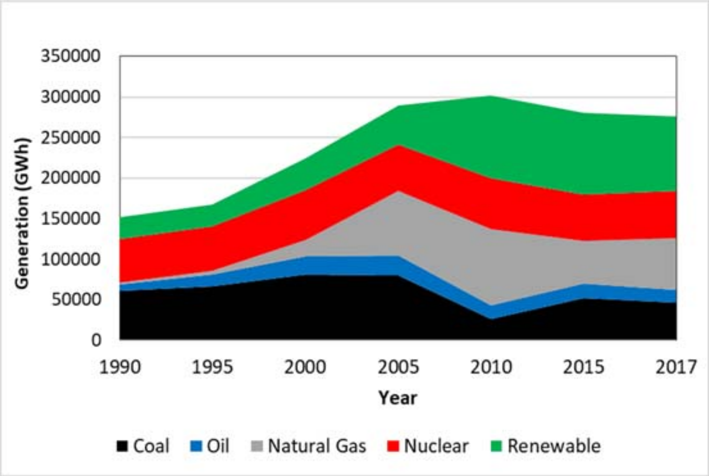


Figure 6. Evolution of electricity generation in Spain.

The first level of renewable sources introduction (LRSI (1)) that we studied corresponds to the current and real one for Spain, with a 27.1% of renewable sources contribution.

LRSI (2) includes an electricity mix derived from the first LRSI where coal resource has null influence, being its contribution supported by the rest of the power sources in a balanced way, except for nuclear. Therefore, renewable sources have a presence of 38.8%. This LRSI (2) reflects the decreasing trend of coal contribution (Figure 7), mainly caused by the expected progressive close of thermal power plants. The process matches European Environmental Requirements 2010/75/UE (UE, 2010) together with the higher CO_2 right of emission price (BOE, 2019) and gradual decarbonization of Spanish electricity generation system (IDAE, 2020; PNIEC, 2019). Moreover, the exclusion of nuclear power plants in redistribution of coal's influence among other sources is in line with no increasing nuclear power plants generation, also reflected in the static growing of nuclear contribution to the mix (Figure 7). Besides, Ecological Transition Spanish Ministry and main electric companies reached an agreement of gradually closing all nuclear power plants in the country (Spanish Nuclear Industry Forum, 2019).

Hence, LRSI (3) reflects this situation with an electricity mix derived from the second LRSI, where also nuclear generation is removed by the year 2028. Its contribution would be covered by renewable resources, which would follow their increasing trend in the Spanish primary sources contributions (Figure 7). This growth answers to the long-term objective of achieving a complete renewable electricity generation mix in a stepped way and also to the first proposed percentage of renewable sources introduction: 74%.

In line with this trend, LRSI (4) derives from the third LRSI and eliminates oil contribution to the electricity mix, being renewable sources responsible for covering its contribution.

Finally, LRSI (5) arises with a 100% renewable sources contribution, achieving a total descarbonizated electricity generation mix (IDAE, 2020; PNIEC, 2019).

Table 8 reflects all the Spanish environmental policies hereby presented.

Table 8. Spanish environmental policies for the ecological transition.

Gradual introduction of renewable sources in the electricity mix	
Spanish climate change draft law (PNIEC, 2019) *2030: 74% of renewable contribution to the mix* *2050: 100% renewable contribution to the mix.*	
Gradual close of thermal power plants	
European Environmental Requirements 2010/75/UE (UE, 2010) *Restrictive limits for the industrial emissions of thermal power plants. Adaptation before 2020.*	European Emissions Trading Scheme (UE, 2020) *Restrictive CO_2 right of emission prices.*
Gradual close of nuclear power plants	
Agreement between Ecological Transition Spanish Ministry and main electric companies (Spanish Nuclear Industry Forum, 2019) *Progressive close until 2040.*	

Table 9 summarizes the contribution of each energy source to the electrical mix of Spain for every LRSI. Although the total renewable generation increases with each LRSI, the contribution of each individual renewable source to the total renewable production remains constant irrespective of the LSRI analysed. Such contribution matches current renewable sources data of (IEA, 2016), also represented in Figure 8.

Every LRSI studied in this paper results completely achievable due to the high presence of renewable resources in the country. Specifically, south-east Spanish regions present more than 1950 annual solar peak hours and vast desert zones to install solar PV systems (Bastida-Molina et al., 2019), whereas more than 118.000 km^2 of the Spanish territory enjoy from suitable wind resources (80 m, speed > 6 m/s) and the total available potential biomass results in 18.715.358 ton/year (IDAE, 2019). Besides, Spain has currently 876 MW of hydropower plants (Acciona, 2020).

Table 9. Contribution of each power source.

	Coal (%)	Nuclear (%)	Oil (%)	Natural Gas (%)	Renewable (%)
LRSI (1)	19.6	35.1	6.7	11.5	27.1
LRSI (2)	0	35.1	9.6	16.5	38.8
LRSI (3)	0	0	9.6	16.5	73.9
LRSI (4)	0	0	0	16.5	83.5
LRSI (5)	0	0	0	0	100

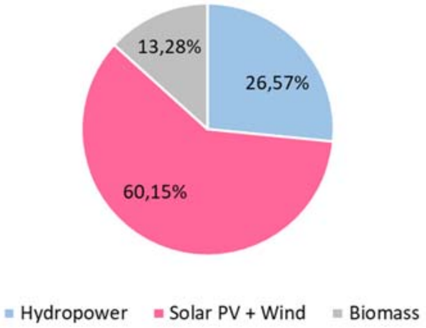


Figure 8. Contribution of each renewable source to the total renewable electricity generation.

CI of each power source will determine the emissivity of the power system due to each configuration (eq. (6)), which also will match WtT emissivity for BEV and PHEV partly. A wide study on CI considering an average value for each source is available on (Turconi et al., 2013; Woo et al., 2017) and Table 10 summarizes the results . The different CI for each renewable source together with its weighted contribution to the total renewable generation (Figure 8) will finally establish the CI for the total renewable generation.

Table 10. CI of each power source.

						Renewables			
		Coal	Nuclear	Oil	Natural Gas	Solar PV	Wind	Biomass	Total
CI (g CO_2/kWh)	Min	660	3.1	530	380	13	3	1	10.29
	Max	1370	35	890	1000	190	41	130	161.52
	Average	942.33	12.23	773.8	533.17	65.05	17.63	51.02	58.69

Table 11. Emissivity for each LRSI (g CO_2/ kWh).

LRSI (1)	318.1
LRSI (2)	189.2
LRSI (3)	205.5
LRSI (4)	136.9
LRSI (5)	58.7

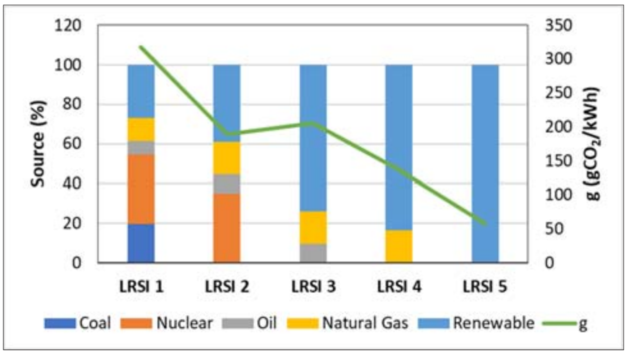


Figure 9. Contribution of each power source and emissivity for different LRSI.

4. Results and discussion

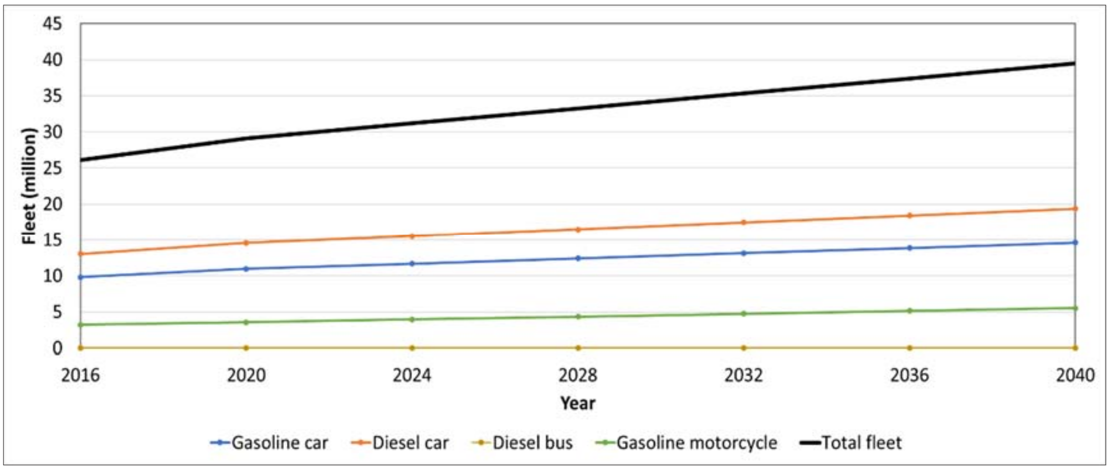
This section presents the results for the application of the submitted methodology to the Spanish case in the mid-term future. Two different scenarios were analyzed. On the one hand, the first one corresponds to a conservative situation where only a net emissions balance with the introduction of EVs is looked for (Huo et al., 2015; Moro and Lonza, 2018) along the period of study. Although on-going environmental changes make this situation an almost difficult to happen in the future (IDAE, 2020; PNIEC, 2019), it shapes an interesting point of comparison with the second scenario in regard of sustainability. On the other hand, the second scenario contemplates not only a net CO_2 emissions balance, but also a considerable reduction in emissions with the penetration of EVs. We propose a progressive degree of decrease in these reductions along the period of study for scenario 2 (Table 12).

Table 12. S_{ref} (%)

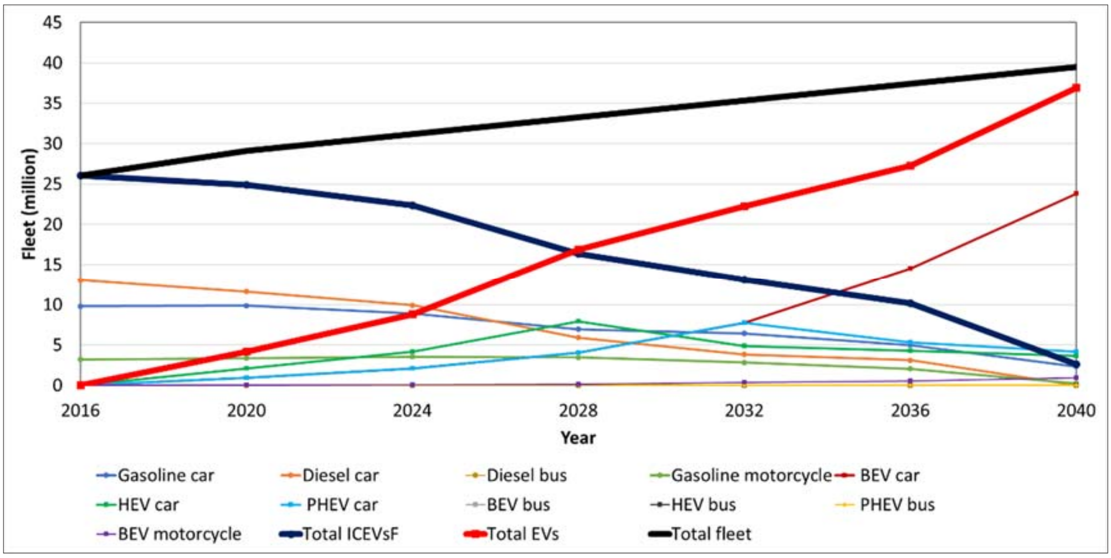
	Scenario 1	Scenario 2
2016	0	0
2020	0	10
2024	0	20
2028	0	30
2032	0	40
2036	0	55
2040	0	70

4.1. Fleet into consideration

Following the methodology proposed in this paper and the constrains presented for the case study, we can deduce the total number of vehicles conforming the urban fleet along the period of study. Figure 10.a. represents the evolution of the fleet that does not include EVs (case 1), whereas Figure 10.b. does for the fleet that considers EVs (case 2). In both cases, the total fleet presents the same linear growth where cars' influence is the highest one, meanwhile urban buses' influence becomes the lowest. Despite the linear growth of ICEVs for the first case, the second case indicates how this kind of vehicles decreases in almost a linear way when EVs are introduced, so that the latter would finally represent 93% of the total urban fleet by 2040.



(a)



(b)

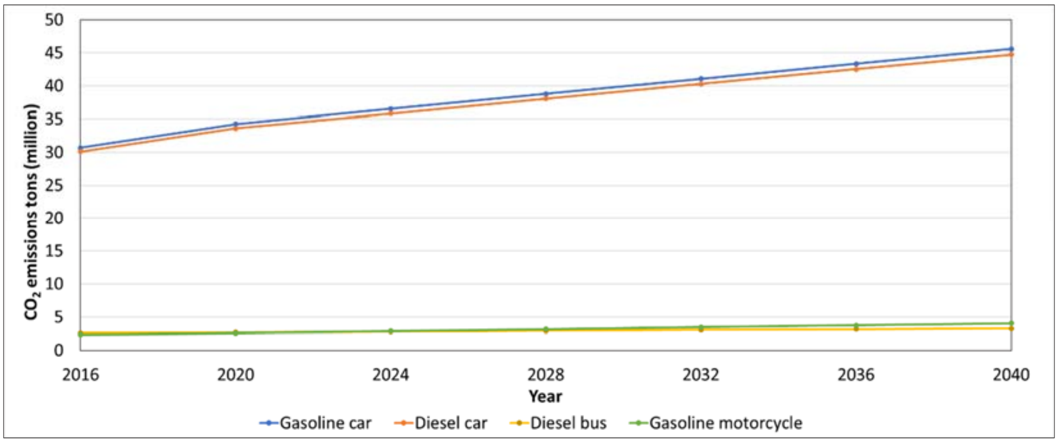
Figure 10. Fleet's evolution. **(a)** Case 1. **(b)** Case 2.

4.2. CO_2 emissions and sustainability verification

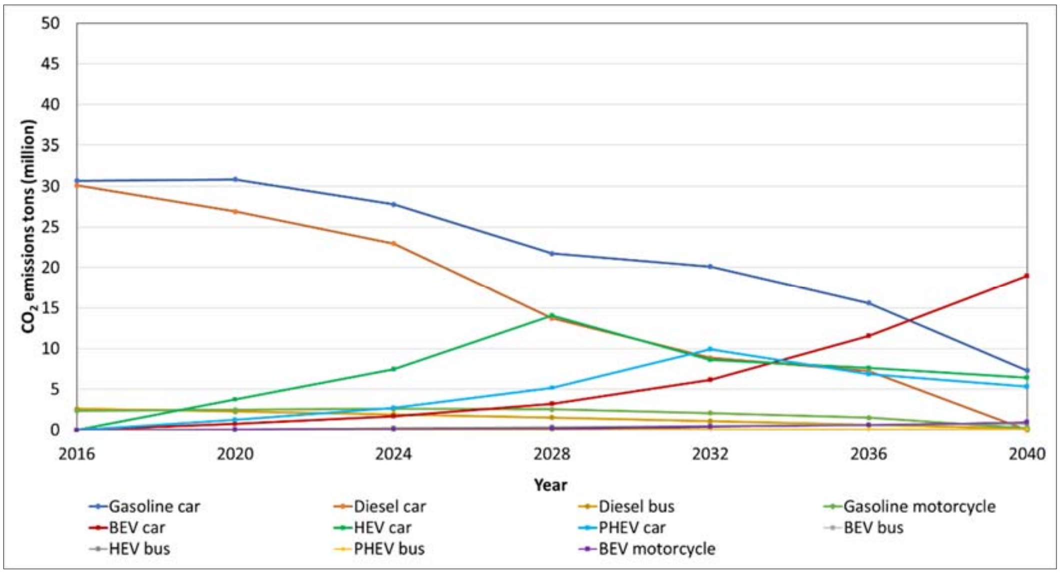
Scenario 1

The application of the iterative methodology explained in section 2 to the first scenario, where only a net CO_2 emissions balance with the introduction of EVs was looked for, indicates that the current emissivity of the system (LRSI (1)) matches this condition for the entire interval. Hence, the electricity emissivity could remain constant along the period of study.

Regarding total CO_2 emissions, Figure 11 illustrates the contribution of each type of vehicle to the emissions generated by the urban transport along the period of study. For the first case where no EVs are considered (Figure 11.a), both diesel and gasoline cars would clearly generate the highest quantities of carbon dioxide emissions in a similar proportion. For the second case, which considers the penetration of EVs in the urban transportation system (Figure 11.b) again cars would have the highest contribution to the CO_2 emissions, but in this case, the different nature of these vehicles should be analyzed. ICEVs cars would generate the largest quantities of CO_2 emissions during almost the whole period, although with a decreasing trend due to their also decreasing rate of growth. Meanwhile, BEVs cars would increase their contribution to the emissions following their exponential rate of penetration, overtaking diesel cars' emissions by 2034 and gasoline cars' by 2038. PHEVs and HEVs would also have a considerable influence on emissions during the middle term of the period, following therefore their trend of penetration. Results also reflect the great influence of cars on emissions, being its contribution 92% of the total CO_2 emissions for urban transport.



(a)



(b)

Figure 11. CO_2 emissions. Scenario 1. **(a)** Case 1. **(b)** Case 2.

Taking up the inherent condition to this first scenario about just searching for a net emissions balance in case 2, results from Figure 12 reveal that the current Spanish power system (LRSI (1)) ensures this condition even for an important introduction of EVs. The allowable maximum value of the electricity system emissivity (g_{lim}), decreases from 1493 to 1121 g CO_2/kWh and remains higher than the real emissivity of the current system (318 g CO_2/kWh) along the entire period. The restriction $g_{lim}(t) > g(t)$ is verified along the interval, so that no increases in LRSI become necessary. Hence, the introduction of EVs in such scenario leads to a progressive reduction in urban transport CO_2 emissions (Figure 13). By 2040, carbon dioxide emissions savings acquire their maximum value for this first case: 56 million tons, which represent a sustainability factor of 58%.

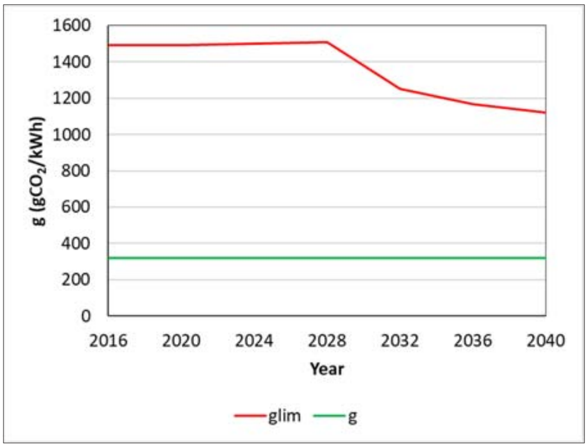


Figure 12. Emissivity of the electricity system. Scenario 1.

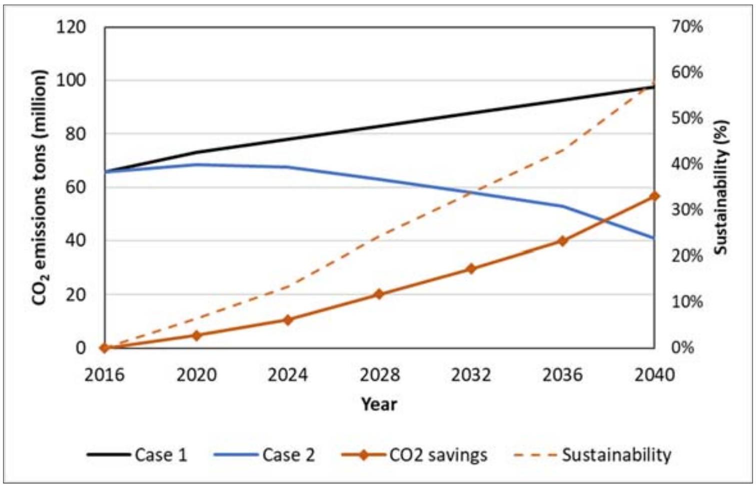


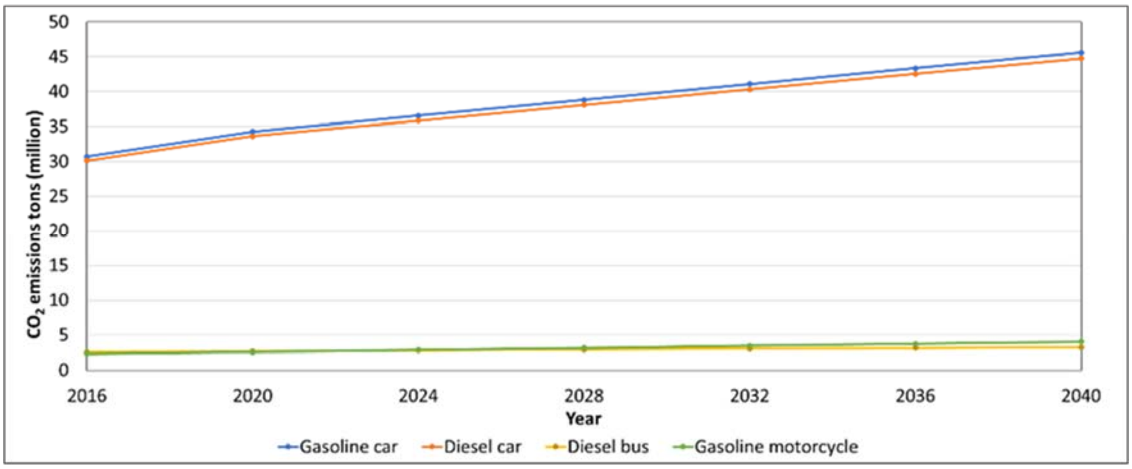
Figure 13. CO_2 savings and sustainability. Scenario 1.

Scenario 2

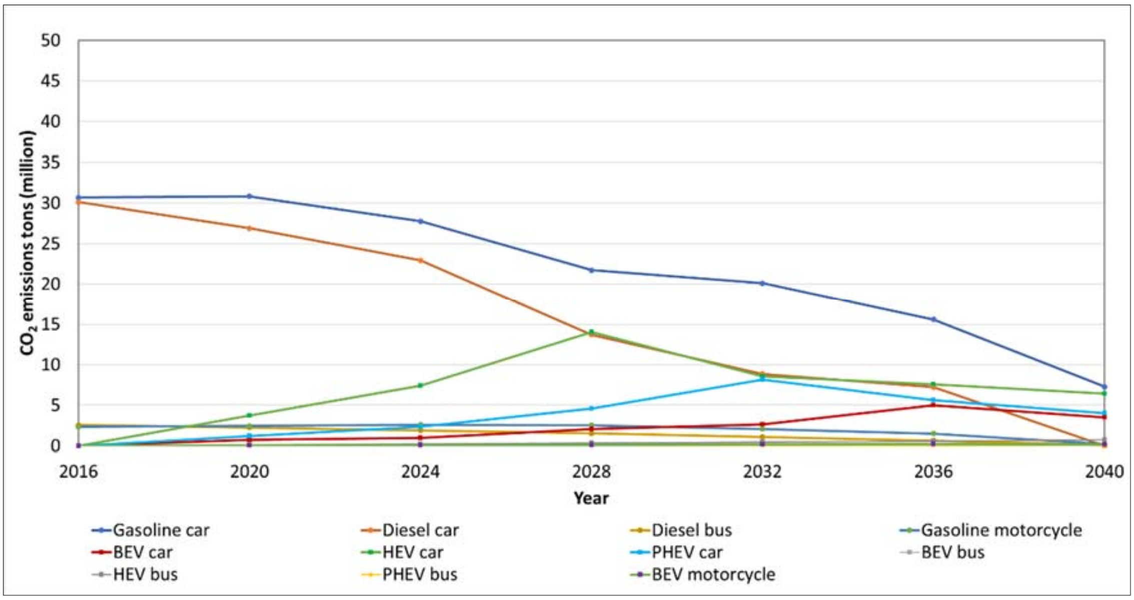
Scenario 2 considers a progressive CO_2 emissions reduction with EVs penetration. Therefore, a stepped introduction of renewable sources into the electrical system is required to match sustainability restrictions (Table 12). Finally, LRSI (5) takes place by 2040, which corresponds to a 100% renewable power system.

Referring to the total carbon dioxide emissions results, Figure 14 reflects the quantity of CO_2 emissions generated by each type of vehicle. The results from the first case (Figure 14.a), where EVs are not considered, do not vary from scenario 1. However, outcomes from the second case, which contemplates EVs introduction into the urban fleet (Figure 14.b) remain constant for all the vehicles types except for the ones dependent on the electricity mix: BEVs and PHEVs.

Besides, in this second scenario again cars contribute the most to CO_2 emissions generation. Both phenomena are reflected particularly during the last years of the period in study: although the emissions of ICEVs gasoline cars are the highest during this last period, the sustainable enhance of the power system decreases the generation of CO_2 emissions for BEVs cars in 82% compared to scenario 1. The same happens to PHEVs cars, although in a softer way due to its partial dependence on the electrical system, so that this reduction becomes 26%.



(a)



(b)

Figure 14. CO_2 emissions. Scenario 2. **(a)** Case 1. **(b)** Case 2.

The current electrical system, with an emissivity of 318 gCO_2/kWh, is already sustainable enough to hold the introduction of EVs in the urban fleet, like results from scenario 1 revealed (Figure 12). However, the second scenario of this research studies concurrently a stepped introduction of renewable sources in the power system to match some reference degrees in emissions reduction (Table 12). Hence, the emissivity of the electricity system would become lower with every LRSI introduction, like Figure 15 reflects. Finally, LRSI (5) takes place by 2040, which corresponds to a 100% renewable power system. With this progressive enhance of the power system, emissions generated by the urban transport would experience a considerable reduction with the penetration of EVs (Figure 16). The highest decrease takes place in the last year of study, 2040, where BEVs experience the largest introduction together with the most sustainable LRSI: 100% of renewable sources. By this year, the savings in carbon dioxide emissions acquiere the value of 74 million tons, which match a sustainability factor of 77%.

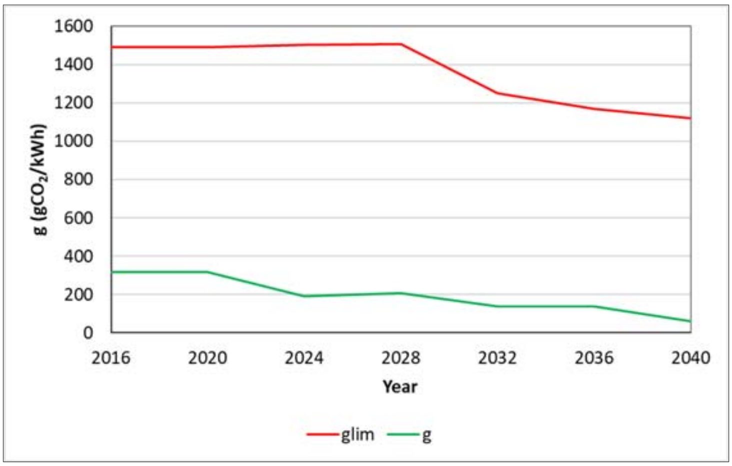


Figure 15. Emissivity of the electricity system. Scenario 2.

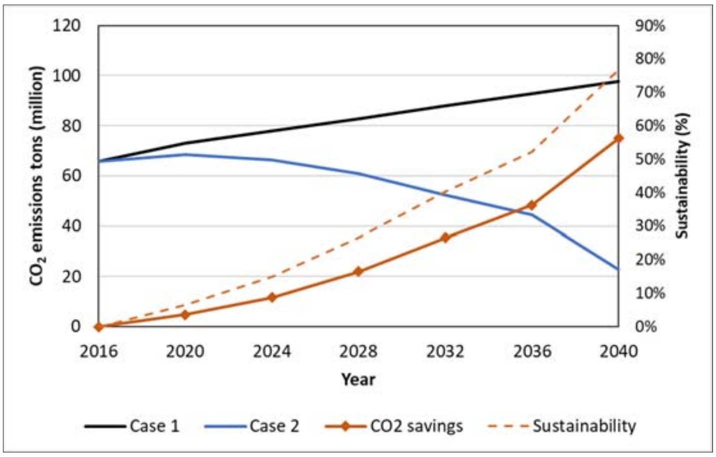


Figure 16. CO_2 savings and sustainability. Scenario 2.

Figure 17 and Figure 18 finally summarize the improvements about moving towards a 100% renewable electricity mix together with the introduction of EVs in the rates of penetrations assumed in these simulations, where by 2040, 93% of EVs are expected to comprise the urban fleet. The emissivity of the electricity system would progressively reduce from 318 gCO_2/kWh to 58.7 gCO_2/kWh in the second scenario, which represents a decrease of 82% compared with the constant value of scenario 1 (Figure 17). Besides, the penetration of EVs proposed in the second scenario leads to higher levels of CO_2 emissions reduction compared with scenario 1. Particularly, the highest decrease takes place in 2040, which corresponds to a 45% and 18 millions tons of carbon dioxide emissions reduction from scenario 1. Moreover, the sustainability factor also enhances in a 33% in scenario 2 for that year (Figure 18).

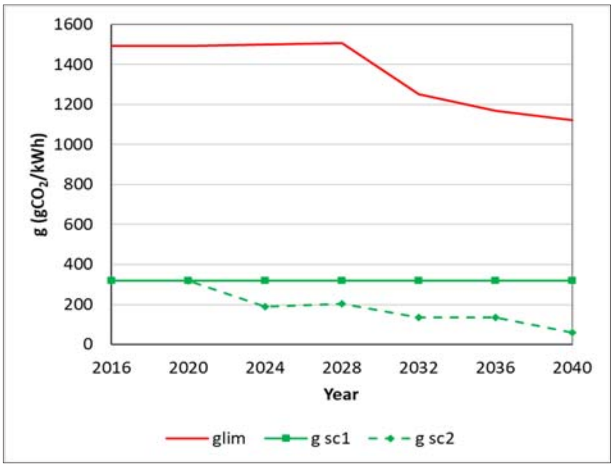


Figure 17. Emissivity of the electricity system. Scenarios 1 and 2.

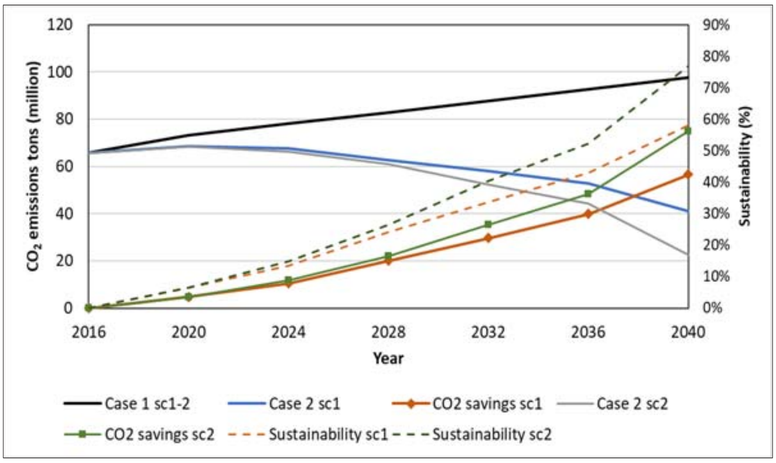


Figure 18. CO_2 savings and sustainability. Scenarios 1 and 2.

4.3. Implications on the reshaping of the electricity load curve and different kinds of charging

The massive introduction of EVs in a society could lead to several problems in the power grid, which have been analysed in various studies. For instance, (Clement-Nyns et al., 2010) demonstrates that a relevant penetration of EVs in the distribution system provokes voltage drops and voltage deviations, which reached 10.3% in the examined case study. Moreover, (Shafiee et al., 2013) states that charging EVs increases the distribution load and consequently the power losses. Besides, such process also increases daily peak load. Hence, (Su et al., 2019) illustrates how the EVs' demand in New Zealand would increase each year, with the consumption concentrated in peak hours. These peak loads are expected to rise until reaching a critical point in 2040, where the highest peak demand would exceed the installed generation capacity of New Zealand in 2018. Considering these issues, several researches have proposed strategies to minimize the impact of EVs in the grid. Their common purpose lies in reshaping the expected electricity demand curve, reducing peak loads and aiming to achieve an almost flat curve. For instance, (Bastida-Molina et al., 2020) proposes a methodology to recharge EVs based on the use of temporal valleys and avoiding peak demand hours in the daily electricity demand to minimize the impact on the grid. This method provides a scheduled optimization of the distribution of recharge between three different recharge strategies: home, public buildings and electrical stations. (Liu et al., 2014) also proposes a timed charging strategy based on spot price for the European Nordic Region, whereas (Limmer and Rodemann, 2019) focuses the reschedule of the recharging activities on dynamic pricing.

Thus, integration of EVs in the grid has been widely addressed. However, there is scarce research regarding the introduction of EVs for public transportation, such as electric buses (EBs). This integration results of utmost importance, since the use of only EVs passenger cars could result in high road congestion (He et al., 2019). Charging systems result vital for the introduction of EVs in public transportation. Hence, four different types of recharging methods arise for EBs: fast plug-in charging, wireless charging, battery swapping stations and pantograph systems. Plug-in charging method corresponds to the traditional method used to recharge private EVs, with three levels of recharge: slow, medium and fast. Due to the high battery capacity of EBs (around 400 kWh), EBs use fast levels of recharge. The wireless charging method allows for battery recharging without connectors, so that EBs have the opportunity to recharge fast and frequently while they are on the roads (Yang et al., 2018). Battery Swapping Stations include stations where users can change their discharged battery for a charged one, so that the recharge becomes faster (Sarker et al., 2015). Finally, the Pantograph System allows EBs to quickly be recharged at bus stops through an automatic connecting system (OPPCharge, 2019).

Some studies have developed load predictions for EBs depending on the charging method. For instance, study (Dai et al., 2014) proposes the forecasting for Battery Swapping Stations based on stochastic modelling, with statistical data of travel patterns. This research also uses neural networks, uniform distributions and Gaussian models to model the hourly number of EBs, starting charging time, travel distance and charging duration. Another study (Mohamed et al., 2017) used a real-time simulation to model EBs in transit networks, considering the transit constraints of Belleville, Ontario and Canada. Besides, (Zhang, 2018) studied a short-term prediction for EBs charging stations using a hybrid model, which combined a least squares support vector machine, fuzzy clustering and wolf pack algorithm. Hence, we find in the literature strong models to deal with the different recharging methods for EBs and their load predictions. These kinds of charging and their different load curves could have an impact on the CO_2 emissions of EBs, depending on the period of the day.

5. Conclusions

This paper introduces a methodology that verifies the sustainable introduction of EVs in terms of CO_2 emissions. By means of the “Well-to-Wheel” (WtW) tool, it makes a comparison between emissions generated by two fleets: one completely formed by ICEVs and another one that contemplates the introduction of EVs: BEVs, HEVs and PHEVs. Main contributions of this methodology are the following.

- Firstly, the method determines the sustainability of the power system in question to ensure at least a net emissions balance while introducing the fleet of EVs.
- Once this first step is verified, the methodology is able to establish a particular level of emissions reduction through a sustainability factor.

- Lastly, this research proposes a stepped introduction of renewable sources in the power system to achieve last mentioned goals. Hence, different levels of renewable sources introduction (LRSI) take place.

The methodology has been applied to the case study of Spain for the medium-term future, until the year 2040. This country is currently experimenting an ecological transition, where two environmental policies stand out: a progressive electrification of the urban transport sector and a stepped introduction of renewable sources in the electricity mix until 2050. We applied therefore the proposed methodology to the Spanish urban transport. The study proposes five different electricity generation systems, moving from the current electrical system to a total renewable one. Finally, two scenarios for the application of the methodology to the Spanish case were studied: one in which only a net emissions balance is looked for and another one in which also a particular sustainability degree in terms of emissions reductions is proposed, both regarding the introduction of EVs in the urban fleet.

Results for scenario 1 indicate the following:

- The emissivity of the system, 318 g CO_2/kWh, remains lower than the limit one, which decreases from 1493 to 1121 g CO_2/kWh along the period in study.
- Although no reference degree in emissions reduction was proposed in this scenario, a final net emissions decrease would take place. The highest value is forecasted by 2040 and corresponds to 56 CO_2 million tons and a sustainability factor of 58%.

Despite the suitability of the current system, results for scenario 2 reveal the following:

- Emissivity of the system decreases for each LRSI, so that the lowest value of 59 g CO_2/kWh in 2040 matches a reduction of 82% compared to scenario 1.
- This improvement would directly affect EVs dependent on the power system: BEVs and PHEVs. For instance, BEVs cars' contribution to CO_2 in 2040 decreases by 82% compared to scenario 1, meanwhile PHEVs cars' does by a 26% since they only depend partly on the electrical system.
- CO_2 savings and sustainability factor in this last scenario acquire the value of 74 million tons and 77% respectively.

Finally, this study has verified that the penetration of EVs in the Spanish society arises as a completely environmentally friendly solution in terms of CO_2 savings, more effective as the renewable sources acquire more influence in the electrical mix and with the highest penetration of BEVs among EVs. Further studies will focus on the possible electrification of interurban transport, together with the possibility of replacing trucks transport by electric trains and their environmental impact.

Acknowledgment

This work was supported in part by the regional public administration of Valencia under the grant ACIF/2018/106.

References

Academic Press, 2017. Units and conversion factors, in: Renewable Energy. Elsevier, pp. xxvii–

xxix. https://doi.org/10.1016/b978-0-12-804567-1.00017-7

Acciona, 2020. Hydroelectric power [WWW Document]. URL https://www.acciona-energia.com/es/areas-de-actividad/otras-tecnologias/hidroelectrica/ (accessed 7.8.20).

Álvarez Fernández, R., 2018. A more realistic approach to electric vehicle contribution to greenhouse gas emissions in the city. J. Clean. Prod. 172, 949–959. https://doi.org/10.1016/j.jclepro.2017.10.158

ANESDOR, 2019. Two wheels vehicles sector in Spain [WWW Document]. URL https://www.anesdor.com/wp-content/uploads/2019/02/190121_PPT_RP_Madrid.pdf (accessed 1.28.20).

ANFAC, 2018. Annual Report [WWW Document]. URL https://anfac.com/categorias_publicaciones/informe-anual/ (accessed 12.5.19).

Athanasopoulou, L., Bikas, H., Stavropoulos, P., 2018. Comparative Well-to-Wheel Emissions Assessment of Internal Combustion Engine and Battery Electric Vehicles, in: Procedia CIRP. Elsevier B.V., pp. 25–30. https://doi.org/10.1016/j.procir.2018.08.169

Bastida-Molina, P., Alfonso-Solar, D., Vargas-Salgado, C., Montuori, L., 2019. Assessing the increase of solar fields in the Iberian Peninsula. https://doi.org/10.4995/CARPE2019.2019.10205

Bastida-Molina, P., Hurtado-Pérez, E., Pérez-Navarro, Á., Alfonso-Solar, D., 2020. Light electric vehicle charging strategy for low impact on the grid. Environ. Sci. Pollut. Res. 1–17. https://doi.org/10.1007/s11356-020-08901-2

BOE, 2019. TEC/1141/2019 [WWW Document]. URL https://www.boe.es/diario_boe/txt.php?id=BOE-A-2019-16856 (accessed 12.12.19).

Burchart-Korol, D., Jursova, S., Folęga, P., Pustejovska, P., 2020. Life cycle impact assessment of electric vehicle battery charging in European Union countries. J. Clean. Prod. 257, 120476. https://doi.org/10.1016/j.jclepro.2020.120476

Canals Casals, L., Martinez-Laserna, E., Amante García, B., Nieto, N., 2016. Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction. J. Clean. Prod. 127, 425–437. https://doi.org/10.1016/j.jclepro.2016.03.120

Choi, H., Shin, J., Woo, J.R., 2018. Effect of electricity generation mix on battery electric vehicle adoption and its environmental impact. Energy Policy 121, 13–24. https://doi.org/10.1016/j.enpol.2018.06.013

Choi, W., Song, H.H., 2018. Well-to-wheel greenhouse gas emissions of battery electric vehicles in countries dependent on the import of fuels through maritime transportation: A South Korean case study. Appl. Energy 230, 135–147. https://doi.org/10.1016/j.apenergy.2018.08.092

Clement-Nyns, K., Haesen, E., Driesen, J., 2010. The impact of Charging plug-in hybrid electric vehicles on a residential distribution grid. IEEE Trans. Power Syst. 25, 371–380. https://doi.org/10.1109/TPWRS.2009.2036481

Dai, Q., Cai, T., Duan, S., Zhao, F., 2014. Stochastic modeling and forecasting of load demand for electric bus battery-swap station. IEEE Trans. Power Deliv. 29, 1909–1917. https://doi.org/10.1109/TPWRD.2014.2308990

DGT, 2017. Vehicle fleet historical data base [WWW Document]. URL http://www.dgt.es/es/seguridad-vial/estadisticas-e-indicadores/parque-vehiculos/series-historicas/ (accessed 1.2.19).

Dong, X., Wang, B., Yip, H.L., Chan, Q.N., 2019. CO2 Emission of Electric and Gasoline Vehicles under Various Road Conditions for China, Japan, Europe and World Average—Prediction through Year 2040. Appl. Sci. 9, 2295. https://doi.org/10.3390/app9112295

Driscoll, Á., Lyons, S., Mariuzzo, F., Tol, R.S.J., 2013. Simulating demand for electric vehicles using revealed preference data. Energy Policy 62, 686–696. https://doi.org/10.1016/j.enpol.2013.07.061

Edwards, R. (Jrc/Ies), Larive, J.-F. (Concawe), Mahieu, V. (Jrc/Ies), Rounveirolles, P. (Renault), 2007. Well-to-Wheels analysis of future automotive fuels and well-to-wheels Report. Europe Version 2c, 88. https://doi.org/10.2788/79018

Ehrenberger, S.I., Dunn, J.B., Jungmeier, G., Wang, H., 2019. An international dialogue about electric vehicle deployment to bring energy and greenhouse gas benefits through 2030 on a well-to-wheels basis. Transp. Res. Part D Transp. Environ. 74, 245–254. https://doi.org/10.1016/j.trd.2019.07.027

ETECNIC, 2020. MOVES Plan 2020: financial support for electric cars and charging points [WWW Document]. URL https://etecnic.es/noticias/sector/ayudas-subvenciones/plan-moves-2020/ (accessed 7.7.20).

Gallet, M., Massier, T., Hamacher, T., 2018. Estimation of the energy demand of electric buses based on real-world data for large-scale public transport networks. Appl. Energy 230, 344–356. https://doi.org/10.1016/j.apenergy.2018.08.086

Hass, H., Huss, A., Maas, H., 2014. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context: Tank-to-Wheels Appendix 1 - Version 4.a, Joint Research Centre of the European Commission, EUCAR, and CONCAWE. https://doi.org/10.2790/95839

He, Y., Song, Z., Liu, Z., 2019. Fast-charging station deployment for battery electric bus systems considering electricity demand charges. Sustain. Cities Soc. 48, 101530. https://doi.org/10.1016/j.scs.2019.101530

Hoekstra, A., 2019. The Underestimated Potential of Battery Electric Vehicles to Reduce Emissions. Joule. https://doi.org/10.1016/j.joule.2019.06.002

Hu, X., Murgovski, N., Johannesson, L., Egardt, B., 2013. Energy efficiency analysis of a series plug-in hybrid electric bus with different energy management strategies and battery sizes. Appl. Energy 111, 1001–1009. https://doi.org/10.1016/j.apenergy.2013.06.056

Huo, H., Cai, H., Zhang, Q., Liu, F., He, K., 2015. Life-cycle assessment of greenhouse gas and air emissions of electric vehicles: A comparison between China and the U.S. Atmos. Environ. 108, 107–116. https://doi.org/10.1016/j.atmosenv.2015.02.073

Huo, H., Zhang, Q., Wang, M.Q., Streets, D.G., He, K., 2010. Environmental implication of electric vehicles in china. Environ. Sci. Technol. 44, 4856–4861. https://doi.org/10.1021/es100520c

IDAE, 2020. National Integrated Plan about Energy and Climate 2021-2030 [WWW Document]. URL https://www.idae.es/informacion-y-publicaciones/plan-nacional-integrado-de-energia-y-clima-pniec-2021-2030 (accessed 12.13.19).

IDAE, 2019. Biomass potential evaluation [WWW Document]. URL https://www.idae.es/uploads/documentos/documentos_11227_e14_biomasa_A_8d51bf1c.pdf (accessed 7.8.20).

IDAE, 2006. Fuel management guide for road transport fleets [WWW Document]. URL https://www.idae.es/uploads/documentos/documentos_10232_Guia_gestion_combusti ble_flotas_carretera_06_32bad0b7.pdf (accessed 11.14.19).

IDAE - UE, 2019. Hybrid electric buses introduction in the Transport Fleet Company S.A.M [WWW Document]. URL https://www.idae.es/uploads/documentos/documentos_detalle_proyecto_Autobuses_Malaga_c260fac8.pdf (accessed 12.5.19).

IEA, 2016. Data and statistics [WWW Document]. URL https://www.iea.org/data-and-statistics/data-tables?country=WORLD&energy=Balances&year=2016 (accessed 12.12.19).

INE, 2018. Average distance covered by vehicles fleet [WWW Document]. URL http://www.ine.es/jaxi/Tabla.htm?path=/t25/p500/2008/p10/l0/&file=10020.px&L=0 (accessed 12.30.18).

Ingeborgrud, L., Ryghaug, M., 2019. The role of practical, cognitive and symbolic factors in the successful implementation of battery electric vehicles in Norway. Transp. Res. Part A Policy Pract. 130, 507–516. https://doi.org/10.1016/j.tra.2019.09.045

Jochem, P., Babrowski, S., Fichtner, W., 2015. Assessing CO 2 emissions of electric vehicles in Germany in 2030. Transp. Res. Part A Policy Pract. 78, 68–83. https://doi.org/10.1016/j.tra.2015.05.007

Ke, W., Zhang, S., He, X., Wu, Y., Hao, J., 2017. Well-to-wheels energy consumption and emissions of electric vehicles: Mid-term implications from real-world features and air pollution control progress. Appl. Energy 188, 367–377. https://doi.org/10.1016/j.apenergy.2016.12.011

Kobashi, T., Yoshida, T., Yamagata, Y., Naito, K., Pfenninger, S., Say, K., Takeda, Y., Ahl, A., Yarime, M., Hara, K., 2020. On the potential of "Photovoltaics + Electric vehicles" for deep decarbonization of Kyoto's power systems: Techno-economic-social considerations. Appl. Energy 275, 115419. https://doi.org/10.1016/j.apenergy.2020.115419

Limmer, S., Rodemann, T., 2019. Peak load reduction through dynamic pricing for electric vehicle charging. Int. J. Electr. Power Energy Syst. 113, 117–128. https://doi.org/10.1016/J.IJEPES.2019.05.031

Liu, F., Zhao, F., Liu, Z., Hao, H., 2018. China's Electric Vehicle Deployment: Energy and Greenhouse Gas Emission Impacts. Energies 11, 3353. https://doi.org/10.3390/en11123353

Liu, Z., Wu, Q., Nielsen, A., Wang, Y., 2014. Day-Ahead Energy Planning with 100% Electric Vehicle Penetration in the Nordic Region by 2050. Energies 7, 1733–1749. https://doi.org/10.3390/en7031733

Manjunath, A., Gross, G., 2017. Towards a meaningful metric for the quantification of GHG emissions of electric vehicles (EVs). Energy Policy 102, 423–429. https://doi.org/10.1016/j.enpol.2016.12.003

Mohamed, M., Farag, H., El-Taweel, N., Ferguson, M., 2017. Simulation of electric buses on a full transit network: Operational feasibility and grid impact analysis. Electr. Power Syst. Res. 142, 163–175. https://doi.org/10.1016/j.epsr.2016.09.032

Moro, A., Helmers, E., 2017. A new hybrid method for reducing the gap between WTW and LCA in the carbon footprint assessment of electric vehicles. Int. J. Life Cycle Assess. 22, 4–14. https://doi.org/10.1007/s11367-015-0954-z

Moro, A., Lonza, L., 2018. Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. Transp. Res. Part D Transp. Environ. 64, 5–14.

https://doi.org/10.1016/j.trd.2017.07.012

Morrissey, P., Weldon, P., O'Mahony, M., 2016. Future standard and fast charging infrastructure planning: An analysis of electric vehicle charging behaviour. Energy Policy 89, 257–270. https://doi.org/10.1016/J.ENPOL.2015.12.001

Mutter, A., 2019. Obduracy and change in urban transport-understanding competition between sustainable fuels in swedish municipalities. Sustain. 11. https://doi.org/10.3390/su11216092

Onn, C.C., Mohd, N.S., Yuen, C.W., Loo, S.C., Koting, S., Abd Rashid, A.F., Karim, M.R., Yusoff, S., 2018. Greenhouse gas emissions associated with electric vehicle charging: The impact of electricity generation mix in a developing country. Transp. Res. Part D Transp. Environ. 64, 15–22. https://doi.org/10.1016/j.trd.2017.06.018

OPPCharge, 2019. Common Interface for Automated Charging of Hybrid Electric and Electric Commercial Vehicles.

PNIEC, 2019. Spanish climate change draft law [WWW Document]. URL https://www.miteco.gob.es/es/prensa/ultimas-noticias/el-consejo-de-ministros-da-luz-verde-al-anteproyecto-de-ley-de-cambio-climático-/tcm:30-487294 (accessed 4.12.19).

Qiao, Q., Zhao, F., Liu, Z., He, X., Hao, H., 2019. Life cycle greenhouse gas emissions of Electric Vehicles in China: Combining the vehicle cycle and fuel cycle. Energy 222–233. https://doi.org/10.1016/j.energy.2019.04.080

REE, 2018. Electric mobility guide for local entities [WWW Document]. URL https://www.ree.es/sites/default/files/downloadable/Guia_movilidad_electrica_para_entidades_locales.pdf (accessed 7.31.19).

Sarker, M.R., Pandžić, H., Ortega-Vazquez, M.A., 2015. Optimal operation and services scheduling for an electric vehicle battery swapping station. IEEE Trans. Power Syst. 30, 901–910. https://doi.org/10.1109/TPWRS.2014.2331560

Scarinci, R., Zanarini, A., Bierlaire, M., 2019. Electrification of urban mobility: The case of catenary-free buses. Transp. Policy 80, 39–48. https://doi.org/10.1016/j.tranpol.2019.05.006

Shafiee, S., Fotuhi-Firuzabad, M., Rastegar, M., 2013. Investigating the impacts of plug-in hybrid electric vehicles on power distribution systems. IEEE Trans. Smart Grid 4, 1351–1360. https://doi.org/10.1109/TSG.2013.2251483

Shamshirband, M., Salehi, J., Gazijahani, F.S., 2018. Decentralized trading of plug-in electric vehicle aggregation agents for optimal energy management of smart renewable penetrated microgrids with the aim of CO2 emission reduction. J. Clean. Prod. 200, 622–640. https://doi.org/10.1016/j.jclepro.2018.07.315

Shen, W., Han, W., Wallington, T.J., 2014. Current and future greenhouse gas emissions associated with electricity generation in China: Implications for electric vehicles. Environ. Sci. Technol. 48, 7069–7075. https://doi.org/10.1021/es500524e

Shen, W., Han, W., Wallington, T.J., Winkler, S.L., 2019. China Electricity Generation Greenhouse Gas Emission Intensity in 2030: Implications for Electric Vehicles. Environ. Sci. Technol. 53, 6063–6072. https://doi.org/10.1021/acs.est.8b05264

Spangher, L., Gorman, W., Bauer, G., Xu, Y., Atkinson, C., 2019. Quantifying the impact of U.S. electric vehicle sales on light-duty vehicle fleet CO2 emissions using a novel agent-based simulation. Transp. Res. Part D Transp. Environ. 72, 358–377. https://doi.org/10.1016/j.trd.2019.05.004

Spanish Ministry of Development, 2016. Urban and metropolitan transport in Spain [WWW Document]. URL https://www.fomento.gob.es/recursos_mfom/00transporteurbano.pdf (accessed 12.16.19).

Spanish Nuclear Industry Forum, 2019. Nuclear Power Plants [WWW Document]. URL https://www.foronuclear.org/es/ (accessed 3.7.20).

Su, J., Lie, T.T., Zamora, R., 2019. Modelling of large-scale electric vehicles charging demand: A New Zealand case study. Electr. Power Syst. Res. 167, 171–182. https://doi.org/10.1016/J.EPSR.2018.10.030

Teixeira, A.C.R., Sodré, J.R., 2018. Impacts of replacement of engine powered vehicles by electric vehicles on energy consumption and CO2 emissions. Transp. Res. Part D Transp. Environ. 59, 375–384. https://doi.org/10.1016/J.TRD.2018.01.004

The German Federal Goverment, 2009. Federal Government's National Electromobility Development Plan.

Tietge, U., Díaz, S., Mock, P., German, J., Bandivadekar, A., Ligterink, N., 2016a. From laboratory to road: A 2016 update of official and "real-world" fuel consumption and CO2 values for passenger cars in Europe. Int. Counc. Clean Transp.

Tietge, U., Mock, P., Zacharof, N., Franco, V., 2016b. Real-world fuel consumption of popular European passenger car models | International Council on Clean Transportation. Int. Counc. Clean Transp.

Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.08.013

UE, 2020. EU Emissions Trading Framework [WWW Document]. URL https://ec.europa.eu/clima/policies/ets_es (accessed 7.7.20).

UE, 2019. Regulation 2019/631 of the European Parliament [WWW Document]. URL https://eur-lex.europa.eu/legal-content/ES/TXT/?uri=CELEX:32019R0631 (accessed 7.9.20).

UE, 2015. Paris agreement [WWW Document]. URL https://ec.europa.eu/clima/policies/international/negotiations/paris_es (accessed 7.7.20).

UE, 2010. 2010/75/UE [WWW Document]. URL https://eur-lex.europa.eu/legal-content/ES/TXT/PDF/?uri=CELEX:32010L0075&from=ES (accessed 7.7.20).

van den Broek, M., Faaij, A., Turkenburg, W., 2008. Planning for an electricity sector with carbon capture and storage. Case of the Netherlands. Int. J. Greenh. Gas Control 2, 105–129. https://doi.org/10.1016/S1750-5836(07)00113-2

Wang, W., Zhao, D., Mi, Z., Fan, L., 2019. Prediction and Analysis of the Relationship between Energy Mix Structure and Electric Vehicles Holdings Based on Carbon Emission Reduction Constraint: A Case in the Beijing-Tianjin-Hebei Region, China. Sustainability 11, 1–20.

Weiss, M., Dekker, P., Moro, A., Scholz, H., Patel, M.K., 2015. On the electrification of road transportation - A review of the environmental, economic, and social performance of electric two-wheelers. Transp. Res. Part D Transp. Environ. 41, 348–366. https://doi.org/10.1016/j.trd.2015.09.007

Woo, J.R., Choi, H., Ahn, J., 2017. Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: A global perspective. Transp. Res. Part D Transp. Environ. 51, 340–350. https://doi.org/10.1016/j.trd.2017.01.005

Wu, Y., Yang, Z., Lin, B., Liu, H., Wang, R., Zhou, B., Hao, J., 2012. Energy consumption and CO 2 emission impacts of vehicle electrification in three developed regions of China. Energy Policy 48, 537–550. https://doi.org/10.1016/j.enpol.2012.05.060

Wu, Y., Zhang, L., 2017. Can the development of electric vehicles reduce the emission of air pollutants and greenhouse gases in developing countries? Transp. Res. Part D Transp. Environ. 51, 129–145. https://doi.org/10.1016/j.trd.2016.12.007

Wu, Z., Guo, F., Polak, J., Strbac, G., 2019. Evaluating grid-interactive electric bus operation and demand response with load management tariff. Appl. Energy 255, 113798. https://doi.org/10.1016/j.apenergy.2019.113798

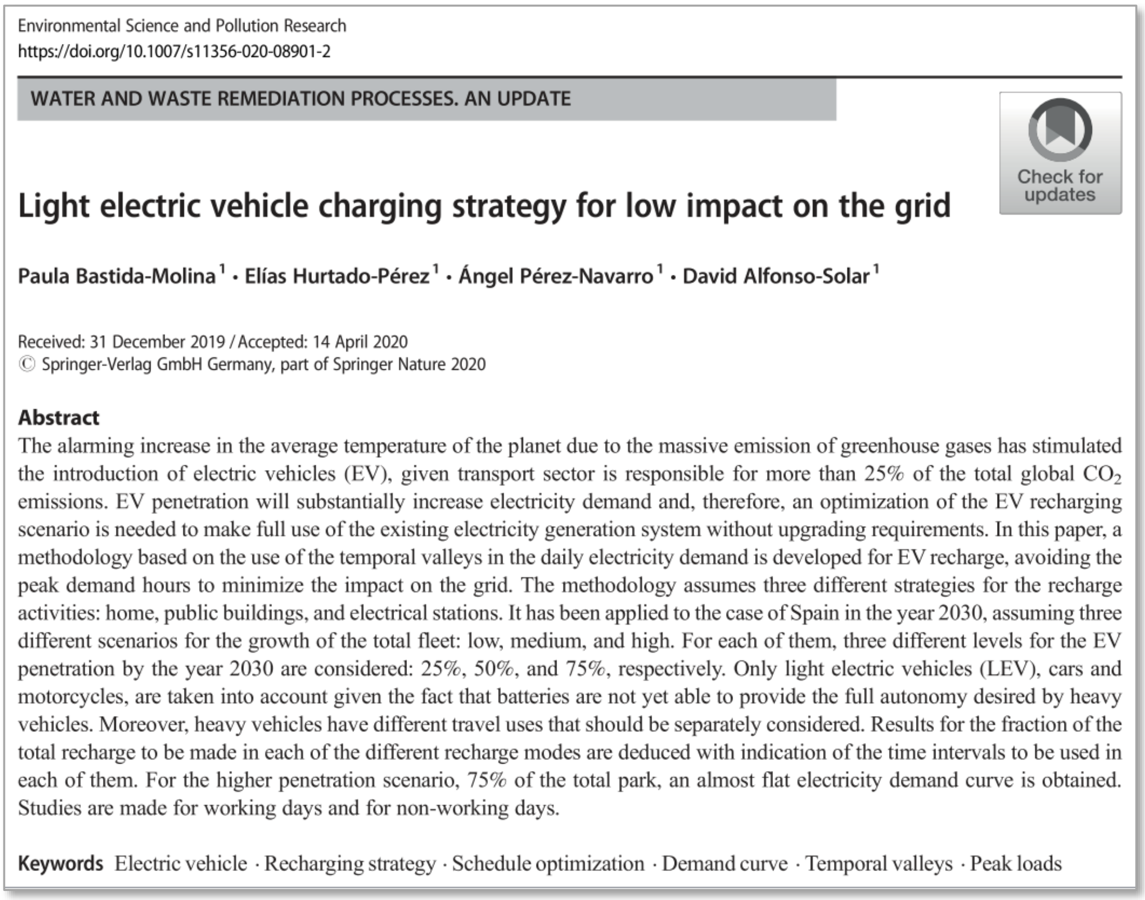
Yang, Y., El Baghdadi, M., Lan, Y., Benomar, Y., Van Mierlo, J., Hegazy, O., 2018. Design Methodology, Modeling, and Comparative Study of Wireless Power Transfer Systems for Electric Vehicles. Energies 11, 1716. https://doi.org/10.3390/en11071716

Zhang, X., 2018. Short-Term Load Forecasting for Electric Bus Charging Stations Based on Fuzzy Clustering and Least Squares Support Vector Machine Optimized by Wolf Pack Algorithm. Energies 11, 1449. https://doi.org/10.3390/en11061449

Zheng, J., Sun, X., Jia, L., Zhou, Y., 2020. Electric passenger vehicles sales and carbon dioxide emission reduction potential in China’s leading markets. J. Clean. Prod. 243, 118607. https://doi.org/10.1016/j.jclepro.2019.118607

Zheng, Y., He, X., Wang, H., Wang, M., Zhang, S., Ma, D., Wang, B., Wu, Y., 2019. Well-to-wheels greenhouse gas and air pollutant emissions from battery electric vehicles in China. Mitig. Adapt. Strateg. Glob. Chang. https://doi.org/10.1007/s11027-019-09890-5

2.2. Light electric vehicle charging strategy for low impact on the grid



Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-020-08901-2

WATER AND WASTE REMEDIATION PROCESSES. AN UPDATE

Light electric vehicle charging strategy for low impact on the grid

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Received: 31 December 2019 / Accepted: 14 April 2020

Abstract

The alarming increase in the average temperature of the planet due to the massive emission of greenhouse gases has stimulated the introduction of electric vehicles (EV), given transport sector is responsible for more than 25% of the total global CO_2 emissions. EV penetration will substantially increase electricity demand and, therefore, an optimization of the EV recharging scenario is needed to make full use of the existing electricity generation system without upgrading requirements. In this paper, a methodology based on the use of the temporal valleys in the daily electricity demand is developed for EV recharge, avoiding the peak demand hours to minimize the impact on the grid. The methodology assumes three different strategies for the recharge activities: home, public buildings, and electrical stations. It has been applied to the case of Spain in the year 2030, assuming three different scenarios for the growth of the total fleet: low, medium, and high. For each of them, three different levels for the EV penetration by the year 2030 are considered: 25%, 50%, and 75%, respectively. Only light electric vehicles (LEV), cars and motorcycles, are taken into account given the fact that batteries are not yet able to provide the full autonomy desired by heavy vehicles. Moreover, heavy vehicles have different travel uses that should be separately considered. Results for the fraction of the total recharge to be made in each of the different recharge modes are deduced with indication of the time intervals to be used in each of them. For the higher penetration scenario, 75% of the total park, an almost flat electricity demand curve is obtained. Studies are made for working days and for non-working days.

Keywords Electric vehicle · Recharging strategy · Schedule optimization · Demand curve · Temporal valleys · Peak loads

Light electric vehicle charging strategy for low impact on the grid

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Abstract

The alarming increase in the average temperature of the planet due to the massive emission of greenhouse gases has stimulated the introduction of electric vehicles (EV), given transport sector is responsible for more than 25% of the total global CO_2 emissions. EV penetration will substantially increase electricity demand and, therefore, an optimization of the EV recharging scenario is needed to make full use of the existing electricity generation system without upgrading requirements. In this paper, a methodology based on the use of the temporal valleys in the daily electricity demand is developed for EV recharge, avoiding the peak demand hours to minimize the impact on the grid. The methodology assumes three different strategies for the recharge activities: home, public buildings and electrical stations. It has been applied to the case of Spain in the year 2030, assuming three different scenarios for the growth of the total fleet: low, medium and high. For each of them, three different levels for the EV penetration by the year 2030 are considered: 25%, 50% and 75%, respectively. Only light electric vehicles (LEV), cars and motorcycles, are taken into account given the fact that batteries are not yet able to provide the full autonomy desired by heavy vehicles. Moreover, heavy vehicles have different travel uses that should be separately considered. Results for the fraction of the total recharge to be made in each of the different recharge modes are deduced with indication of the time intervals to be used in each of them. For the higher penetration scenario, 75% of the total park, an almost flat electricity demand curve is obtained. Studies are made for working days and for non-working days.

Keywords

Electric vehicle, recharging strategy, schedule optimization, demand curve, temporal valleys, peak loads.

1. Introduction

During the last years, climate change has become one of the most worrisome problems. The huge quantity of greenhouse gases emitted to the atmosphere is leading to a dangerous temperature increase, whose negative effects are duly documented (Akitt, 2018).

Transport sector, with almost a quarter of the total carbon dioxide emissions, is one of the most polluting sectors (Bjerkan et al., 2016; Hasan et al., 2019; Teixeira and Sodré, 2018). Besides, transport depends mostly on fossil fuels whose reserves are finite and could be exhausted in a short or medium term. Both phenomena, environmental impact and finite reserves, have motivated the electrification of the transport sector (Adnan et al., 2017; Dijk et al., 2013). The balance between the CO_2 emissions due to the generation of a surplus of electricity to supply EV and the emissions avoided by the use of these EV could be highly favorable (Canals Casals et al., 2016; Morrissey et al., 2016), making EV an environmental solution for transport. Therefore, a high penetration of EV in the transport sector is taking place.

The electrical behavior of this kind of vehicles lies in both their electrical charge depleting and recharging electrical demand, which are hugely affected by the EV driving cycle and the state of the battery. Regarding the EV driving cycle, the study (Zhao et al., 2018a) develops a methodology to construct an EV urban driving cycle for analyzing the differences in estimated EV energy consumption. It is based on the general topological structure of the studied urban roads and their traffic flow. Authors apply the methodology to the city of Xi'an as a case of study. Finally, the application of the developed driving cycle together with other international driving cycles to the city revealed that when the latter are used, energy consumption errors increase up to 21.17%. The research (Zhao et al., 2018b) goes a step further and proposes a methodology based on a k-means and a support vector machines hybrid clustering algorithm to select the most representative EV urban driving cycle. The application of the methodology to Xi'an EV urban driving cycle effectively matches the speed-time driving pattern of the real-world cycle, proving therefore the feasibility of the method. Referring to the state of batteries, Zhang *et al* (Zhang et al., 2019) focus their study on the accurate estimation of the State of Charge (SOC) of lithium-ion batteries, which are widely used for energy storage in EV. Their novel methodology allows for an optimization of the noise information by means of an "ant-lion" optimizer algorithm. Results verify the suitable noise optimization making use of the developed algorithm, so that SOC of batteries could be accurately estimated with error ratios lower than 1%. Another research (Wang et al., 2019) develops a diagnosis of the state of health of lithium-ion batteries based on charge transfer resistance and taking different temperature and SOC parameters as inputs. The study leads to a battery state of health estimation method that eliminates the need of controlling the temperate and SOC of batteries during the measurement.

After the analyses of EV electrical behavior, different studies (Ahmadi et al., 2012; Deb et al., 2018; Galiveeti et al., 2018; Gong et al., 2018) claim that a massive introduction of EV would create negative impacts on the grid, leading to new power network challenges (Clairand et al., 2018). With this problem in mind, several studies have lately proposed different solutions to minimize the impact of EV on the grid (Wang and Chen, 2019).

One study has focused on the reshape of electricity load demand from EV recharge in the case of a high expected introduction of EV (López et al., 2015). The study for EV penetration in New Zealand (Su et al., 2019) shows how the EV demand would increase each year with the consumption concentrated in peak hours, particularly at the end of the day. Under these circumstances, peak loads increase until arriving to a critical point in 2040 when the highest peak demand would exceed 2018 New Zealand installed generation capacity. Other studies, applied to Brazil (Baran and Legey, 2013) and to the European Nordic Region (Liu et al., 2014), reach the same conclusion: the electricity demand due to the introduction of EV would substantially increase peak loads, with the corresponding negative impacts on the electricity network and the installed capacity of those regions.

EV recharging processes tend to have a random behavior (Dang, 2018; Mao et al., 2019; Ortega-Vazquez et al., 2013) when compared to traditional electricity load profiles, but no limitations measures have been yet applied to control those recharging processes due to the recent appearance of EV in transportation. Nowadays, users freely choose the charging time to recharge their batteries, so the process schedule is a self-personalized one (Dang and Huo, 2018). This uncontrolled situation is the responsible for an overlapping between EV charging loads with the grid peak loads that could increase the requirements at the peak periods. Therefore, scheduling the different recharging options is completely necessary to avoid peak demand increases with the consequent grid problems (Sundstrom and Binding, 2012).

Although several studies have analyzed the impact of EV introduction in the grid, just only a few have based their investigation on scheduling the recharge activities. One of this is the above mentioned in New Zealand (Su et al., 2019), based on time restrictions to be applied to private and utility EV and electric buses. Following these constraints, The European Nordic Region study (Liu et al., 2014) considers also a timed charging strategy based on the spot price, but this method is applied only for EV passenger cars. Reschedule of the charging processes based on dynamic pricing is studied and applied to a case of study in Germany (Limmer and Rodemann, 2019).

None of these studies consider real drivers recharging patterns, that should be the basis for real recharging strategies, and can be included in three different categories: recharge at home, electrical stations or public buildings (Danté et al., 2019; IDAE, 2012; Martínez-Lao et al., 2017; REE, 2018; Wang and Infield, 2018). The aim of this paper is to deduce an optimization methodology to avoid peak demand hours by the introduction of EV. This methodology is based on the use of electricity demand temporal valleys and provides an optimization of the distribution of recharge between the three different recharge options.

The methodology considers only the contribution of light electric vehicles (LEV) by including cars and motorcycles. Main reason for this limitation lies in the different recharging behavior and travel use of heavy vehicles, like trucks or buses. Furthermore, the currently available batteries are not yet able to provide the full autonomy desired for heavy vehicles.

This methodology has been applied to the case of Spain in the year 2030, assuming three different scenarios for the growth of the total fleet: low, medium and high. For each of them, three different levels for the LEV penetration are considered: 25%, 50% and 75%, respectively. Spain is one of the countries where a large-scale introduction of LEV is expected to happen in the near future. This is because the recent Climate Change and Energy Transition draft proposed by the Spanish Government (PNIEC, 2019) forbids by 2040 the registration and sale of any light vehicle which emits CO_2. Some previous studies have addressed the effect of EV on the grid for this country or some of their regions. For instance, in (Ceballos Delgado et al., 2016) the impact of EV on the distribution network is analyzed for Spain, Chile and Colombia. The impact of charging EV on the distribution grid of a region in Spain (Barcelona) is detailed in (Valsera-Naranjo et al., 2012) with emphasis on the importance of mobility variables when studying this impact. Despite the importance of all these studies, a scheduling of the EV charging has not been yet studied. This research gap and the forecasted high introduction of LEV in Spanish society, make 2030 Spain case study a certainly suitable one to prove the feasibility of the suggested methodology.

This paper is organized as follows: the developed methodology is described in section 2; the case of study with the application to Spain in the year 2030 with different degrees of LEV penetration including results and discussion is presented in section 3; finally, some general conclusions are presented in section 4.

2. Methodology

In this section, a LEV recharging strategies optimization methodology is presented. This methodology is based on the reschedule of LEV recharge using temporal valleys in the electricity demand curve and its distribution between the different options for recharging. A brief overview of the methodology is shown on the flowchart at the Figure 1.

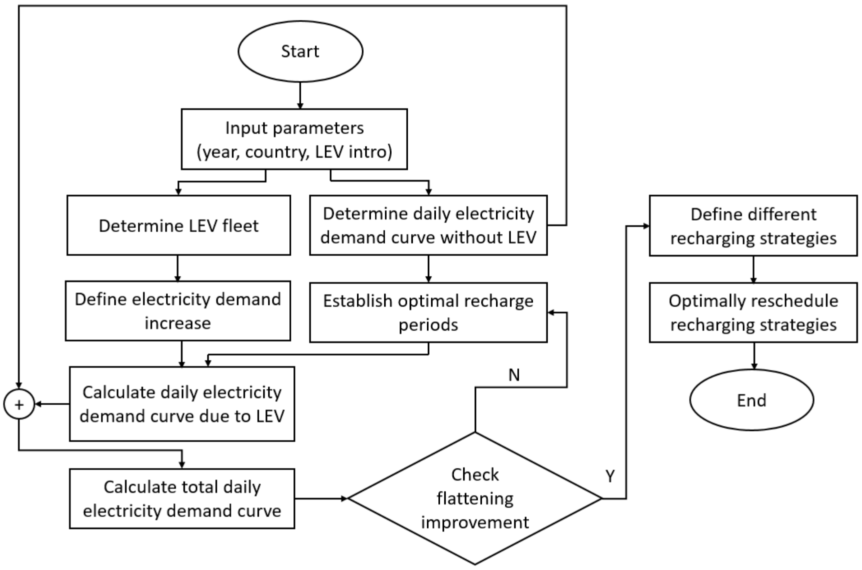


Figure 1. Flowchart of the proposed methodology.

The recharge approach starts with the determination of the expected LEV fleet using data from different official sources and its extrapolation to the year under consideration. The electricity demand from the calculated LEV fleet is determined and distributed along the optimal recharging periods deduced from the valleys in the total electricity daily demand curve. By adding this total electricity demand to the LEV demand, a final daily demand curve is obtained and its possible flattening is analyzed to check how much the initial demand curve has been affected. Once an adequate flattening is obtained, the distribution of the total LEV electricity demand between the different recharging methods (home, electrical stations and public buildings) is optimized.

2.1. LEV fleet

During these last years, almost every developed country has experimented a large-scale introduction of LEV (Baran and Legey, 2013; Canals Casals et al., 2016; REE, 2018). This trend is ever increasing now, so that forecasting LEV fleet in a long term becomes a difficult data to obtain, but critical for the determination of the impact on the electrical grid.

To determine the LEV fleet, the methodology considers four different vehicle types (Al-Alawi and Bradley, 2013; Martínez-Lao et al., 2017): pure electric cars (PEC), hybrid electric cars (HEC), pure electric motorcycles (PEM) and hybrid electric motorcycles (HEM). From the extrapolation of the historical data (DGT, 2017) for light combustion cars (LCC) and motorcycles (LCM), and the assumption of penetration factors for each of the different considered LEV, the total LEV fleet (N_T) is deduced for the particular year under consideration:

$$N_T = \sum_{i=1}^{4} N_i = \left[f_{LCC}(t_0) \cdot \sum_{i=1}^{2} p_i(t_0)\right] + \left[f_{LCM}(t_0) \cdot \sum_{i=3}^{4} p_i(t_0)\right] \quad (1)$$

where: N_i represents the fleet for the different types of LEV i (i=1 (PEC); i=2 (HEC); i=3 (PEM) and i=4 (HEM)); $f_{LCC}(t_0)$ and $f_{LCM}(t_0)$ are the extrapolated values in the year t_0 of the different LCC and LCM, respectively, and p_i is the penetration factor of the different types of electric vehicles i.

Hence, the nature (cars/motorcycles) of the introduced LEV matches the nature of the LCV replaced. Therefore, the introduction of electric cars (PEV and HEV) would influence LCC, whereas electric motorcycles (PEM and HEM) would affect LCM.

2.2. Electricity demand increase

The electricity demand from the total LEV fleet will be given by:

$$\Delta_{ED} = \sum_1^4 \left(C_a \cdot f_h \cdot \bar{d}_a\right)_i \cdot N_i \quad (2)$$

where the electrical consumption of each type of electric vehicle is affected by three factors: the average certified electrical consumption (C_a); a real increase consumption factor (f_h) over those certified values, and the average annual travel distance ($\bar{d}_a$).

Values for all these parameters are summarized in Table 1. C_a can be obtained from the review of the certified consumption for a large quantity of existing and planned LEV models (Luca de Tena and Pregger, 2018). However, different studies (Tietge et al., 2016a, 2016b; Zhao et al., 2018a) claim that those average certified consumption values differ from the real ones, since values obtained under the tested conditions are lower than those obtained under real road conditions due to the low demanding conditions of the former tests. Factor f_h is deduced by using extrapolated data from (Tietge et al., 2016b). Averaged annual traveling distances, $\bar{d}_a$, could be deduced from (INE, 2018).

Table 1. LEV electrical consumption parameters

	C_a (kWh/100 km)	f_h	$\bar{d}_a$ (km/year)
PEC	13.7	1.67	12563
HEC	4.6	1.67	12563
PEM	6.3	1.67	6302
HEM	2.1	1.67	6302

2.3. Total daily electricity demand curve

To deduce the total daily electricity demand curve, we should add to the demand from the different sectors (industry, residential, commercial and services, agriculture and fishing), the demand due to the LEV recharge. This sectorial demand curve can be calculated by assuming that its shape is unchanged in the future and only a multiplying factor for the entire profile, due to the increase in demand, should be applied. This factor (M_f) is given by eq. 3

$$M_f = \frac{E_y}{E_{y_0}} \qquad (3)$$

where E_y corresponds to the total forecasted electricity demand for the year into consideration and E_{y_0} to the electricity demand for the current year.

Historical data from official sources contain information about the electricity consumed in each country along the years. For instance, in the case of Spain, (REE, 2017a) contains national electricity consumption data from 1990 to our days, with the possibility of different period visualizations (diary, monthly, yearly) or locations selection (regions, peninsula, national). Therefore, E_{y_0} is directly obtained from the historical data of the country in question, whereas E_y corresponds to a lineal extrapolation of them to the year under study.

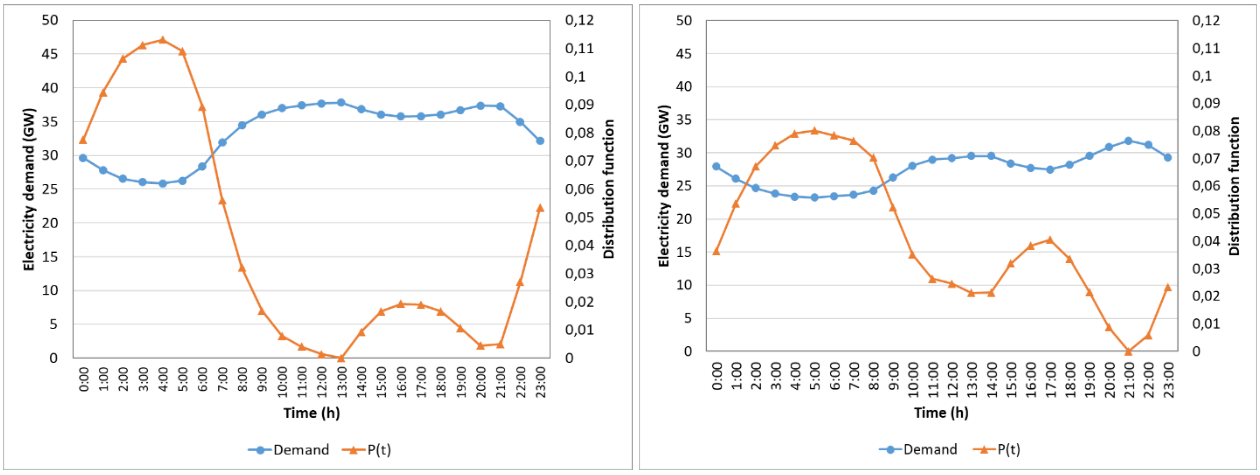
Besides, load users' patterns present considerable differences between working and non-working days (REE, 2017b), so two different predicted daily demand curves should be determined in the methodology application.

Once the sectorial demand profiles are deduced, the distribution along the day of the electricity demanded by the LEV is made in accordance with a distribution function deduced from those profiles. This distribution function (P(t)) is given by:

$$P\,(t) = (D_0(t) - \widehat{D_0}) / \int_0^{24} (D_0(t) - \widehat{D}_0) \cdot dt \qquad (4)$$

where $D_0(t)$ is the sectorial daily demand profile for the considered year and $\widehat{D}_0$ is the maximum value on that profile.

Typical total sectorial electricity demand profiles for working and non-working days are presented in figure 2, together with the corresponding distribution function for the LEV electricity demand deduced using eq.4.



(a) **(b)**

Figure 2. Sectorial demand profile and deduced LEV recharge distribution functions for working **(a)** and non-working **(b)** days

The distribution of the LEV electricity demand along the day is deduced by using this distribution function.

$$D_{LEV}(t) = \Delta_{ED} \cdot P(t) \tag{5}$$

Therefore, the total electricity demand profile will be given by:

$$D_T(t) = D_{LEV}(t) + D_0(t) \tag{6}$$

Using this approach, the total daily electricity demand curve is expected to be a flatter one. To verify this effect, a flat factor F_f is calculated as:

$$F_f = \frac{1}{24} \cdot \int_0^{24} \frac{D_T(t)}{\hat{D}_T} \cdot dt \tag{7}$$

Figure 3 displays the application of this methodology to the distribution of the demand of electricity from LEV, assuming this demand as a 50% of the total one. There is a clear improvement in the flattening of the profile, without any increase in the peak demand value, by displacing the LEV charge to the valleys in the demand curve.

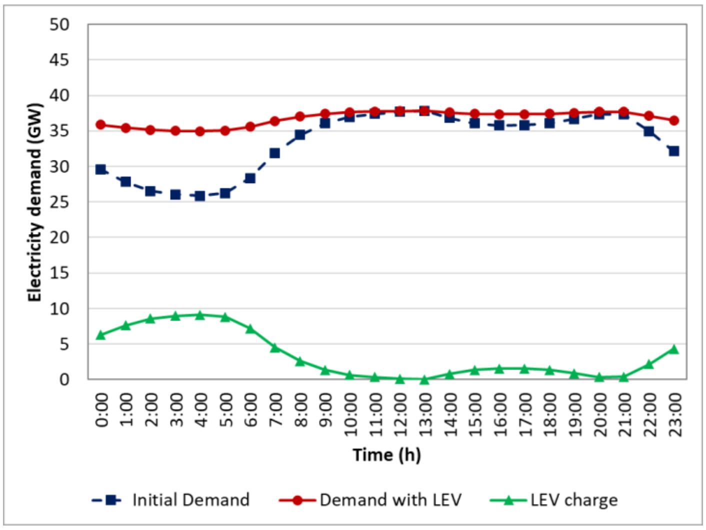


Figure 3. Demand curve flattening

2.4. LEV recharging strategies

An optimal distribution of the LEV electricity demand could be obtained using the above-described methodology. However, another barrier needs to be considered regarding the different recharging strategies for LEV (Dang, 2018; Desai et al., 2018; Liu et al., 2014; Su et al., 2019). These strategies would consider the recharging behavior of the users, which basically are: recharging at home, electrical stations or public buildings (Danté et al., 2019; IDAE, 2012; Martínez-Lao et al., 2017; REE, 2018; Wang and Infield, 2018) and should optimize the distribution of the required demand between these options.

2.4.1 Recharge at home

This type of recharging mode corresponds to the users who would recharge LEV in their garages while they are at home. Hence, recharging hours are related to working schedules of citizens. During working days, most of the citizens using this option would connect their LEV as soon as they arrive home from their work and would disconnect them next morning before going back to work. During non-working days, the most remarkable period of recharging would still be night hours. However, daily hours would experiment an increase, since some people stay at home on these days.

According to (IDAE, 2012; Martínez-Lao et al., 2017; REE, 2018), given the high number of available hours for recharge, this strategy corresponds to a slow mode of recharging. Hence, the recharger unit to supply a complete charge in about 8 hours could be based in a system with a maximum intensity of 16 A at 230 V.

2.4.2 Recharge at electrical stations

Recharging at electrical stations involves users who would specifically stop in a public point because they want the LEV batteries quickly be recharged, so that they can continue with the trip. Electrical stations would be equivalent to current petrol stations (Alhazmi et al., 2017;

Bagher Sadati et al., 2019) with a quick recharging mode (IDAE, 2012; Martínez-Lao et al., 2017; REE, 2018). Hence, the charge duration should be about 30-45 minutes, and the recharger should be able to supply around 400 A at 400 V.

2.4.3 Recharge in public buildings

Refilling LEV batteries in public buildings like parking, supermarkets, shopping centers, etc., during the periods owners are developing other activities corresponds to this type of recharge. This strategy corresponds to an semi-quick mode of recharging (IDAE, 2012; Martínez-Lao et al., 2017; REE, 2018) with a standard charge duration of about 2 hours, and the recharger should supply 64 A at 400 V.

An adequate splitting between these three recharging options should cover the obtained distribution of the total LEV electricity demand, as eq. 8 indicates.

$$\mathrm{D_{LEV}(t) = H(t) + E(t) + P(t)} \tag{8}$$

Being $\mathrm{H(t), E(t)}$ and $\mathrm{P(t)}$ the contributions to the demand from home, electrical stations and public buildings, respectively. Each of these contributions depend on their daily recharging probability profiles, as eq. 9 to 11 indicate.

$$\mathrm{H(t) = D_{LEV}(t) \cdot p_h(t)} \tag{9}$$

$$\mathrm{E(t) = D_{LEV}(t) \cdot p_e(t)} \tag{10}$$

$$\mathrm{P(t) = D_{LEV}(t) \cdot p_p(t)} \tag{11}$$

where $\mathrm{p_h(t), p_e(t)}$ and $\mathrm{p_p(t)}$ are the daily recharging probability profiles for home, electrical stations and public buildings, respectively.

For each case, these parameters arise as proportional contributions to the daily pattern for each recharging option, as eq. 12 to 14 show.

$$\mathrm{p_h(t) = \frac{h(t)}{h(t)+e(t)+p(t)}} \tag{12}$$

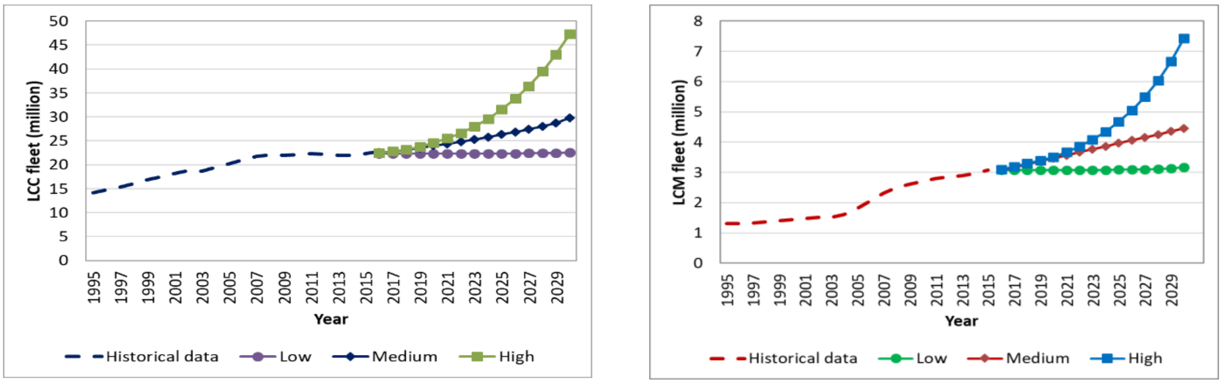
$$\mathrm{p_e(t) = \frac{e(t)}{h(t)+e(t)+p(t)}} \tag{13}$$

$$\mathrm{p_p(t) = \frac{p(t)}{h(t)+e(t)+p(t)}} \tag{14}$$

where $\mathrm{h(t), e(t)}$ and $\mathrm{p(t)}$ represent the daily patterns for home, electrical stations and public buildings strategies, respectively. These patterns would match not only the typical recharging schedule from each strategy (section 2.4.1, 2.4.2 and 2.4.3) but also the way of life of users for the specific region under consideration, to deduce from each country official data.

3. Case of study: Spain in 2030

As an application of the developed methodology for the optimization of the impact on the grid due to the penetration of the LEV, this study has been addressed for the case of Spain in the year 2030. In 2018, there were 25.500 electric cars and 12.350 electric motorcycles (REE, 2018), which represented just a 1% of the total Spanish light transport fleet. Despite this small presence, the introduction of LEV in Spain has experimented a big growth in the last few years and even a bigger increase is forecasted for the medium term. In this study, we are assuming three different scenarios for the growth of the total LCV fleet: low, medium and high, as detailed at figure 4. For each of them, three different levels for the LEV penetration by the year 2030 are considered: 25%, 50% and 75%, respectively.



(a) **(b)**

Figure 4. Scenarios for the growth of LCV in Spain. (a) LCC. (b) LCM.

3.1. LEV fleet

Following the methodology proposed in this paper, we can deduce the total number of electric cars and motorcycles by applying an increasing factor to the values deduced from the extrapolation to the year 2030 of the historical data available for LCV in Spain (DGT, 2017). Table 2 shows the LEV fleet composition for the different penetration levels in each of the assumed scenarios with the assumption of an equal distribution between pure electric and hybrid vehicles.

Table 2. LEV fleet composition for the different scenarios

		Number of vehicles (millions)			
Scenario	LEV fraction (%)	PEC	HEC	PEM	HEM
Low	25	2,8	2,8	0,4	0,4
	50	5,6	5,6	0,8	0,8
	75	8,4	8,4	1,2	1,2
Medium	25	3,7	3,7	0,6	0,6
	50	7,4	7,4	1,2	1,2
	75	11,2	11,2	1,7	1,7
High	25	5,9	5,9	0,9	0,9
	50	11,8	11,8	1,9	1,9
	75	17,7	17,7	2,8	2,8

3.2. Electricity demand increase

If no LEV were introduced in Spain, the total sectorial electricity demand in the year 2030 would be around 279 TWh, deduced from a lineal extrapolation to that year of the electricity consumption in Spain during the period 2013-2017 (REE, 2017a). This represents an increase of 10,3% in relation to the last available data for 2017.

The increases in electricity demand due to the LEV introduction are calculated by using eq.2 with values from the table 1. Results for the different penetration levels in each of the assumed fleet scenario are summarized in table 3 and figure 5.

Table 3. LEV Electricity demand

		LEV electricity demand		
Scenario	LEV fraction (%)	Annual (TWh)	Daily (GWh)	Increase (%)
Low	25	11,1	30,5	4,0
	50	22,2	60,9	8,0
	75	33,4	91,4	12,0
Medium	25	14,7	40,3	5,3
	50	29,4	80,7	10,6
	75	44,2	121,0	15,8
High	25	23,5	64,3	8,4
	50	46,9	128,5	16,8
	75	70,4	192,8	25,2

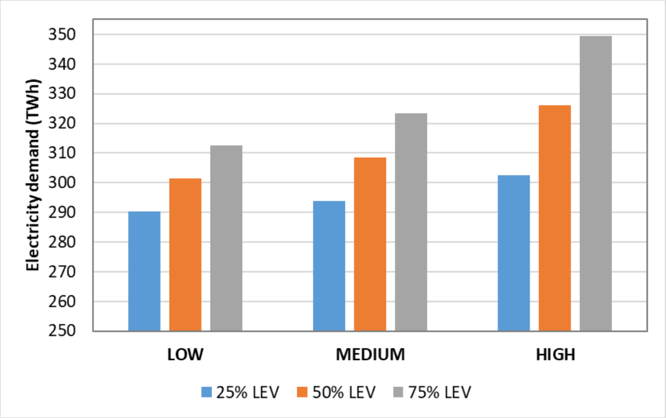


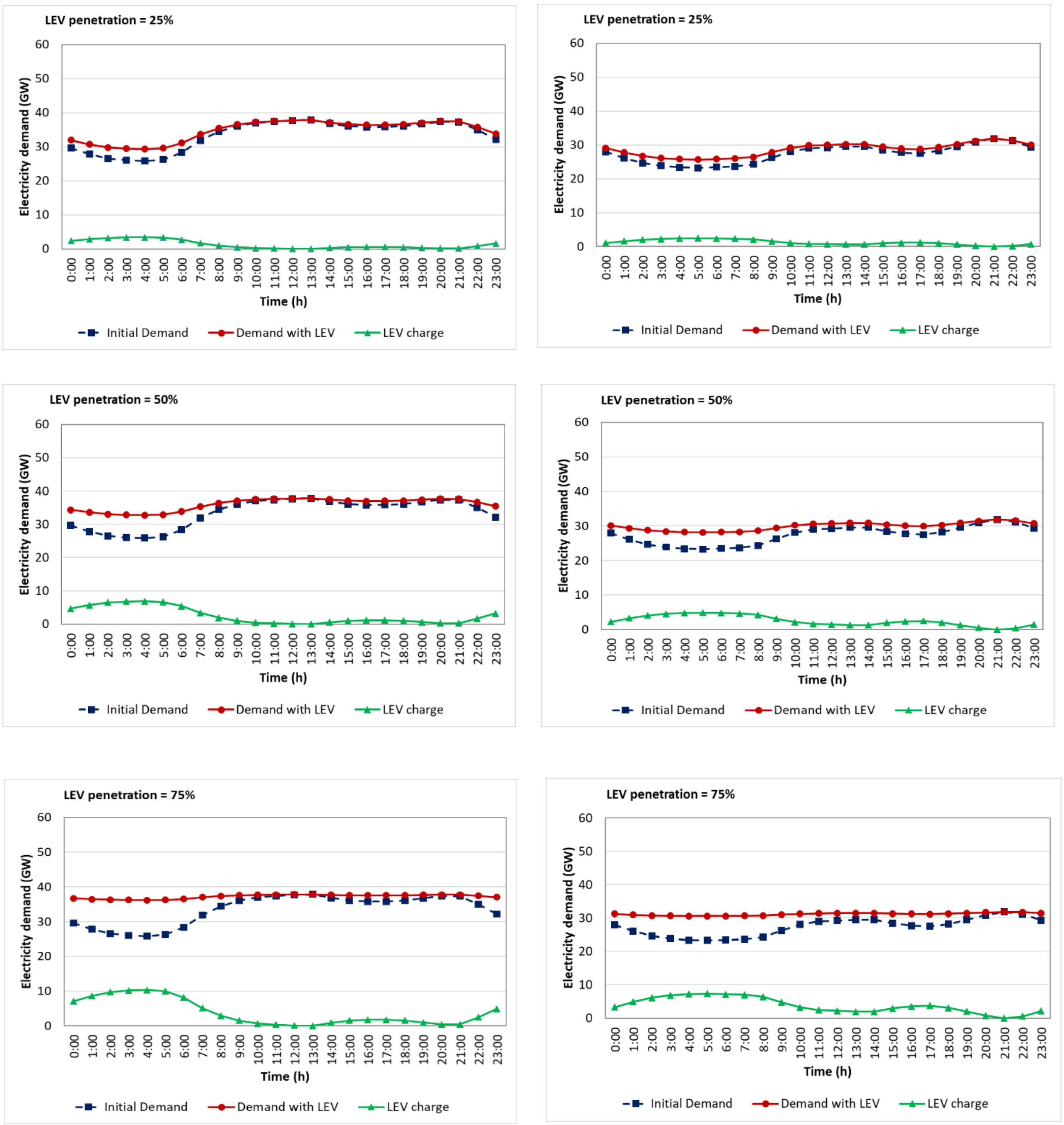
Figure 5. Total electricity demand

A maximum increase of 25,2% is obtained for the most demanding scenario: 75% LEV penetration for a high growth of the total light vehicle fleet.

3.3. Total daily electricity demand curves

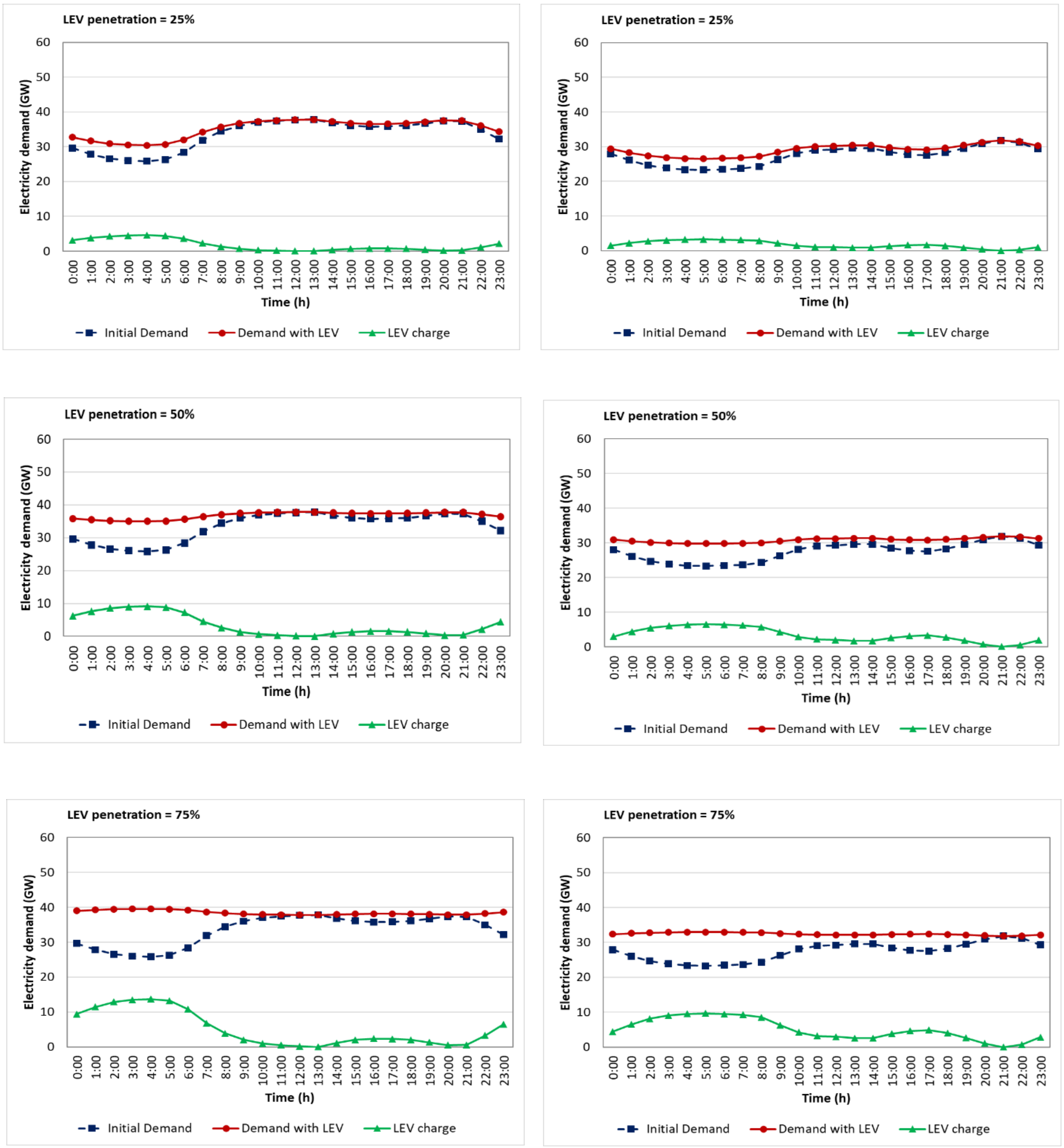
Nowadays, current load patterns for electricity users present considerable differences between working and non-working days (REE, 2017b). Therefore, two different predicted 2030 Spanish daily demand curves have been used in this study. If these demand profiles are the same all along the year, we can distribute the total electricity LEV consumptions between working and non-working days, by considering the total number of days for each type along the entire year. The profile for the deduced daily electricity demand in each case is deduced by applying the probability distribution function of eq.4.

Assuming for the year 2030 the conservation of the sectorial electricity demand curve shape existing at 2017 (REE, 2017b), we can upgraded it by application of the multiplication factor of the total demand deduced in paragraph 3.2. By adding the two demand profiles: sectorial and LEV demand ones, we obtain the total daily demand profile, both for working and non-working days. Figures 6 to 8 display those demand curves for the three scenarios under consideration.



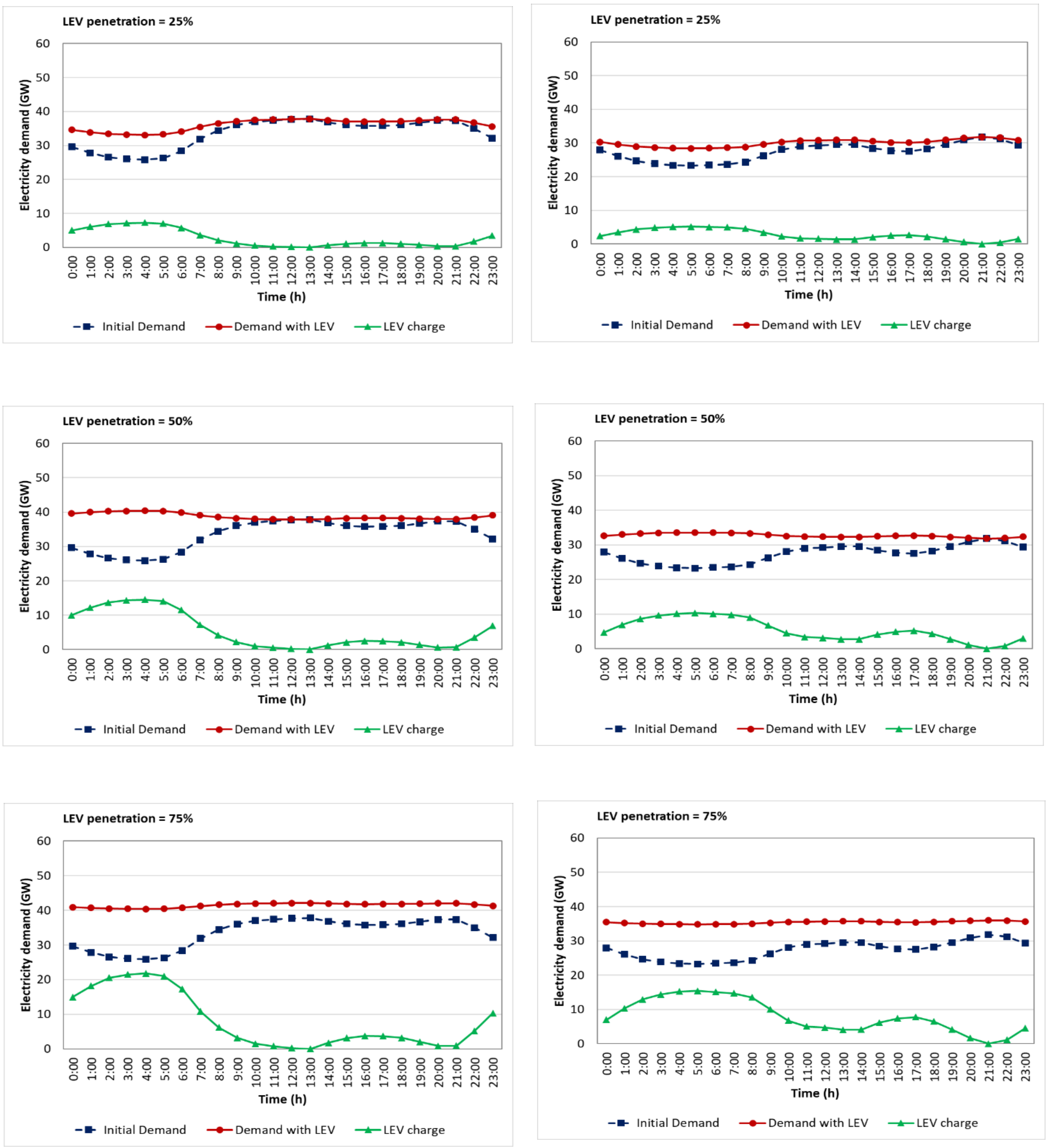
(a) **(b)**

Figure 6. Total demand profiles in the low growth scenario. **(a)** Working day. **(b)** Non-working day.



(a) **(b)**

Figure 7. Total demand profiles in the medium growth scenario. (a) Working day. (b) Non-working day.



(a) **(b)**

Figure 8. Total demand profiles in the high growth scenario. (a) Working day. (b) Non-working day.

To quantify the effect of the LEV penetration with this controlled recharging method, the flat parameter for each profile is calculated by using eq. 7 and, together with the maximum demand power, the obtained values are compared with the corresponding ones for the initial profile. Results are presented in Table 4 for working days where it can be deduced that in all the scenarios a flatter profile than the initial one is obtained. The maximum value of the electricity demand is preserved for most of the cases and only in the higher penetration for the medium growth and in the intermediate and high penetration for the high growth scenario is necessary an increase of power in the electricity system. Similar behavior is obtained for the case of non-working days as table 5 shows.

Table 4. Profile flattening of the demand profile for working days.

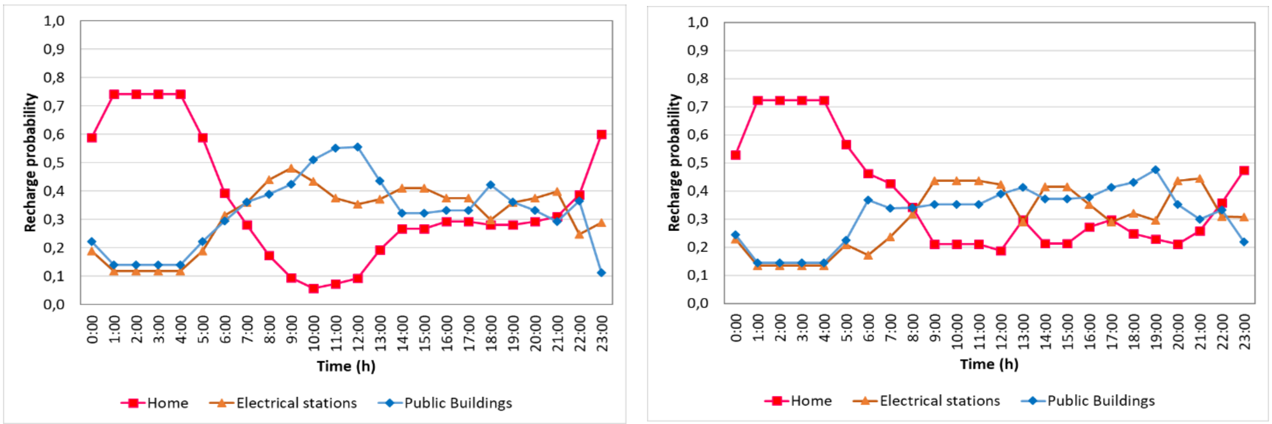
	Initial demand curve			Total demand curve	
Scenario	Maximum (GW)	Flat factor	LEV fraction (%)	Maximum (GW)	Flat factor
Low	37,8	0,883	25	37,8	0,917
			50	37,8	0,950
			75	37,8	0,984
Medium	37,8	0,883	25	37,8	0,928
			50	37,8	0,972
			75	39,5	0,973
High	37,8	0,883	25	37,8	0,954
			50	40,4	0,960
			75	42,1	0,985

Table 5. Profile flattening of the demand profile for non-working days

	Initial demand curve			Total demand curve	
Scenario	Maximum (GW)	Flat factor	LEV fraction (%)	Maximum (GW)	Flat factor
Low	31,8	0,860	25	31,8	0,900
			50	31,8	0,940
			75	31,8	0,980
Medium	31,8	0,860	25	31,8	0,913
			50	31,8	0,966
			75	32,9	0,983
High	31,8	0,860	25	31,8	0,944
			50	33,5	0,975
			75	36,0	0,983

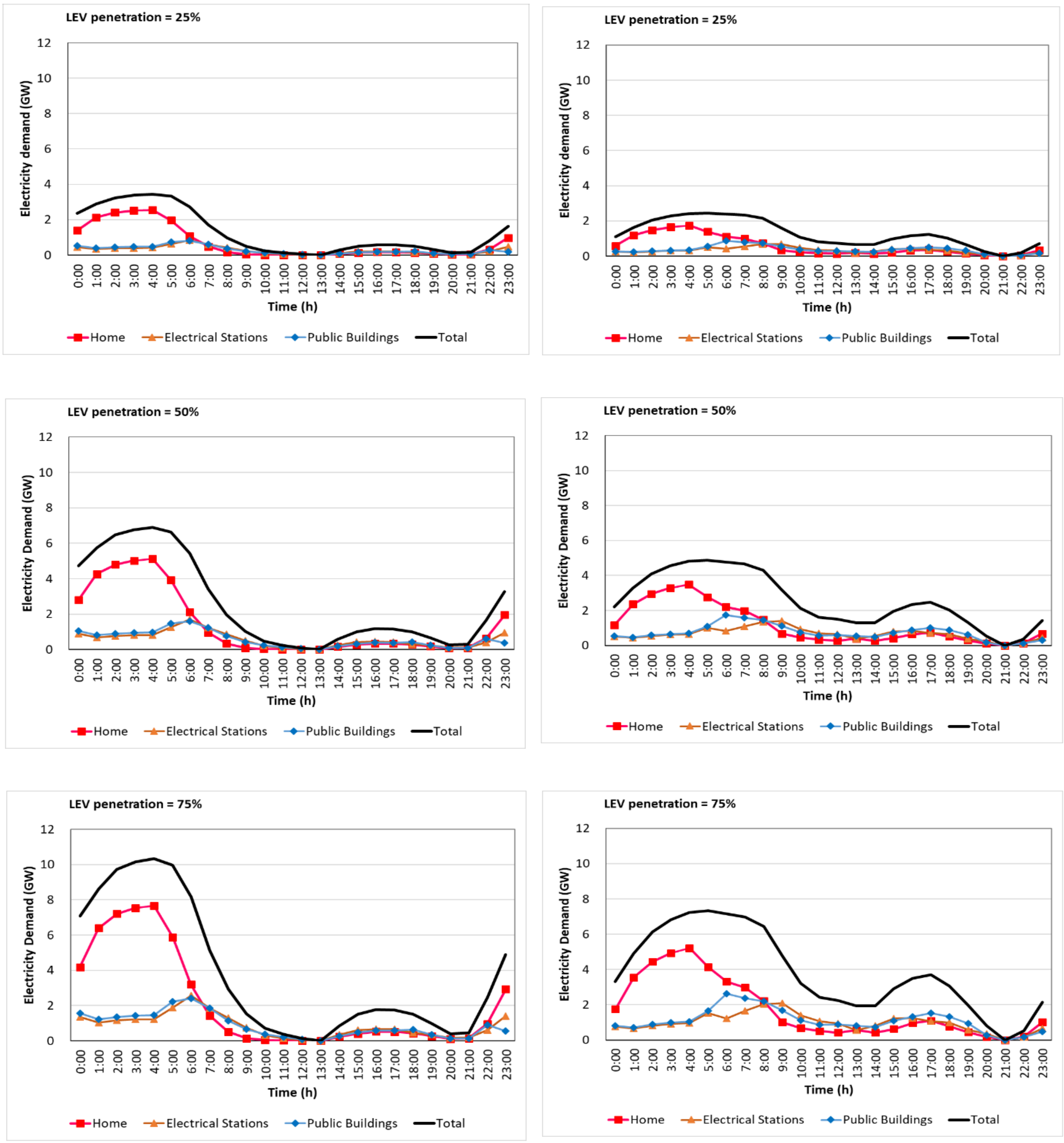
3.4. LEV recharging strategies

Different studies boosted by the Spanish Government have been carried out in relation to LEV recharging strategies (home, electrical stations and public buildings). Based on these studies (AECC, 2018; DGT, 2019; Eurostat, 2018), the daily recharging probability profiles for each of them are deduced (Figure 9), as well as the contribution of each option to the total LEV demand (Figures 10 to 12).



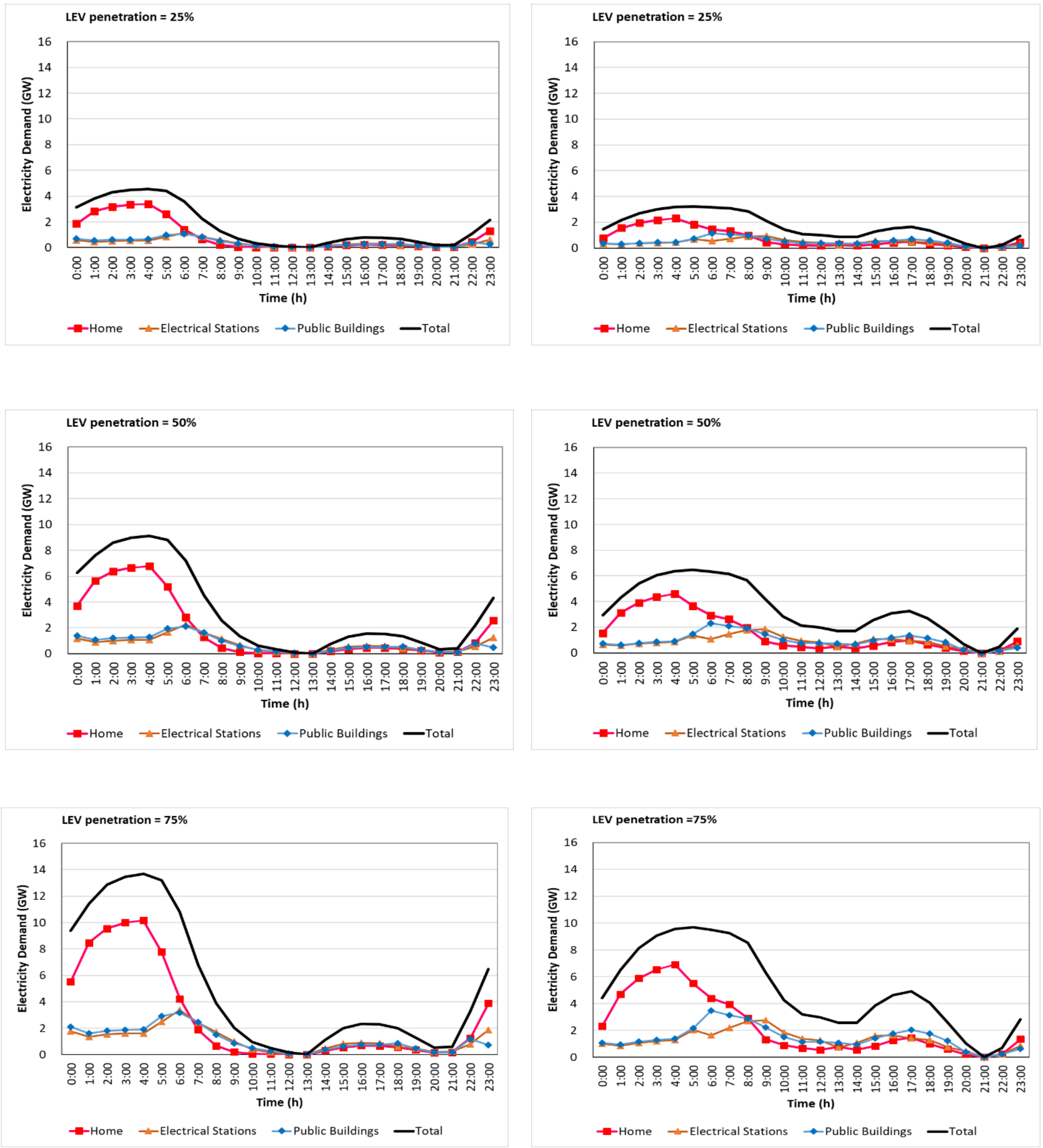
(a) **(b)**

Figure 9. Daily recharging probability profiles. (a) Working day. (b) Non-working day.



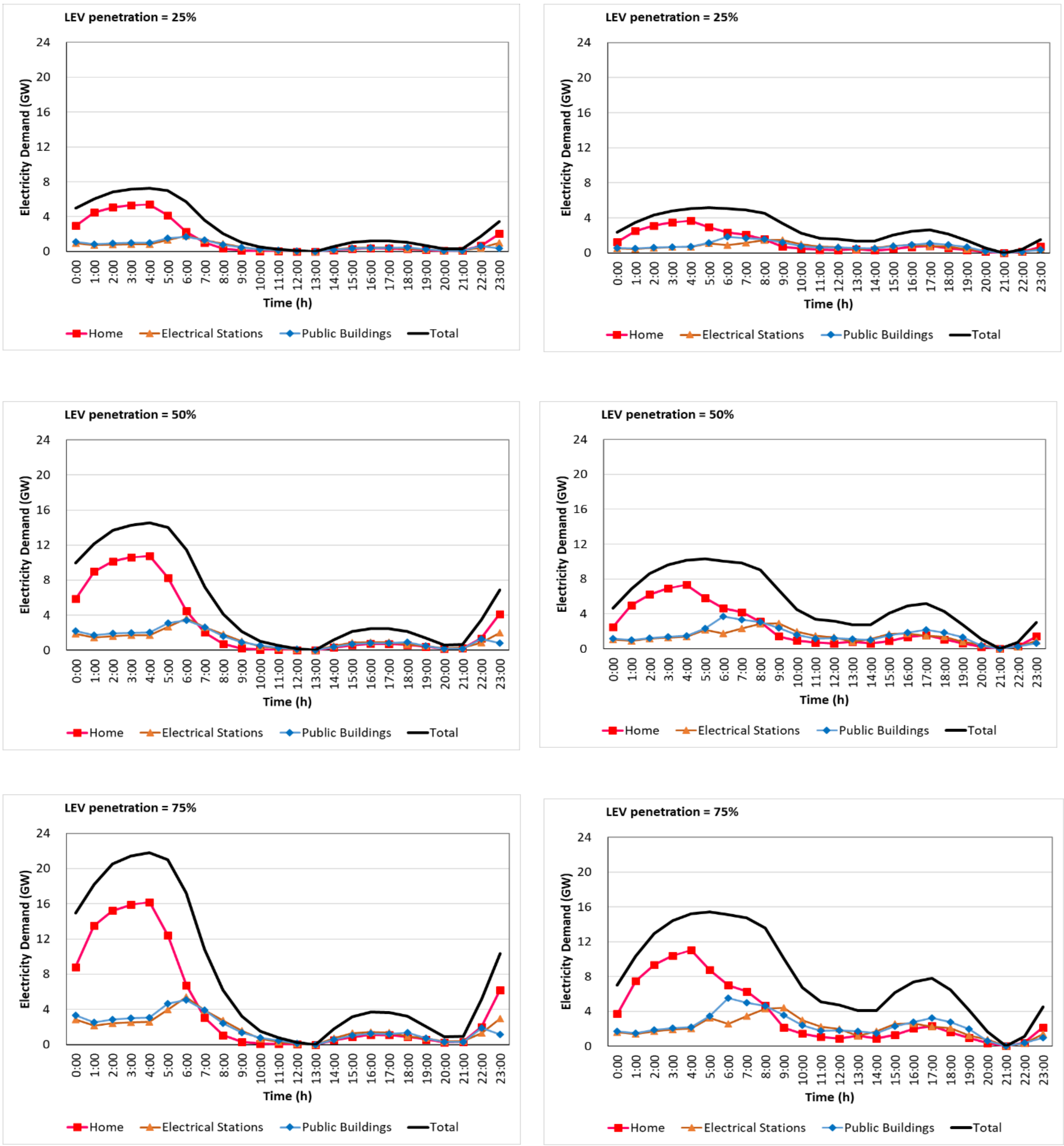
(a) **(b)**

Figure 10. Electricity contributions to LEV demand for low growth scenario. (a) Working day. (b) Non-working day.



(a) **(b)**

Figure 11. Electricity contributions to LEV demand for medium growth scenario. (a) Working day. (b) Non-working day.



(a) **(b)**

Figure 12. Electricity contributions to LEV demand for high growth scenario. (a) Working day. (b) Non-working day.

For the low and medium growth of LEV, the recharge is mainly concentrated in the night hours by using the home option and no increase in the peak value of the total electricity demand is required. When this growth increases, it is also possible to obtain a flat profile after several iterations of the method, where an increase in the peak value is given. Moreover, the contribution of every recharge option remains constant compared to the other scenarios. Numerical results for the different contributions are detailed in table 6 and relative contributions to the total recharge from the different options are presented in figure 13.

Table 6. Power and energy requirements for the different recharge options in working/non-working days

		Home *(Working/Non working day)*		Electrical stations *(Working/Non working day)*		Public buildings *(Working/Non working day)*	
Scenario	LEV fraction (%)	Max Power (GW)	Total Energy (GWh)	Max Power (GW)	Total Energy (GWh)	Max Power (GW)	Total Energy (GWh)
Low	25	2,56/1,74	16,91/13,79	0,85/0,69	6,73/7,88	0,8/0,88	6,84/8,80
	50	5,11/3,48	33,82/27,59	1,71/1,39	13,45/15,76	1,60/1,75	13,68/17,60
	75	7,67/5,22	50,73/41,38	2,56/2,08	20,18/23,64	2,41/2,63	20,51/26,40
Medium	25	3,39/2,30	22,40/18,27	1,13/0,92	8,91/10,44	1,06/1,16	9,06/11,66
	50	6,77/4,61	44,80/36,54	2,26/1,84	17,82/20,88	2,13/2,32	18,12/23,31
	75	10,16/6,91	67,20/54,81	3,39/2,76	26,73/31,32	3,19/3,48	27,18/34,97
High	25	5,39/3,67	35,66/29,09	1,80/1,47	14,19/16,62	1,69/1,85	14,42/18,56
	50	10,78/7,34	71,33/58,18	3,60/2,93	28,37/33,24	3,38/3,70	28,85/37,12
	75	16,17/11,01	106,99/87,27	5,40/4,40	42,56/49,87	5,08/5,54	43,27/55,68

(a) **(b)**

Figure 13. Relative contributions of each recharging mode. (a) Working day. (b) Non-working day.

4. Conclusions

The foreseeable high penetration of light electric vehicles (LEV) in the transport fleet of any country generates an increase in electricity demand, whose daily distribution should be optimized to avoid a substantial increment of the peak value in the existing electricity demand curve prior to the LEV penetration. This optimization would help to avoid the requirement for uploading of the actual installed power in the country. A methodology to optimize the daily distribution of this LEV electricity demand has been developed in this work. This methodology is based on the distribution of the LEV recharge by following an inverse trend when compared with the initial electricity consumption from the other demand sectors, apart from transport. The electricity consumption for LEV recharging is assigned to each time interval by the application to this recharge process of a distribution function, deduced from the initial demand curve by giving high priority to the valleys and maintaining as much as possible its peak value. Flattening of the total electricity demand curve is analyzed and the methodology iterates until a fixed improved value is obtained with the minimum impact of the initial peak value. The obtained LEV demand distribution is later divided among the different recharging options, such as: home, electrical stations and public buildings. The distribution probability along the day for the use of these different recharge options is deduced from reliable studies about driving patterns. In this way, an optimal scenario for recharge is deduced and its application should be addressed from the development of tariff structures and social campaigns.

This methodology has been applied to the case of Spain by the year 2030 assuming three different scenarios for the growth of the light vehicle fleet, that to say: cars and motorcycles, with a low, medium and high growth, respectively. For each of these scenarios, three different levels of penetration for the electric vehicles were considered: 25%, 50% and 75% of the total fleet. Considering the different driving behavior and electricity consumption for working and non-working days, two different initial electricity demand profiles were used, deduced from the database of official organizations, and extrapolated to 2030. Results from the methodology indicate an improvement in the profile flattening up to reach 0,972, maintaining the peak value in the initial value of 37,8 GW. Only in the case of the medium growth scenario with 75% penetration and the high growth with 50% and 75% LEV penetrations was necessary to increase the peak value in a 5%,7% and 11.4%, respectively, but with high flattening in all of them, higher than 0,95, so the peak value was maintained almost all the time along the day. The allocation of the recharge between the different systems: home, electrical stations and public buildings, is dominated by the home option in all the scenarios, with a share in the order of 50% of the total demand, concentrated in the night hours.

This study has verified that it is possible a high penetration of LEV in the fleet of Spain by 2030 without increasing peak load, making use of the temporal valleys and optimally rescheduling the electricity demand increase among the different recharging options. Governments should play a key role when applying this methodology. Adequate policies should be carried out in order to ensure the installation of the required recharging points of any of the options, different taxes of recharging depending on the hour, subsidies for recharging during nights at home, etc. Future research will explore how these incentives would affect the expected recharging contributions. Moreover, future works will also study how the electricity demand increase could be covered with renewable energy sources, with the support of the grid or just in island configuration. Additionally, the methodology has been oriented to the search for flat profiles, but it could be applied to other requirements on the profile shape, such as to obtain the maximum exploitation of the generation profiles coming from renewable sources, such as solar photovoltaic.

Acknowledgment

One of the authors was supported by the Generalitat Valenciana under the grant ACIF/2018/106.

References

Adnan, N., Nordin, S.M., Rahman, I., Amini, M.H., 2017. A market modeling review study on predicting Malaysian consumer behavior towards widespread adoption of PHEV/EV. Environ. Sci. Pollut. Res. 24, 17955–17975. https://doi.org/10.1007/s11356-017-9153-8

AECC, 2018. Recharge electric vehicles [WWW Document]. URL http://www.aedecc.com/enlaces-de-interes/informacion-estadistica/ (accessed 8.5.19).

Ahmadi, L., Croiset, E., Elkamel, A., Douglas, P., Unbangluang, W., Entchev, E., 2012. Impact of PHEVs Penetration on Ontario's Electricity Grid and Environmental Considerations. Energies 5, 5019–5037. https://doi.org/10.3390/en5125019

Akitt, J.W., 2018. Some observations on the greenhouse effect at the Earth's surface. Spectrochim. Acta Part A Mol. Biomol. Spectrosc. 188, 127–134. https://doi.org/10.1016/J.SAA.2017.06.051

Al-Alawi, B.M., Bradley, T.H., 2013. Review of hybrid, plug-in hybrid, and electric vehicle market modeling Studies. Renew. Sustain. Energy Rev. 21, 190–203. https://doi.org/10.1016/j.rser.2012.12.048

Alhazmi, Y.A., Mostafa, H.A., Salama, M.M.A., 2017. Optimal allocation for electric vehicle charging stations using Trip Success Ratio. Int. J. Electr. Power Energy Syst. 91, 101–116. https://doi.org/10.1016/j.ijepes.2017.03.009

Bagher Sadati, S.M., Moshtagh, J., Shafie-khah, M., Rastgou, A., Catalão, J.P.S., 2019. Operational scheduling of a smart distribution system considering electric vehicles parking lot: A bi-level approach. Int. J. Electr. Power Energy Syst. 105, 159–178. https://doi.org/10.1016/J.IJEPES.2018.08.021

Baran, R., Legey, L.F.L., 2013. The introduction of electric vehicles in Brazil: Impacts on oil and electricity consumption. Technol. Forecast. Soc. Change 80, 907–917. https://doi.org/10.1016/J.TECHFORE.2012.10.024

Bjerkan, K.Y., Nørbech, T.E., Nordtømme, M.E., 2016. Incentives for promoting Battery Electric Vehicle (BEV) adoption in Norway. Transp. Res. Part D Transp. Environ. 43, 169–180. https://doi.org/10.1016/J.TRD.2015.12.002

Canals Casals, L., Martinez-Laserna, E., Amante García, B., Nieto, N., 2016. Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction. J. Clean. Prod. 127, 425–437. https://doi.org/10.1016/j.jclepro.2016.03.120

Ceballos Delgado, J.E., Caicedo Bravo, E., Ospina Arango, S., 2016. A Methodological Proposal to Measure the Impact of Electric Vehicles on the Electric Grid. Ingeniería 21, 154–175. https://doi.org/10.14483/udistrital.jour.reving.2016.2.a03

Clairand, J.-M., Rodríguez-García, J., Álvarez-Bel, C., 2018. Electric Vehicle Charging Strategy for Isolated Systems with High Penetration of Renewable Generation. Energies 11, 3188. https://doi.org/10.3390/en11113188

Dang, Q., 2018. Electric Vehicle (EV) Charging Management and Relieve Impacts in Grids. 9th IEEE Int. Symp. Power Electron. Distrib. Gener. Syst. https://doi.org/10.1109/PEDG.2018.8447802

Dang, Q., Huo, Y., 2018. Modeling EV fleet Load in Distribution Grids: A Data-Driven Approach, in: 2018 IEEE Transportation Electrification Conference and Expo (ITEC). IEEE, pp. 720–724. https://doi.org/10.1109/ITEC.2018.8450195

Danté, A.W., Agbossou, K., Kelouwani, S., Cardenas, A., Bouchard, J., 2019. Online modeling and identification of plug-in electric vehicles sharing a residential station. Int. J. Electr. Power Energy Syst. 108, 162–176. https://doi.org/10.1016/J.IJEPES.2018.12.024

Deb, S., Tammi, K., Kalita, K., Mahanta, P., 2018. Impact of Electric Vehicle Charging Station Load on Distribution Network. Energies 11, 178. https://doi.org/10.3390/en11010178

Desai, R.R., Chen, R.B., Armington, W., 2018. A Pattern Analysis of Daily Electric Vehicle Charging Profiles: Operational Efficiency and Environmental Impacts. J. Adv. Transp. 2018, 1–15.

https://doi.org/10.1155/2018/6930932

DGT, 2019. Traffic information [WWW Document]. URL http://infocar.dgt.es/etraffic/ (accessed 9.19.19).

DGT, 2017. Vehicle fleet historical data base [WWW Document]. URL http://www.dgt.es/es/seguridad-vial/estadisticas-e-indicadores/parque-vehiculos/series-historicas/ (accessed 1.2.19).

Dijk, M., Orsato, R.J., Kemp, R., 2013. The emergence of an electric mobility trajectory. Energy Policy 52, 135–145. https://doi.org/10.1016/J.ENPOL.2012.04.024

Eurostat, 2018. Database - Eurostat [WWW Document]. URL https://ec.europa.eu/eurostat/web/lfs/data/database (accessed 8.2.19).

Galiveeti, H.R., Goswami, A.K., Dev Choudhury, N.B., 2018. Impact of plug-in electric vehicles and distributed generation on reliability of distribution systems. Eng. Sci. Technol. an Int. J. 21, 50–59. https://doi.org/10.1016/J.JESTCH.2018.01.005

Gong, L., Cao, W., Liu, K., Zhao, J., Li, X., 2018. Spatial and Temporal Optimization Strategy for Plug-In Electric Vehicle Charging to Mitigate Impacts on Distribution Network. Energies 11, 1373. https://doi.org/10.3390/en11061373

Hasan, M.A., Frame, D.J., Chapman, R., Archie, K.M., 2019. Emissions from the road transport sector of New Zealand: key drivers and challenges. Environ. Sci. Pollut. Res. 26, 23937–23957. https://doi.org/10.1007/s11356-019-05734-6

IDAE, 2012. Technological electric mobility map [WWW Document]. URL http://www.idae.es/uploads/documentos/documentos_Movilidad_Electrica_ACC_c603f868.pdf (accessed 1.7.19).

INE, 2018. Average distance covered by vehicles fleet [WWW Document]. URL http://www.ine.es/jaxi/Tabla.htm?path=/t25/p500/2008/p10/l0/&file=10020.px&L=0 (accessed 12.30.18).

Limmer, S., Rodemann, T., 2019. Peak load reduction through dynamic pricing for electric vehicle charging. Int. J. Electr. Power Energy Syst. 113, 117–128. https://doi.org/10.1016/J.IJEPES.2019.05.031

Liu, Z., Wu, Q., Nielsen, A., Wang, Y., 2014. Day-Ahead Energy Planning with 100% Electric Vehicle Penetration in the Nordic Region by 2050. Energies 7, 1733–1749. https://doi.org/10.3390/en7031733

López, M.A., de la Torre, S., Martín, S., Aguado, J.A., 2015. Demand-side management in smart grid operation considering electric vehicles load shifting and vehicle-to-grid support. Int. J. Electr. Power Energy Syst. 64, 689–698. https://doi.org/10.1016/J.IJEPES.2014.07.065

Luca de Tena, D., Pregger, T., 2018. Impact of electric vehicles on a future renewable energy-based power system in Europe with a focus on Germany. Int. J. Energy Res. 42, 2670–2685. https://doi.org/10.1002/er.4056

Mao, D., Gao, Z., Wang, J., 2019. An integrated algorithm for evaluating plug-in electric vehicle’s impact on the state of power grid assets. Int. J. Electr. Power Energy Syst. 105, 793–802. https://doi.org/10.1016/J.IJEPES.2018.09.028

Martínez-Lao, J., Montoya, F.G., Montoya, M.G., Manzano-Agugliaro, F., 2017. Electric vehicles in Spain: An overview of charging systems [WWW Document]. Renew. Sustain. Energy Rev. https://doi.org/10.1016/J.RSER.2016.11.239

Morrissey, P., Weldon, P., O’Mahony, M., 2016. Future standard and fast charging infrastructure planning: An analysis of electric vehicle charging behaviour. Energy Policy 89, 257–270. https://doi.org/10.1016/J.ENPOL.2015.12.001

Ortega-Vazquez, M.A., Bouffard, F., Silva, V., 2013. Electric Vehicle Aggregator/System Operator Coordination for Charging Scheduling and Services Procurement. IEEE Trans. Power Syst. 28, 1806–1815. https://doi.org/10.1109/TPWRS.2012.2221750

PNIEC, 2019. Spanish climate change draft law [WWW Document]. URL https://www.miteco.gob.es/es/prensa/ultimas-noticias/el-consejo-de-ministros-da-luz-verde-al-anteproyecto-de-ley-de-cambio-climático-/tcm:30-487294 (accessed 4.12.19).

REE, 2018. Electric mobility guide for local entities [WWW Document]. URL https://www.ree.es/sites/default/files/downloadable/Guia_movilidad_electrica_para_entidades_locales.pdf (accessed 7.31.19).

REE, 2017a. Historical Data Base [WWW Document]. URL https://www.ree.es/es/estadisticas-del-sistema-electrico-espanol/series-estadisticas/series-estadisticas-nacionales (accessed 12.26.18).

REE, 2017b. Electrical demand, energy generation structure and CO2 emissions [WWW Document]. URL https://demanda.ree.es/visiona/peninsula/demanda/total/2018-10-16 (accessed 12.27.18).

Su, J., Lie, T.T., Zamora, R., 2019. Modelling of large-scale electric vehicles charging demand: A New Zealand case study. Electr. Power Syst. Res. 167, 171–182. https://doi.org/10.1016/J.EPSR.2018.10.030

Sundstrom, O., Binding, C., 2012. Flexible Charging Optimization for Electric Vehicles Considering Distribution Grid Constraints. IEEE Trans. Smart Grid 3, 26–37. https://doi.org/10.1109/TSG.2011.2168431

Teixeira, A.C.R., Sodré, J.R., 2018. Impacts of replacement of engine powered vehicles by electric vehicles on energy consumption and CO2 emissions. Transp. Res. Part D Transp. Environ. 59, 375–384. https://doi.org/10.1016/J.TRD.2018.01.004

Tietge, U., Díaz, S., Mock, P., German, J., Bandivadekar, A., Ligterink, N., 2016a. From laboratory to road: A 2016 update of official and “real-world” fuel consumption and CO2 values for passenger cars in Europe. Int. Counc. Clean Transp.

Tietge, U., Mock, P., Zacharof, N., Franco, V., 2016b. Real-world fuel consumption of popular European passenger car models | International Council on Clean Transportation. Int. Counc. Clean Transp.

Valsera-Naranjo, E., Sumper, A., Villafafila-Robles, R., Martínez-Vicente, D., Valsera-Naranjo, E., Sumper, A., Villafafila-Robles, R., Martínez-Vicente, D., 2012. Probabilistic Method to Assess the Impact of Charging of Electric Vehicles on Distribution Grids. Energies 5, 1503–1531. https://doi.org/10.3390/en5051503

Wang, L., Chen, B., 2019. Distributed control for large-scale plug-in electric vehicle charging with a consensus algorithm. Int. J. Electr. Power Energy Syst. 109, 369–383. https://doi.org/10.1016/J.IJEPES.2019.02.020

Wang, X., Wei, X., Dai, H., 2019. Estimation of state of health of lithium-ion batteries based on charge transfer resistance considering different temperature and state of charge. J. Energy Storage 21, 618–631. https://doi.org/10.1016/j.est.2018.11.020

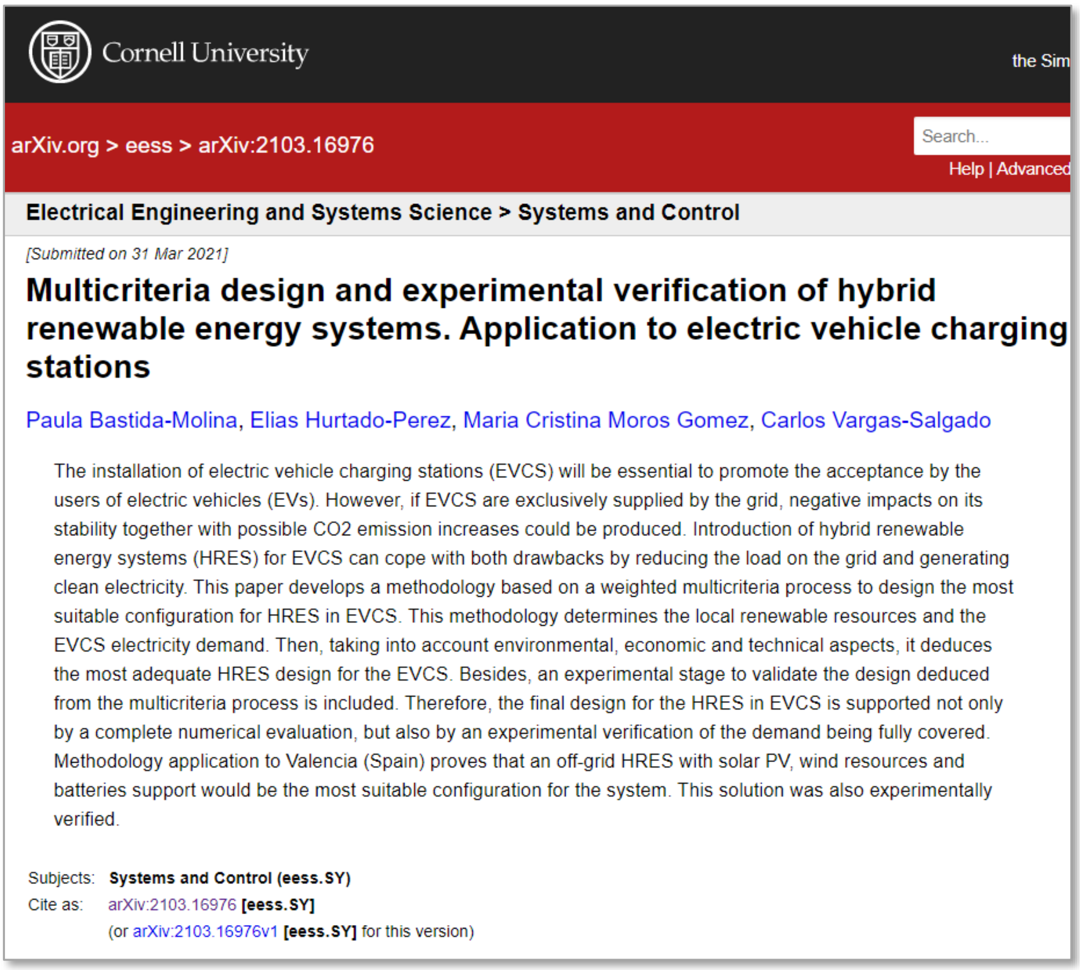
Wang, Y., Infield, D., 2018. Markov Chain Monte Carlo simulation of electric vehicle use for network integration studies. Int. J. Electr. Power Energy Syst. 99, 85–94. https://doi.org/10.1016/J.IJEPES.2018.01.008

Zhang, K., Ma, J., Zhao, X., Liu, X., Zhang, Y., 2019. Parameter Identification and State of Charge Estimation of NMC Cells Based on Improved Ant Lion Optimizer. Math. Probl. Eng. 1–18. https://doi.org/10.1155/2019/4961045

Zhao, X., Ma, J., Wang, S., Ye, Y., Wu, Y., Yu, M., 2018a. Developing an electric vehicle urban driving cycle to study differences in energy consumption. Environ. Sci. Pollut. Res. 26, 13839–13853. https://doi.org/10.1007/s11356-018-3541-6

Zhao, X., Yu, Q., Ma, J., Wu, Y., Yu, M.S., Ye, Y., 2018b. Development of a Representative EV Urban Driving Cycle Based on a k- Means and SVM Hybrid Clustering Algorithm. J. Adv. Transp. 1–18. https://doi.org/10.1155/2018/1890753

2.3. Multicriteria design and experimental verification of hybrid renewable energy systems. Application to electric vehicle charging stations



Electrical Engineering and Systems Science > Systems and Control

[Submitted on 31 Mar 2021]

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Paula Bastida-Molina, Elias Hurtado-Perez, Maria Cristina Moros Gomez, Carlos Vargas-Salgado

The installation of electric vehicle charging stations (EVCS) will be essential to promote the acceptance by the users of electric vehicles (EVs). However, if EVCS are exclusively supplied by the grid, negative impacts on its stability together with possible CO2 emission increases could be produced. Introduction of hybrid renewable energy systems (HRES) for EVCS can cope with both drawbacks by reducing the load on the grid and generating clean electricity. This paper develops a methodology based on a weighted multicriteria process to design the most suitable configuration for HRES in EVCS. This methodology determines the local renewable resources and the EVCS electricity demand. Then, taking into account environmental, economic and technical aspects, it deduces the most adequate HRES design for the EVCS. Besides, an experimental stage to validate the design deduced from the multicriteria process is included. Therefore, the final design for the HRES in EVCS is supported not only by a complete numerical evaluation, but also by an experimental verification of the demand being fully covered. Methodology application to Valencia (Spain) proves that an off-grid HRES with solar PV, wind resources and batteries support would be the most suitable configuration for the system. This solution was also experimentally verified.

Subjects: **Systems and Control (eess.SY)**
Cite as: arXiv:2103.16976 **[eess.SY]**
(or arXiv:2103.16976v1 **[eess.SY]** for this version)

Multicriteria design and experimental verification of hybrid renewable energy systems. Application to electric vehicle charging stations

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Abstract

The installation of electric vehicle charging stations (EVCS) will be essential to promote the acceptance by the users of electric vehicles (EVs). However, if EVCS are exclusively supplied by the grid, negative impacts on its stability together with possible CO_2 emission increases could be produced. Introduction of hybrid renewable energy systems (HRES) for EVCS can cope with both drawbacks by reducing the load on the grid and generating clean electricity. This paper develops a methodology based on a weighted multicriteria process to design the most suitable configuration for HRES in EVCS. This methodology determines the local renewable resources and the EVCS electricity demand. Then, taking into account environmental, economic and technical aspects, it deduces the most adequate HRES design for the EVCS. Besides, an experimental stage to validate the design deduced from the multicriteria process is included. Therefore, the final design for the HRES in EVCS is supported not only by a complete numerical evaluation, but also by an experimental verification of the demand being fully covered. Methodology application to Valencia (Spain) proves that an off-grid HRES with solar PV, wind resources and batteries support would be the most suitable configuration for the system. This solution was also experimentally verified.

Keyword

Electric vehicles, charging station, hybrid renewable energy system, multicriteria assessment, modelling, experimental verification.

1. Introduction

By the end of the 20th century, climate change became one of the most disturbing global issues. The exorbitant amount of greenhouse gases (GHG), especially CO_2 emissions, sent to the atmosphere is leading to an environmental destruction, whose effects could be very detrimental for the nature and, as a consequence, for our society (Akitt, 2018; Dino and Meral Akgül, 2019).

Transport sector has traditionally depended on fossil fuels, which are non-renewable resources and the main responsible for CO_2 emissions (Woo et al., 2017). For instance, almost 93% of the global transport consumption in 2017 derived from oil products (IEA, 2017b). Moreover, around 23% of total CO_2 emissions in the world were generated by this sector (Teixeira and Sodré, 2018). Due to two different reasons: finite oil resources and environmental concerns, efforts have focused on the electrification of the transportation sector (Dijk et al., 2013). Hence, a high penetration of EVs is expected to happen in almost all developed countries in a short/mid-term future (Liu et al., 2014; Su et al., 2019). Despite the environmental suitability of these vehicles while riding on the roads, two drawbacks arise in this context. On the one hand, the extra electricity generated to cover EVs demand could lead to an increase of CO_2 emissions depending on the carbon intensity (CI) of the power sources involved in the electricity generation system (Álvarez Fernández, 2018; Manjunath and Gross, 2017). On the other hand, this electricity increase could create negative impacts on the grid when recharging strategies remain unscheduled, concentrating the electrical consumption in peak demand hours (Bastida-Molina et al., 2020b; Deb et al., 2018; Dixon et al., 2020; Galiveeti et al., 2018). The use of microgrids with integration of renewable sources to recharge EVs emerges as a solution to cope with the two previously mentioned difficulties (Wu et al., 2021). First, the low CI of the renewable sources would decrease the CO_2 emissions generated during the electricity generation stage. Secondly, the pressure on the grid would decrease due to the demand reduction by using these microgrids (Quddus et al., 2019). These microgrids, known as Hybrid Renewable Energy Systems (HRES), combine the potential of different renewable sources: solar photovoltaic, wind generators, biomass gasifiers, etc., with the possibility to be supported by the grid or by other dispatchable resources as batteries, diesel generators or even hydrogen system in the most cutting-edge systems.

Currently, the number of electric vehicle charging stations (EVCS) is very limited and far enough to cope with the expected introduction of electric vehicles (EVs) in the coming years. In fact, the concerns of being unable to find an EVCS to recharge the EVs emerges as one of the highest barriers for the users to acquire this kind of vehicles (Xie et al., 2018). Therefore, the development of fast recharging strategies together with the integration of renewable sources result essential to the integration and acceptance of EVs in our society. Several studies have addressed these topics. For instance, Huang et al. (Huang et al., 2019) developed a novel Geographic Information System to select the optimal location for the installation of new renewable EVCS depending on the current number of charging stations and renewable potentials, with the aim of minimizing the life cycle cost of the EVCS. Regarding the design process for the configuration of the HRES for EVCS, Domínguez-Navarro et al. (Domínguez-Navarro et al., 2019) used a genetic algorithm to determine the HRES configuration for EVCS that maximizes the profit measured by its Net Present Cost (NPC), selecting finally a configuration with renewable generation and storage resources. Chowdhury et al. (Chowdhury et al., 2018) studied the incorporation of a HRES for EVCS supported by the grid at the University Campus in Dhaka (Bangladesh), achieving a 21% of renewable generation and reducing GHG emissions by 52.9 tCO_2/year. They used software HOMER® (HOMER, 2020) for the optimization process, looking for the lowest NPC configuration. Study (Vermaak and Kusakana, 2014) presents the configuration design process of an energy storage HRES in a rural community of the Democratic Republic of Congo with no access to the electrical grid for the recharge of electric Tuk-tuks (a traditional means of transport of the Democratic Republic of Congo). The installation of this HRES enhances the replacement of the traditional combustion engine Tuk-tuk vehicles by electric ones, together with the future deployment of EVs in these rural areas. Similarly, research in (Nizam and Wicaksono, 2019) boosts also the use of off-grid HRES systems for EVCS in rural remote areas. Namely, this research discusses the best configuration option for an EVCS in Labuhan Bajo (Indonesia) considering three types of batteries for energy storage: Lead Acid, Li-Ion (NCA) and Lithium Ferro Phosphate (LFP).

The methodologies presented in these above-mentioned studies only rely on economic parameters to design the HRES configuration for EVCS. However, other studies indicate that more parameters have to be considered for the system optimisation. For instance, Karmaker et al. (Karmaker et al., 2018) used also the HOMER ® code to decide the configuration of the HRES in an EVCS, but analized also the technical, economic and environmental feasibility of the selected configuration. Rashid et al. (Rashid et al., 2019) focus the study on the electrical production and cost analysis, whereas Tulpule et al. (Tulpule et al., 2013) included environmental impacts, together with economic ones, in the design.

Another important issue to consider in the application of HRES to EVCS is the experimental validation of any optimized design. There are very few studies in this direction. In particular (Losev et al., 2020; Savio et al., 2019) state that, despite the suitability of numerical methodologies, the experimental verification of the HRES configuration ensures its reliability and real implementation. Research (Losev et al., 2020) describes the experimental results of a fast EVCS based on solar PV, wind sources and fuel cells and the necessity of implementing these systems in many remote regions of Russia with grid-connection problems. Research (Savio et al., 2019) focuses on the power system analyses of a microgrid that combines solar PV, utility grid and batteries to supply a fast charging EVCS. The experimental results verify the current flow and power balance of the system that were previously calculated with a simulation software.

Hence, this paper proposes a novel methodology that tries to cope with both aspects: to develop a weighted iterative multicriteria process based on economic, environmental and technical parameters to design the configuration of HRES in EVCS, and the experimental validation of the deduced designs by using a power balance and State of Charge (SOC) boundary criteria. The method is based on a previous characterization stage of the system in terms of energy by determination of the electricity demand of the EVCS and the evaluation of the local energy resources.

The study includes the application of the developed methodology, including the experimental verification, to Valencia (Spain). This region is expected to have a step mobility transition to EVs according to the Electric Mobility Plan (“Electric Mobility Plan,” 2017), approved in 2017 by the Valencian Ministry of Sustainable Economy, Productive Sectors, Trade and Work. The plan aims to achieve an increasing penetration of both EVs and recharging points:

2030 EVs and 105/350 fast/semi-fast recharging points by the year 2020; 78.100 EVs and 210/950 fast/semi-fast recharging points in the year 2025 and 260.000 EVs and 270/2100 fast/semi-fast recharging points by the year 2030. Moreover, this Plan is framed within the Valencian Climate Change and Energy Strategy 2030 (GVA, 2017), which looks for the reduction of the GHG emissions, the inclusion of renewable sources in electricity generation and the energy efficiency enhancement by 2030. This legal framework boosts the installation of fast recharge points for the expected EVs fleet in the Comunidad Valenciana. Moreover, the renewable supply of such stations arises also as an environmental breakthrough to achieve, in line with that Strategy 2030. In this context, the application of the methodology presented in this paper for the design of a HRES for EVCS in the roads of Valencia has a remarkable interest.

The paper is organized as follows: section 2 presents the methodology, section 3 describes the case study of Valencia and section 4 provides the results and discussion of this application. Finally, the paper conclusions are outlined in section 5.

2. Methodology

This section presents the methodology developed to design a Hybrid Renewable Energy System to supply the electricity demand of EVCS. The method contemplates four different stages. The first one comprises the electricity demand modelling of the EVCS, together with the evaluation of the local energy resources analysis to determine the renewable technologies to be considered. The second phase makes an initial predesign of the system based on the NPC optimization by using the HOMER® software. Then, all the obtained configurations are evaluated and ranked in the third stage by using a multicriteria process that takes into account the technical, economic and environmental aspects for each of them. Finally, the last phase of the methodology addresses the experimental validation of the best-positioned configurations.

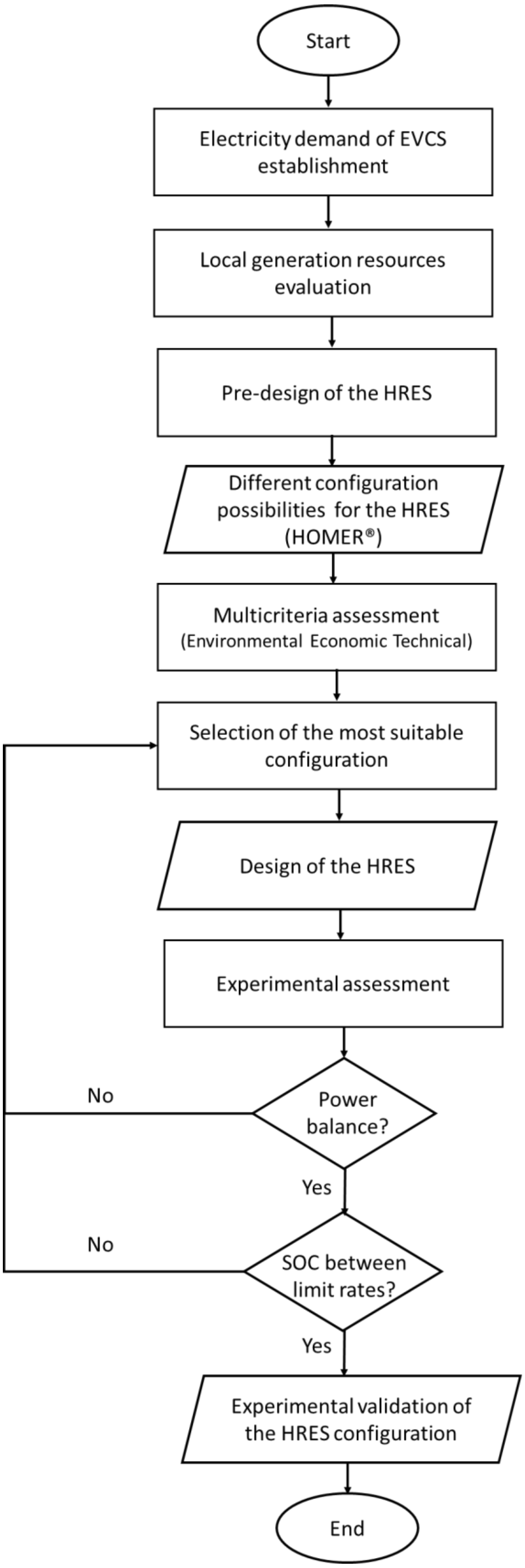


Figure 1. Flowchart of the proposed methodology.

2.1. Electricity demand of electric vehicles charging stations

EVCS demand depends on total amount of EVs refilling their batteries in the station and on the power consumption of each of these EVs. Regarding the first factor, this methodology establishes a temporary curve for each type of EV recharging in an EVCS: Battery Electric Vehicles (BEVs) and Plug-in-Hybrid Electric Vehicles (PHEVs), considering also their nature (cars and motorcycles). Taking a base fleet affected by two rates (penetration and recharge of EVs in the station (Bastida-Molina et al., 2020b)), the method determines each curve making use of eq.(1):

$$n(i,t) = N(t) \cdot f(i) \cdot r(i) \tag{1}$$

where n(i,t) is the number of EV of type i (i=1 for BEV cars, i=2 for PHEV car and i=3 for BEV motorcycle) recharging at time t; N(t) represents the total number of vehicles on the road passing by the EVCS at that time, f(i) represents the fraction of these vehicles being electric and r(i) is the rate of those EVs needing recharge.

Referring to the second factor, the capacity of the battery, together with its state of charge (SOC) and the time duration of the recharging process determine the power demand of each EV type while recharging (Karmaker et al., 2018). This power demand is given by eq.(2):

$$P_{EV}(i) = \frac{C_{bat}(i) \cdot [SOC_{Max} - SOC]}{T(i)} \tag{2}$$

Where $P_{EV}(i)$ corresponds to the power demand of EVs; $C_{bat}(i)$ represents the capacity of the EVs' batteries; SOC_{Max} is the maximum level of the batteries' state of charge; SOC corresponds to the real level of the batteries state of charge and $T(i)$ represents the time duration of the recharging process.

Finally, the power demand of the EVCS, $P_{EVCS}(t)$ arises as the electrical demand of every type of EV recharging there, like eq.(3) indicates:

$$P_{EVCS}(t) = \sum_{i} n(i,t) \cdot P_{EV}(i) \tag{3}$$

2.2. Local energy resources evaluation

At this stage, the methodology should determine the availability of renewable resources to be included in the HRES for EVCS. This implies the determination, for the place where the EVCS will be located and with the highest possible resolution, of some parameters: the solar irradiation and the clear index average (Hansen and Xydis, 2020), wind speed measured at the wind turbine height (Chowdhury et al., 2020), the sustainable biomass production availability (Singh and Balachandra, 2019), etc.. Moreover, the necessity to support the system with batteries, the grid or with a generator should be also considered as potential back up to guarantee the reliability of the HRES in the EVCS.

2.3. Predesign of the HRES

HOMER® Pro software (HOMER, 2020) is a well-known and widely used tool in the design of HRES, including its application to EVCS (Nizam and Wicaksono, 2019; Rashid et al., 2019). With the information of the technological options and the local resources to include in the HRES as an input to HOMER®, a list of different configurations for the system, ranked by their NPC, is obtained.

Despite the importance of the economic factor, the design of HRES for EVCS should also rely on environmental and technological criteria (Karmaker et al., 2018). In line with this consideration, the present method utilizes the software HOMER® only in a predesigning phase of the HRES for the EVCS.

2.4. Multicriteria assesment

After the pre-design stage of the HRES, all the configuration options proposed by HOMER® are rank ordered using the methodology proposed in this section (2.4), based on a weighted multicriteria assessment of environmental, economic and technical parameters. This section describes the parameters and the multicriteria methodology.

2.4.1. Environmental criteria

The introduction of EVs is intended for a decarbonisation of the transport sector (Bastida-Molina et al., 2020a; Driscoll et al., 2013; Teixeira and Sodré, 2018). However, a recharge of these vehicles exclusively based on the grid could even lead to an increase of the emissions, depending on the carbon intensity (CI) generation mix of the grid (Álvarez Fernández, 2018; Bastida-Molina et al., 2020a; Manjunath and Gross, 2017). Hence, this methodology proposes two factors to assess the environmental suitability of using a HRES for the EVs recharge in EVCS: CO_2 emissions reduction and renewable generation degree.

CO_2 emissions reduction (EmR)

This parameter determines the relative reduction in carbon emissions while using a HRES instead of the grid alone to supply the EVCS. CO_2 emissions reduction (EmR) can be obtained using eq. (4) .

$$EmR = \frac{\left[E_{grid} \cdot g_{grid}\right] - \left[E_{HRES} \cdot g_{HRES}\right]}{\left[E_{grid} \cdot g_{grid}\right]} \tag{4}$$

Where E_{grid} is the electricity demanded to the grid if the EVCS has no any HRES support; g_{grid} is the emissivity of the electricity from the grid; E_{HRES} is the electricity provided to the EVCS from a HRES, and g_{HRES} is the emissivity of the electricity from the HRES.

Specifically, the emissivity for the HRES (g_{HRES}) corresponds to a weighted combination of the generation resources of the system, which depend on their energy generation influence (eq. (5)).

$$g_{HRES} = \sum_{j} \frac{E_{HRES_j}}{E_{HRES}} \cdot g_j \tag{5}$$

$$E_{HRES} = \sum_j E_{HRES_j}. \tag{6}$$

Being E_{HRES_j} the electricity provided by the component *j* of the HRES and g_j its specific emissivity.

Extreme values for EmR are 0 (no renewable sources in the HRES) and 1 (full renewable system without any CO_2 emission), as eq. (7) indicates:

$$EmR \in \{0,1\} \tag{7}$$

Renewable generation degree (ReG)

The contribution of renewable sources to the electricity consumption of the EVCS is another significant factor when analysing the environmental behaviour of the system (Hurtado et al., 2015). Eq (8) determines this parameter (ReG), where not only the renewable contribution to the HRES take part, but also the renewable percentage of the electricity taken from the grid by the HRES.

$$ReG = \frac{\sum_r E_{HRES_r} + x_r \cdot E_{HRES_{grid}}}{E_{HRES}} \tag{8}$$

Being E_{HRES_r} the electricity coming from the renewable source *r* of the HRES, $E_{HRES_{grid}}$ the electricity taken by the HRES from the grid and x_r the fraction of renewable contribution in $E_{HRES_{grid}}$.

ReG values are in the interval 0 (when no renewable sources are involved in the HRES and in the electricity grid) and 1 (if all the electricity used by the HRES, including the grid, is generated with renewable sources), as eq. (9) reflects:

$$ReG \in \{0,1\} \tag{9}$$

2.4.2. Economic criteria

The importance of a thorough economic analysis for the design of the HRES EVCS appears in a wide range of researches (Nizam and Wicaksono, 2019; Vermaak and Kusakana, 2014; Xu et al., 2020). In this methodology, the economic study uses the levelized cost of energy (LCOE). This is a widely used parameter to compare and evaluate different electricity generation procedures (Hansen, 2019; Ribó-Pérez et al., 2020; Zhang et al., 2020). The LCOE indicates the average total cost of building and operating the corresponding energy system per unit of total electricity generated along its lifetime (Corporate Finance Institute, 2020), as eq. (10) shows:

$$LCOE = \frac{\sum_j \sum_{t=1}^{t=n} \frac{\left(I_{tj} + O\&M_{tj} + F_{tj}\right)}{(1+r)^t}}{\sum_{t=1}^{t=n} \frac{\left(E_{HRES_t}\right)}{(1+r)^t}} \tag{10}$$

Where I_{tj}, $O\&M_{tj}$ and F_{tj}represent the investment cost, operation and maintenance cost and fuel cost respectively of each generation resource j at the time t into consideration of the lifetime of the system (n), whereas r corresponds to the discount rate.

The methodology introduces a normalized LCOE $(NLCOE)$ to compare the LCOE for an EVCS supplied by the grid $\left(LCOE_{grid}\right)$ with the LCOE for an EVCS supplied by the HRES in study $(LCOE_{HRES})$, as eq. (11) indicates:

$$NLCOE = \frac{LCOE_{grid}}{LCOE_{HRES}} \tag{11}$$

Hence, an economic factor (EcF) for the multicriteria analysis can be defined as:

$$EcF= Min\ (1;\ NLCOE) \tag{12}$$

Moreover, EcF values range in the interval of 0 (for very high $LCOE_{HRES}$) and 1 (if the HRES has a lower LCOE that the grid one), as eq. (13) shows:

$$EcF \in \{0,1\} \tag{13}$$

2.4.3. Technical criteria

The technical study comprises two remarkable parameters: the security of supply and the adequacy sizing of the system.

<u>Security of supply (SS)</u>

This factor evaluates the guarantee of electricity supply taking into account the different combination of generation sources and back-up systems in the HRES for EVCS (Ribó-Pérez et al., 2020), as eq. (14) indicates.

$$SS = 1 - \sum_{j} \left(1 - f_j\right) \tag{14}$$

Being $f_j$the reliability of the generation source *j*.

For non-dispatchable generation sources, i.e.: solar PV and wind generation, we can consider the magnitude of the energy contribution related to the demanded one and the fraction of the time these sources are available, as eq. (15) indicates.

$$f_j = Min\left\lfloor 1;\ \frac{E_j}{E_{EVCS}} \right\rfloor \cdot\ \delta_j \tag{15}$$

Where E_j represents the electricity provided by the non-dispatchable sourcesin question, E_{EVCS} is the total electricity demanded by the EVCS and δ_j corresponds to the fraction of hours that the source is available.

For dispatchable electricity sources, such as the grid and the backup generator, eq. (16) determines their feasibility as follows:

$$f_j = Min\left\lfloor 1;\ \frac{P_j}{P_{EVCS}} \right\rfloor \cdot\ \delta_j \tag{16}$$

Where P_j represents the generator maximum power and the contracted power from the grid, and P_{EVCS} corresponds to the maximum power of the EVCS. Values for the security factor δ_j are available for diesel generators (Hidalgo Batista and Villavicencio Proenza, 2011) and for the grid (Kruyt et al., 2009; Sovacool and Mukherjee, 2011).

In the case of the storage battery bank, the feasibility factor can be defined as:

$$f_b = Min\left\lfloor 1;\ \frac{E_b}{E_{EVCS}} \right\rfloor \cdot \delta_b \tag{17}$$

Being E_b the nominal capacity of the battery bank and δ_b the security factor, also available in (Bastida-Molina et al., 2020c).

SS values are in the interval of 0 (when the system cannot ensure the electricity supply at all) and 1 (if the security of supply is completely assured), as eq. (18) reflects:

$$SS \in \{0,1\} \tag{18}$$

Electricity sizing adequacy (ESA)

Finally, this last parameter assesses the adequacy of the system in relation to its power sizing. Systems should be designed in such a way that they cover all the demand requirements, but the minimum excess of generation, as eq. (19) indicates.

$$ESA = Min\left\lfloor 1;\ \frac{E_{EVCS}}{E_{HRES}} \right\rfloor \tag{19}$$

ESA values are in the interval of 0 (when the power sizing is not adequate at all) and 1 (If its power sizing is completely achieved), as eq. (20) indicates:

$$ESA \in \{0,1\} \tag{20}$$

2.4.4. Multicriteria assessment

In this stage, the proposed methodology evaluates all the configuration possibilities obtained in the predesigning phase with HOMER® Pro Software for the HRES EVCS in question. For this evaluation, the methodology applies a weighted multicriteria assessment on each of these configurations based on the above-explained criteria. Hence, a merit figure (CP) is deduced for each configuration option.

Table 1 shows the evaluation criteria together with their corresponding weighting factors. Moreover, eq. (21) describes the multicriteria evaluation for each configuration, where constraint (22) applies.

Table 1. Criteria and weighting factors for the evaluation.

	Criteria	Weighting factor
Environmental	CO_2 emissions reduction (EmR)	α_{EmR}
	Renewable generation degree (ReG)	α_{ReG}
Economic	Economic Factor (EcF)	α_{EcF}
Technologic	Security of supply (SS)	α_{SS}
	Electricity sizing adequacy (ESA)	α_{ESA}

$$CP = \alpha_{EmR} \cdot EmR + \alpha_{ReG} \cdot ReG + \alpha_{EcF} \cdot EcF + \alpha_{SS} \cdot SS + \alpha_{ESA} \cdot ESA \tag{21}$$

$$\alpha_{EmR} + \alpha_{RG} + \alpha_{EcF} + \alpha_{SS} + \alpha_{ESA} = 1 \tag{22}$$

Finally, once all the configurations have been analyzed, they are ranked in accordance with their CP values. Hence, the one with the highest value would be the best design solution for a HRES in an EVCS, based on a complete study of the system including environmental, economic and technical aspects.

2.5. Experimental verification of the hybrid renewable energy system

The last stage of the methodology consists of an experimental verification of the selected design for the HRES in the EVCS after the previously explained multicriteria assessment phase (Pérez-Navarro et al., 2016; Savio et al., 2019). The theoretical design needs to be accurately reproduced in a laboratory with all the required technologies. Therefore, a scaled version of the selected configuration results necessary (Hurtado et al., 2015), being the scale factor (SF) determined by the capabilities of the experimental system to be used (P_{lab}), and the maximum power of the EVCS (P_{EVCS}) as eq. (23) indicates:

$$SF = \frac{P_{EVCS}}{P_{lab}} \tag{23}$$

Consequently, this scale factor affects the EVCS power demand curve, determined in section 2.1., so that the experimental EVCS power demand $\left(P_{EVCS\,exp}(t)\right)$ is determined by eq. (24). The power of each generation system $\left(P_j\right)$ is scaled as well, being the experimental generation power $\left(P_{j\,exp}\right)$ obtained by eq.(25).

$$P_{EVCS\,exp}(t) = \frac{P_{EVCS}(t)}{SF} \tag{24}$$

$$P_{j\,exp} = \frac{P_j}{SF} \tag{25}$$

The methodology imposes two conditions to be satisfied before accepting the system configuration (Bastida-Molina et al., 2020c; Chowdhury et al., 2020; Hurtado et al., 2015). Firstly, the EVCS load requirements should be covered at each time of the day, so to reach this goal the power balance should accept a certain rate of power losses (L) in the system (eq. (26)). Then, for systems with a storage capacity based on batteries, the state of charge (SOC) of these batteries should be all the time in the range between the allowed minimum and maximum values. (eq. (27)).

$$\frac{\left|\sum P_{j\,exp}\,(t) - P_{EVCS\,exp}(t)\right|}{P_{j\,exp}(t)} \leq L \tag{26}$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{27}$$

The fulfilment of these conditions ensures the correct design of the HRES for the EVCS. If any of them were not met, the methodology includes an iterative process on the selection of the theoretical design of the system, following the rank order deduced from the multicriteria assessment.

3. Case study: Valencia (Spain)

The paper applies the previously explained methodology to Valencia, the capital province of the Comunidad Valenciana, located in the East of Spain. This region is experimenting a deep ecological transition in terms of mobility motivated by its Electric Mobility Plan ("Electric Mobility Plan," 2017). The plan establishes as final 2030 objective that the EVs represent 25% of the market share of the Comunidad Valenciana along with establishing one fast recharge point for every ten EVs. The final achievement of these goals would lead to a considerable GHG emission reduction, specifically the Plan foresees a total 622.000 tons of CO_2 emissions decrease. This Plan is framed within the Valencian Climate Change and Energy Strategy 2030 (GVA, 2017), whose three central goals lie in a reduction of the GHG emissions, the renewable sources increase in electricity generation and a substantial energy efficiency enhancement by 2030.

This legal framework boosts the installation of fast recharge points for the expected EVs fleet in the Comunidad Valenciana, namely in the form of EVCS. Moreover, the renewable supply of such stations arises also as an environmental breakthrough to achieve, in line with the above mentioned 2030 Energy Strategy. In this context, we decided to apply the methodology presented in this paper to the design of a HRES for EVCS in the roads of Valencia in an imminent future. Moreover, this work only considers the recharge of light electric vehicles (LEVs) in EVCS with possibilities of recharge: BEV cars, PHEV cars and BEV motorcycles. Nowadays, heavy internal combustion vehicles, like private buses or trucks, represent a 15% of the recharge in petrol stations located at roads of Valencia (DGT, 2019). However, the currently available batteries of their equivalent heavy EVs are not yet developed enough to provide the autonomy desired by these vehicles in roads (Bastida-Molina et al., 2020b). Therefore, it is not realistic to assume this type of vehicles being recharged at EVCS.

3.1. Electricity demand of electric vehicles charging stations

The determination of the EVCS electricity demand in Valencia could be deduced from the current flow of light internal combustion engine vehicles (LICEVs) passing by the roads close to petrol stations in the region. The accurate traffic information for Valencian territory provided by the Spanish data base (DGT, 2019) allowed us to model the average flow of LICEVs in study,

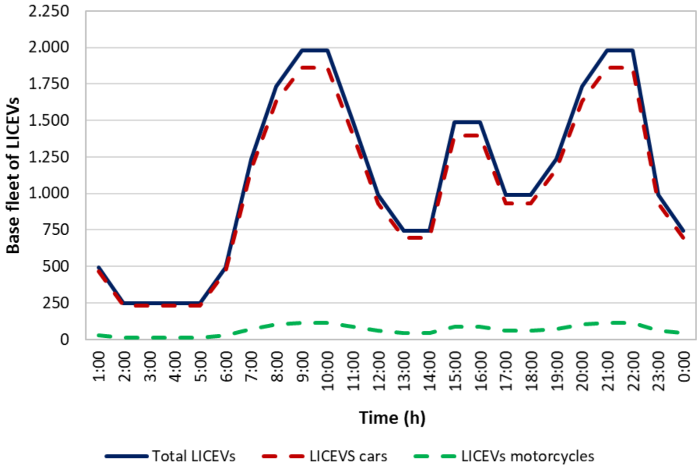


Figure 2. Base fleet of LICEVs for Valencia N(t).

represented by N(t) in eq. (1) (Figure 2). 94% of this fleet was formed by cars and 6 % by motorcycles.

The rate of penetration of LEVs in this base fleet of LICEVs will match their expected penetration in the Spanish fleet by an imminent future (Bastida-Molina et al., 2020a): 2.5% for BEVs cars, 2.5% for PHEVs cars and 5% for BEVs motorcycles, considering just the LEVs with possibilities of recharging in EVCS due to their configuration (BEVs and PHEVs) (Zheng et al., 2020).

Finally, study (Philipsen et al., 2018) claims that the percentage of LEVs passing by the EVCS that will finally recharge there is expected to be slightly higher than the equivalent traditional refueling behavior. Hence, this percentage increases up to 6%. Table 2 reflects all these parameters to be used in eq. (1).

Table 2. Rate of penetration and recharge of LEVs.

	f (%)	r (%)
BEVS cars	2.5	6
PHEVS cars	2.5	6
BEVS motorcycles	5	6

For the determination of the power consumption of each type of LEV at EVCs, we made a detailed analysis on their battery capacity, SOC and required time for recharging at the EVCS, assuming only a fast recharging mode (Bastida-Molina et al., 2020b; Martínez-Lao et al., 2017). Regarding the first parameter, researches (Li et al., 2019; Luca de Tena and Pregger, 2018; Sehar et al., 2017) shed light on the determination of battery capacity for BEVs cars and motorcycles, and PHEVs cars. Referring to the initial SOC, we took the hypothesis that the SOC for the LEVs recharging at the EVCS will be 20% (REE, 2018). Table 3 indicates the assumed values for the different parameters of the full recharge of the different types of EV.

Table 3. LEVs' recharging parameters

	C_{bat} (kWh)	SOC_{Max} (%)	SOC (%)	T (min)	P_{EV} (kW)
BEVs cars	40	100	20	40	48
PHEVs cars	14	100	20	14	48
BEVs motorcycles	3	100	20	3	48

Using these data, it is possible to deduce the electricity demand of the EVCS for the Valencian case study, shown at Figure 3. Maximum power demand is 270 kW, and takes place during the early morning (from 9:00 to 10:00) and at early night again (from 21:00 to 22:00). Final contribution of BEVs motorcycles to the electricity demand results in a 6%, in front of 49% for BEVs cars and 45% for PHEVs cars, respectively.

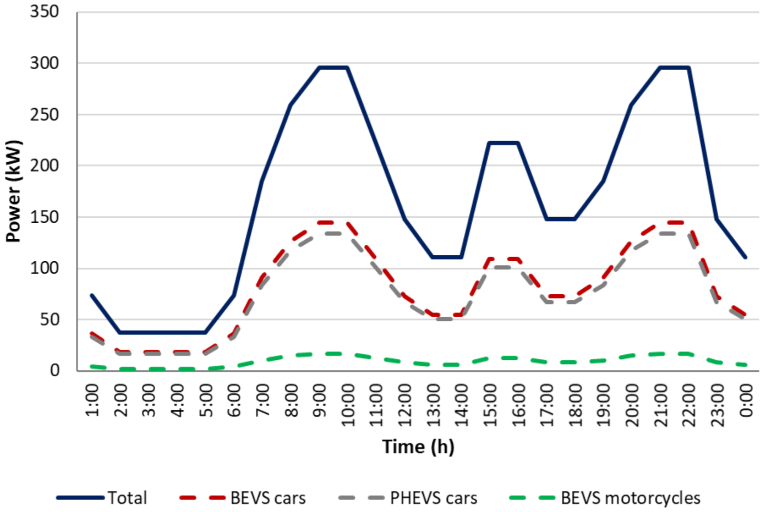


Figure 3. Electricity demand in EVCS.

3.2. Generation resources analyses

Valencia is a province located at the East of Spain, next to the Mediterranean Sea. Its geographical position corresponds to the coordinates 39°28’00”North 0°22’30”West and it has an elevation of 16 meter above sea level. The analysis of the renewable potential of Valencia highlighted solar resources as the most suitable ones, followed by wind resources.

According to PVGIS-CMSAF (PVGIS, 2020), Valencia has an average annual irradiation of 1735 kWh/m^2/year with the monthly dependence shown at Figure 4. The highest irradiation data corresponds to the summer months, reaching the highest values in June and July, with approximately 7.8 kWh/m^2/day. On the contrary, the lowest irradiation values correspond to

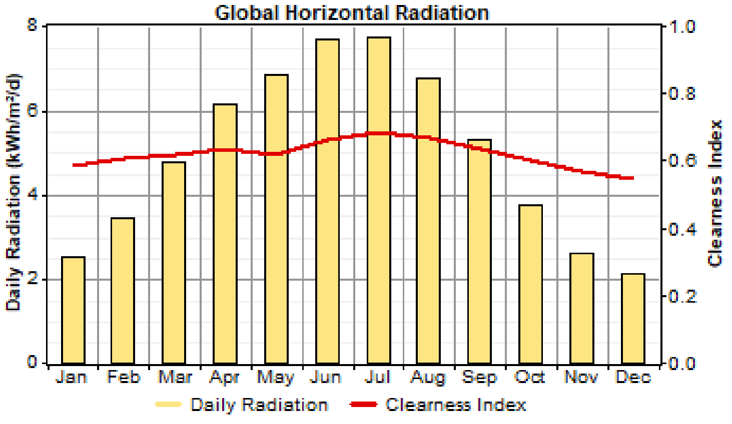


Figure 4. Average solar daily irradiation and clearness index in Valencia.

the winter months, specifically December and January, with 2.1 and 2.5 kWh/m^2/day respectively. From these data, we can deduce an average solar daily irradiation of 5 kWh/m^2/day and a clearness average index of 0.65.

Moreover, data from (IDAE, 2020b) indicated that the average wind speed of Valencia is 3.6 m/s, measured at 18 m above the ground. Figure 5 reflects the daily average data for each month. These values revealed the suitability of wind resources in Valencia, although they do not have the high potential of the solar resources. The availability of this resource presents a trend which results ideal for the HRES: solar irradiation offers its highest values during summer months; meanwhile wind speed reaches the highest data during the winter ones. Hence, each type of renewable generation would ideally complement the other, helping to the reliability of the HRES.

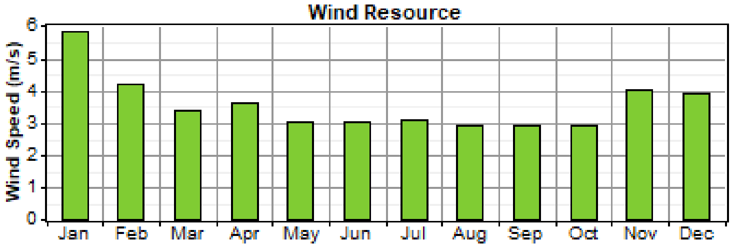


Figure 5. Wind speed in Valencia.

Regarding back-up systems, grid connection is a feasible possibility for EVCS (Rashid et al., 2019), since Valencia is a complete electrified area. Furthermore, batteries and diesel generators can be also considered as possibilities to support the HRES, especially if the EVCS is intended to be off-grid (Vermaak and Kusakana, 2014).

3.3. Inputs for the design of the hybrid renewable energy system

Taking into account the power demand from the EVCS and the availability of solar and wind resources in Valencia, an initial estimation of the HRES system configuration to be used as input for the HOMER simulation was defined (Table 4).

Table 4. HRES EVCS components sizing.

Solar PV (kW)	Wind (kW)	Grid connection (kW)	Diesel Generator (kW)	Battery (kWh)
500	330	270	280	960, 1920, 2880, 4800

To ensure a reliable supply, the maximum acceptable capacity shortage of the system was established in 10% for the HOMER® simulations. HOMER ® results provided a list with 55 configuration possibilities ordered by their NPC values. Before applying the multicriteria evaluation, configurations without renewable generation were discarded. Besides, alternatives including grid and diesel generator were also rejected, considering the generator was not necessary in the presence of grid. Table 5 summarizes the discarded design options, meanwhile

Table 6 reflects the 27 selected configuration alternatives to be analysed with the multicriteria methodology.

Table 5. Discarded design options.

Discarded design scenarios	HOMER options	Reason
Grid	2	Lack of renewable generation.
Grid + gen	5	
Grid + bat	13, 22, 28, 36	
Grid + gen + bat	17, 24, 31, 40	
Gen + bat	50, 51	
Gen	55	
Ren + grid + gen	3, 7, 14	The diesel generator does not contribute to energy generation, due to the presence of the grid.
Ren + grid + gen + bat	8, 12, 19, 20, 21,26 27, 33, 34, 35, 41,42	

gen: diesel generator; bat: batteries; ren: renewable resources.

Table 6. Selected configuration options to be analysed by the methodology.

	HOMER Option	Solar PV (kW)	Wind (kW)	Grid connection	Generator (kW)	Battery (kWh)
Ren + grid	1	500	0	Yes	0	0
Ren + grid	4	0	330	Yes	0	0
Ren + grid + bat	6	500	0	Yes	0	960
Ren + grid + bat	9	500	0	Yes	0	1920
Ren + bat	10	500	330	No	0	4800
Ren + grid	11	500	330	Yes	0	0
Ren + grid + bat	15	500	0	Yes	0	2880
Ren + grid + bat	16	0	330	Yes	0	960
Ren + grid + bat	18	500	330	Yes	0	960
Ren + grid + bat	23	500	0	Yes	0	1920
Ren + grid + bat	25	500	330	Yes	0	1920
Ren + grid + bat	29	500	0	Yes	0	4800
Ren + grid + bat	30	0	330	Yes	0	2880
Ren + grid + bat	32	500	330	Yes	0	2880
Ren + gen + bat	37	500	330	No	280	4800
Ren + grid + bat	38	0	330	Yes	0	4800
Ren + grid + bat	39	500	330	Yes	0	4800
Ren + gen + bat	43	500	330	No	280	2880
Ren + gen + bat	44	500	330	No	280	1920
Ren + gen + bat	45	500	0	No	280	4800
Ren + gen + bat	46	500	0	No	280	2880
Ren + gen + bat	47	0	330	No	280	2880
Ren + gen + bat	48	0	330	No	280	4800
Ren + gen + bat	49	0	300	No	280	1920
Ren + gen	52	500	330	No	280	0
Ren + gen	53	500	0	No	280	0
Ren + gen	54	0	330	No	280	0

The application of the multicriteria methodology to the Valencian case study required the definition of some input parameters regarding the environmental, economic and technical criteria, as well as the weighting factors.

Environmental criteria

The relative decrease of CO_2 emissions achieved when using a HRES instead of the traditional grid for charging vehicles in EVCS together with the renewable generation degree comprise the environmental factors to assess each design option for the system. Thus, the emissivity for each renewable source results of utmost importance, as well as the emissivity and renewable presence for the Spanish grid. A wide study of renewable and non-renewable sources' emissivity is available on (Karmaker et al., 2018) and (Bastida-Molina et al., 2020a; IEA, 2016) contain all the information regarding the Spanish electricity mix. Using this information, Table 7 summarizes the emissivity values to be used.

Table 7. Emissivity for generation sources and renewable contribution to the grid.

	Solar PV	Wind	Diesel	Spanish grid
g (g CO_2/kWh)	40	20	600	318.1
X_r (%)	-	-	-	27.1

Economic criteria

This paper uses the NLCOE to assess the economic behaviour of each design option, where the economic modelling of such parameter includes the investment, operation and maintenance and fuel costs for each element of the HRES, as well as its corresponding discount rate and the lifetime of the project. A thorough research (Chowdhury et al., 2020; Hurtado et al., 2015) was made to accurately determine these values for the case study. These are presented in Table 8.

Table 8. Economic modelling.

	Investment cost (€/kW)	O&M cost (€/kW)	Fuel cost (€/L)	n (years)	r (%)
Solar PV	1200	40	-	-	-
Wind	2020	60	-	-	-
Diesel generator	380	1.5[a]	1.05	-	-
Batteries	950[c]	10[c]	-	-	-
Grid	-	0.15[b]	-	-	-
General project	-	-	-	25	8

[a]€/h; [b]Grid power price; [c]€/unit

Technical criteria

The technical evaluation of the methodology includes an analysis of the power selected for each power source together with the application of a security coefficient to each one of them to ensure the feasibility of the system. To determine this security coefficient for dispatchable technologies, study (Hidalgo Batista and Villavicencio Proenza, 2011) quantifies its value for diesel generator, and (Kruyt et al., 2009; Sovacool and Mukherjee, 2011) for the Spanish grid.

Moreover, the security coefficient for batteries matches its depth of discharge according to (HOMER, 2020). This coefficient varies for non-dispatchable sources, depending on the number of equivalent hours (1735 for solar PV (PVGIS, 2020) and 1889 for wind in Valencia (IDAE, 2020b). Table 9 summarises the security coefficient data for each generation source in the HRES.

Table 9. Security coefficient for the generation sources (δ_j).

Solar PV (%)	Wind (%)	Diesel generator (%)	Spanish Grid (%)	Batteries (%)
19.8	21.6	85.7	98	70

Multicriteria assessment

The methodology presented in this paper allows users to arbitrarily decide through a series of weighting factors the importance that each criteria will play during the evaluation process. In this case of study, we have decided to apply a balanced evaluation process, where all the criteria have the same weight: 20% each.

4. Results and discussion

This section presents the results for the application of the methodology to the Valencian case study. Namely, it exposes the selected designs of the HRES in EVCS of Valencia after applying the multicriteria assessment, together with the experimental validation of such designs in the Laboratory of Distributed Energy Resources (LabDER) of the Polytechnic University of Valencia (UPV) (Pérez-Navarro et al., 2016).

4.1. Design of the hybrid renewable energy system: multicriteria assessment

The application of the multicriteria methodology presented in this paper to the Valencian case study gave rise to a rank ordered list of the design options for the HRES in EVCS. Table 10 reflects the individual percentage assessment of the environmental, economic and technical criteria for each option, as well as the final evaluation considering equal ponderation values for all of them.

Table 10. Multicriteria assessment of the HRES configurations. Selected designs for the HRES in EVCS.

Configuration	**HOMER position #**	**Methodology position #**	**EmR (%)**	**ReG (%)**	**EcF (%)**	**SS (%)**	**ESA (%)**	**Total (%)**
Ren + bat	10	1	88,84	100	83,13	83,29	88,85	88,82
Ren + gen + bat	37	2	67,95	91,04	68,56	98,14	80,89	81,32
Ren + grid	11	3	49,05	80,96	88,08	98,44	65,64	76,43
Ren + gen + bat	43	4	56,65	86,83	63,94	96,17	77,15	76,15
Ren + grid + bat	18	5	49,05	80,96	83,13	98,73	65,65	75,50
Ren + grid	4	6	31,70	57,81	97,79	98,20	88,62	74,83
Ren + grid	1	7	31,11	64,80	100,00	98,26	79,53	74,74
Ren + grid + bat	25	8	49,09	80,97	78,24	99,02	65,66	74,59
Ren + grid + bat	6	9	31,12	64,80	95,68	98,58	79,54	73,94
Ren + grid + bat	32	10	49,11	80,98	74,30	99,31	65,67	73,87
Ren + grid + bat	39	11	49,67	81,18	67,86	99,67	65,91	72,86
Ren + grid + bat	9	12	31,12	64,80	89,86	98,91	79,53	72,84
Ren + grid + bat	16	13	31,71	57,81	83,65	98,54	88,63	72,07
Ren + grid + bat	15	14	31,12	64,80	84,18	99,05	79,54	71,74
Ren + grid + bat	23	15	31,74	57,82	78,70	98,80	88,65	71,14
Ren + grid + bat	30	16	31,76	57,82	75,14	98,80	88,67	70,44
Ren + grid + bat	29	17	31,13	64,81	75,57	99,05	79,55	70,02
Ren + gen + bat	44	18	40,15	81,35	56,60	94,55	72,28	68,98
Ren + grid + bat	38	19	31,76	57,82	67,86	98,80	88,67	68,98
Ren + gen + bat	45	20	0	56,46	47,16	94,71	86,84	57,04
Ren + gen + bat	46	21	0	54,94	45,70	94,71	84,50	55,97
Ren + gen + bat	47	22	0	40,97	39,00	93,33	86,19	51,90
Ren + gen + bat	48	23	0	41,11	38,55	93,33	86,49	51,89
Ren + gen + bat	49	24	0	40,78	38,55	93,33	85,81	51,69
Ren + gen	52	25	0	59,77	25,63	91,30	53,11	45,96
Ren + gen	53	26	0	40,47	23,54	90,30	62,24	43,31
Ren + gen	54	27	0	31,69	22,06	90,01	66,67	42,09

Note: the dimension values (kW or kWh) of each option could be consulted in Table 6.

It is possible to see the difference between the method hereby presented and the one followed by HOMER® when assessing the alternatives. For instance, the best-valued option of this method corresponds to the 10th one of the HOMER® ranking, whereas the best-valued option using HOMER ® corresponds to the 7th one of the multicriteria method. These outcomes result coherent with the behavior of both tools and verify one of the aims of the work: meanwhile HOMER ® bases its evaluation just on an NPC optimization, the method hereby presented takes into account every factor that could affect HRES in EVCS, resulting in a more complete and realist evaluation.

Figure 6 shows the evaluation of each of the multicriteria parameters for each of the analyzed configurations. Regarding environmental parameters (EmR and ReG), the configurations with renewable generation and batteries are by far the most influential one. The configurations that include renewable generation, batteries and the support of diesel generators result also influential in environmental criteria for the options that use diesel generator during short periods. However, the design options that use diesel generators during long time periods have the worst environmental behavior. Alternatives including renewable generation with the support of the grid are the best economic options (EcF), and they also present good technical criteria (SS, ESA). However, configurations with renewable generation and diesel generators result the worst choice in all the aspects: environmental, economic and technical.

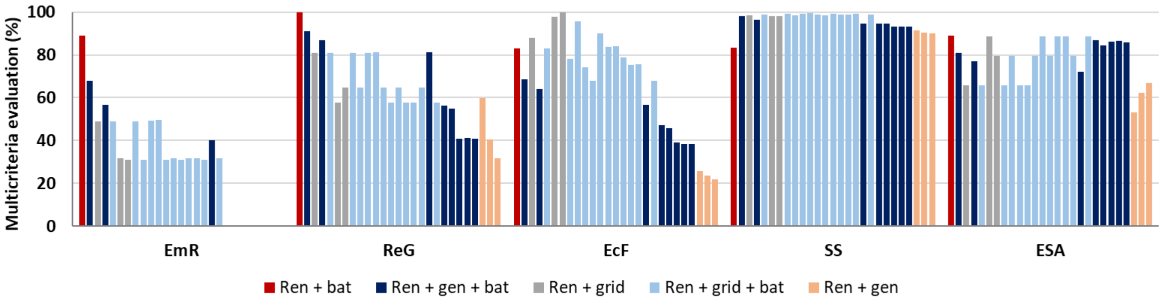


Figure 6. Multicriteria assessment.

Note: the design options are ordered according to Table 10-Multicriteria methodology.

From the configuration ranking in Table 10 we can deduce the three most suitable configuration options for the HRES in the Valencia case study. The highest-scored option is related to an off grid energy scenario that includes renewable generation (500 kW solar PV and 330 kW wind) and the support of a group of batteries (4800 kWh). The second alternative corresponds to another off grid scenario, similar to the first one, but with the support of a diesel generator (280 kW). The third-highest scored option finally represents an on-grid scenario, where the grid supports the renewable generation (500 kW solar PV and 330 kW wind).

Most of the pioneers HRES EVCS' projects developed in regions where grid connection results possible tend to rely on such kind of support for the system (Bastida Molina et al., 2017; Karmaker et al., 2018) mainly motivated by its ease of use, security of supply and economic performance. However, the multicriteria assessment presented in this paper reveals the influence that the environmental aspects could play in the selection process favoring off grid solutions, if possible. Figure 7 presents a comparison among the parameter evaluation for each of the three most suitable scenarios.

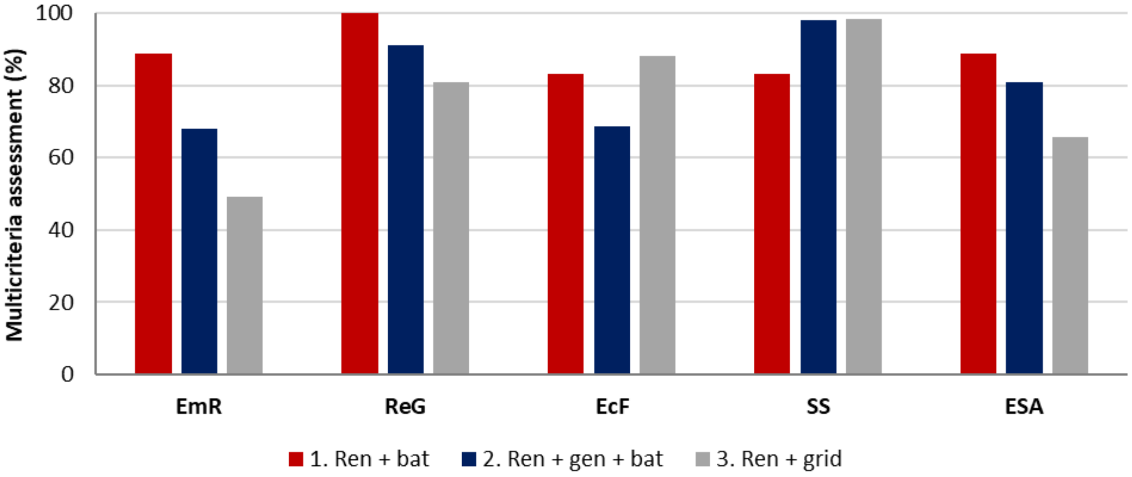


Figure 7. Selected designs for the HRES in EVCS.

Note: the design options are ordered according to Table 10-Multicriteria methodology.

The off grid configuration with renewable generation and batteries storage presents the best environmental behavior, since it does not depend on polluting sources. However, the second off grid configuration (renewable generation with diesel generator and batteries) is penalized by the use of the diesel generator. Moreover, the on-grid configuration, given the dependence of the Spanish electrical mix in some high polluting sources (IEA, 2016), is the worst in terms of environmental influence, especially referring to CO_2 reduction. However, this on-grid configuration arises as the most economic one, having the second off-grid configuration the lowest economic parameter due to the expenses of the diesel generator and its fuel. On the contrary, the on grid configuration together with the off grid configuration that includes a diesel generator have the highest security of supply, since they both count with dispatchable support sources.

4.2. Experimental verification of the hybrid renewable energy system

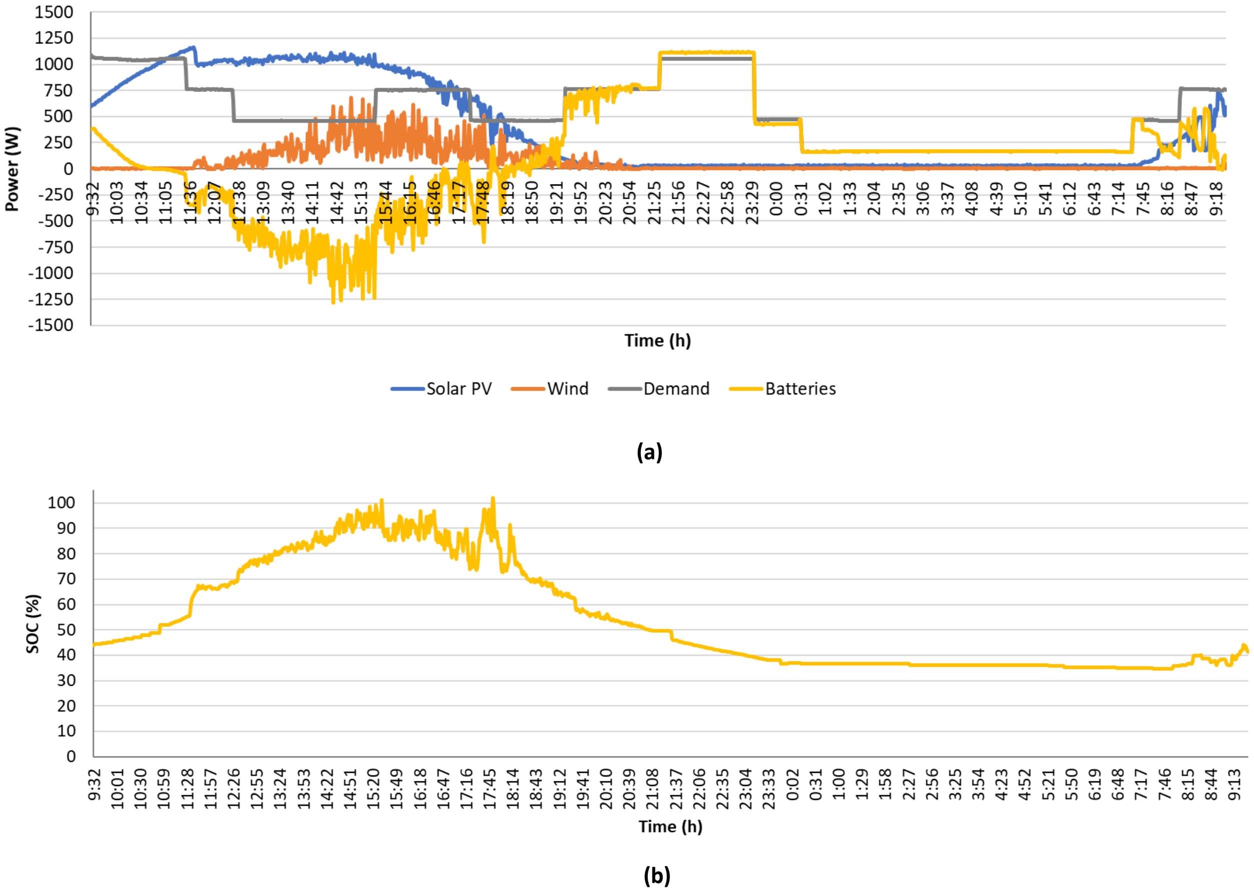
To conclude the complete design process of the HRES for EVCS for the case study, the selected design alternatives through the multicriteria assessment were experimentally validated in the Laboratory of Distributed Energy Resources (labDER) (Pérez-Navarro et al., 2016) of the Institute for Energy Engineering of the Polytechnic University of Valencia (Spain). This laboratory includes a hybrid combination of generation resources (2 kW_p solar PV, 1.5 kW wind turbine, 10 kW biomass gasifier, 1.7 kW diesel generator, optimal grid connection and 1.2 kW fuel cell). It also includes storage systems (12 kWh batteries and 7 kW hydrogen system) and a programmable load system (from 0.5 to 9.2 kW) that enables to simulate any time dependence of the demand. Hence, to experimentally validate the suitability of the selected HRES configurations, they were reproduced in labDER with a scale factor of 1:250.

Each scaled experiment comprise a complete day of simulation for the three most suitable HRES designs for EVCS. For each simulation, the batteries SOC limits were fixed to 30% and 100%, according to their discharge limits. Moreover, authors fixed the maximum acceptable rate of power losses in 5%, considering previous experimental studies in such field (Hurtado et al., 2015; Pérez-Navarro et al., 2016).

Figure 8 plots the energy balance and SOC results for the highest-scored configuration, which includes renewable generation and the support of batteries.

At the beginning of the experiment, the demand requirements were the highest. However, at that period, solar irradiation was still low and wind contribution was practically null. Therefore, batteries contributed in part to meet electricity demand. Later, solar PV and wind contribution reached their maximum values. Hence, the HRES was able to meet the EVCS supply with an excess of energy, which was used to recharge batteries. The SOC of batteries increased during this period, achieving its full charge status. The highly fluctuating behavior of the wind generation, characteristic in small wind turbines like the labDER one (Pérez-Navarro et al., 2016), is also reflected in the power supplied by the batteries and in their SOC. At late afternoon, solar irradiation started to disappear and wind contribution was low. Finally, at night, both solar and wind contribution were null and load supply was based exclusively on batteries, reaching their lowest SOC value at the experiment in the early morning, when solar irradiation was again available and recharge was initiated again.

These results demonstrated the energy achieved with the HRES in question could cope with the assumed electricity demand. Moreover, the maximum rate of power losses in this experiment was 4.5% and the rates of batteries SOC oscillated between 35% and 100%. Hence, the experiment met with the limit requirements. Finally, the SOC at the end and at the beginning of the experiment were similar, about 40%, which ensured the adequacy of the batteries for the next experimental cycles.



(a)

(b)

Figure 8. Experimental validation for the highest-scored configuration. **(a)** Energy Balance. **(b)** SOC.

Figure 9 plots the energy balance and SOC results for the second highest-scored configuration, which includes renewable generation and the support of batteries and a diesel generator.

The energy balance presented in this experiment is comparable to the previous one, with one main difference: the contribution of the diesel generator. The generator supplied energy during 1.5 h, at the beginning of the day. This option is very convenient because it guarantees the electricity supply during the period where the load demand is highest and solar irradiation and wind are still very low. Besides, the contribution of the diesel generator led to an increase of the batteries SOC from 35% to 85%.

The optimal use of the diesel generator demonstrated its suitability for the experiment: the rate of power losses was 4%, and the battery SOC at the end of the experiment (41%) was slightly higher than this value at the beginning of the experiment (35%), ensuring therefore the adequacy of the batteries for future energy cycles.

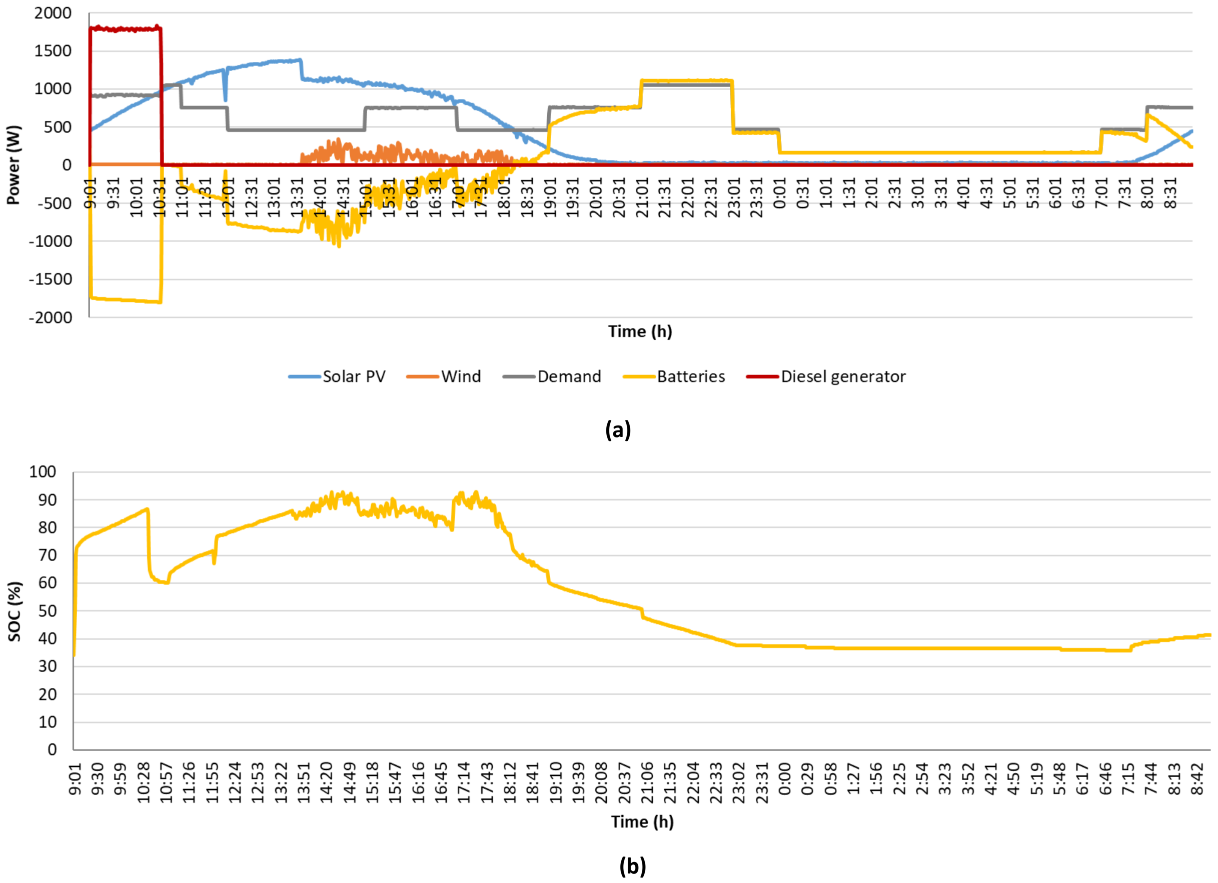


Figure 9. Experimental validation for the second highest-scored configuration. (a) Energy Balance. (b) SOC.

Figure 10 plots the energy balance results for the third highest-scored configuration, which includes renewable generation with the support of the grid.

As Figure 10 reflects, at early morning the grid covered the low solar irradiation at the period of maximum load demand. Later, there was an excess in generation from solar PV that was inyected into the grid. During this period, solar irradiation was available and wind contribution was higher than in the previous configuration checks. Hence, the grid was also responsible for absorbing the variability of the wind generation. Besides, the grid supplied the required electricity during the evening and night period. For this experiment, power losses acquired the value of 4%, meeting therefore the limit conditions.

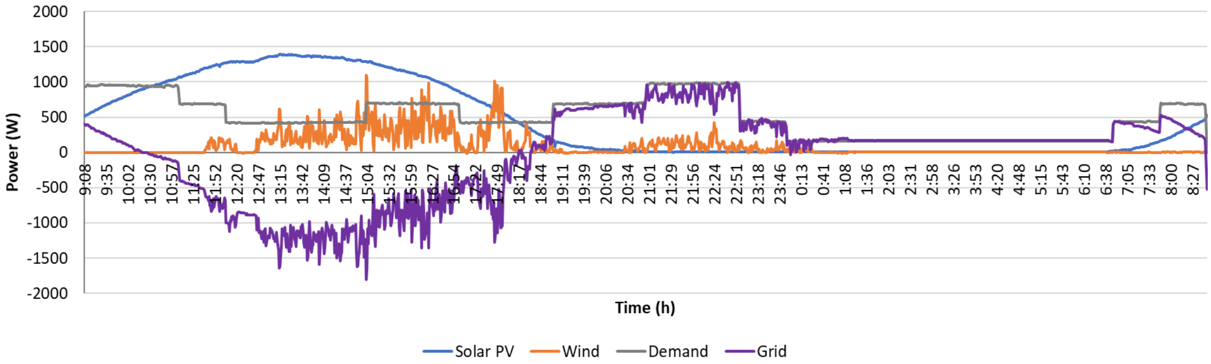


Figure 10. Experimental validation for the third highest-scored configuration. Energy Balance.

These experimental results demonstrated the energy balance suitability of the three selected configurations for the HRES in EVCS, both in the level of power losses and batteries' SOC limits and with a full time coverage of the load demand.

5. Conclusions

A high penetration of EVCS is expected to happen to cope with the electricity requirements of the also foreseeable high introduction of EVs in the medium-term future for almost all developed countries. This electrification of the transport sector arises as an environmental solution since EVs emit zero emissions while riding on the roads, although careful attention should be paid to the emissions in the generation of the electricity they need. The use of microgrids with renewable generation (HRES) in EVCS seems necessary, since this use would decrease both the CI content of the electricity generation and the pressure on the grid that the recharge of EVCS would produce. Choosing the most suitable configuration for HRES in EVCS, taking into account in its design the different constraints in the technical, economic and environmental aspects, would be an essential task.

This paper has defined a novel multicriteria methodology that takes into consideration all the above-mentioned constraints and includes an experimental stage to verify the configuration of the HRES for EVCS. The methodology, after the determination of the available renewable resources and the electricity demand of the EVCS, uses HOMER® code to deduce possible HRES configurations and evaluates them with a new multicriteria analysis, considering weighted technical, economic and environmental parameters to rank them. Finally, configurations with the highest scores are experimentally tested to check their reliability, power balance and SOC range. Hence, the selected final configuration design ensures the suitability of the HRES for the EVCS, supported not only by a complete numerical evaluation, but also by an experimental verification.

To illustrate the viability of the methodology, the article applies the method to the case study of Valencia, the capital province of Comunidad Valenciana, (in the east of Spain). This province is immersed in a remarkable mobility transition, with the aim of increasing the quantity of EVs and EVCS, together with a significant introduction of renewable sources in the electricity generation system.

Results for the electricity demand modelling of these vehicles in EVCS led to a maximum load demand of 270 kW that takes place during the early morning (from 9:00 to 10:00 h) and at early night again (from 21:00 to 22:00 h). On the other hand, the generation resources analysis revealed the suitability of solar PV and wind resources, with and average solar daily irradiation of 5 kWh/m^2/day and an average wind speed of 3.6 m/s at 18 m, respectively. Regarding back-up systems, batteries, diesel generator and grid connection were contemplated.

An initial simulation of the system considering both restrictions (generation resources availability and electricity demand) and making use of HOMER ® resulted in a starting filtered list of 27 configuration alternatives. These options were later evaluated by means of the hereby presented multicriteria methodology, with the same weights for the different constraints. Simulation results indicated that the most suitable configuration for the case study is an off-grid system with renewable generation and batteries support, followed by another off-grid system that includes also the support of a diesel generator. The third highest-scored configuration resulted in an on-grid system with renewable generation.

The selected configurations were experimentally validated in the Laboratory of Distributed Energy Resources (labDER) at the Polytechnic University of Valencia (Spain). Both the generation and demand resources were scaled according to the laboratory components with a factor of 1:250. Results indicated that the demand was fully covered in all the scenarios, with maximum power losses of 4.5% and SOC of batteries between 35% and 100%.

To conclude, this study provides a methodology that ensures the suitability of the HRES for the EVCS, supported not only by a complete multicriteria assessment, but also by an experimental verification. Its application to the case study of Valencia proves the viability of applying HRES for recharging EVs at EVCSs in a technical, economic and environmental acceptable way.

Acknowledgment

One of the authors (PBM) was supported by the regional public administration of Valencia under the grant ACIF/2018/106.

References

Akitt, J.W., 2018. Some observations on the greenhouse effect at the Earth's surface. Spectrochim. Acta Part A Mol. Biomol. Spectrosc. 188, 127–134. https://doi.org/10.1016/J.SAA.2017.06.051

Álvarez Fernández, R., 2018. A more realistic approach to electric vehicle contribution to greenhouse gas emissions in the city. J. Clean. Prod. 172, 949–959. https://doi.org/10.1016/j.jclepro.2017.10.158

Bastida-Molina, P., Hurtado-Pérez, E., Peñalvo-López, E., Moros-Gómez, M.C., 2020a. Assessing transport emissions reduction while increasing electric vehicles and renewable generation levels. Transp. Res. Part D Transp. Environ. 88, 102560. https://doi.org/10.1016/j.trd.2020.102560

Bastida-Molina, P., Hurtado-Pérez, E., Pérez-Navarro, Á., Alfonso-Solar, D., 2020b. Light electric vehicle charging strategy for low impact on the grid. Environ. Sci. Pollut. Res. 1–17. https://doi.org/10.1007/s11356-020-08901-2

Bastida-Molina, P., Hurtado-Pérez, E., Vargas-Salgado, C., Ribó-Pérez, D., 2020c. Microrredes híbridas, una solución para países en vías de desarrollo. Técnica Ind. 325, 28–34. https://doi.org/10.23800/10218

Bastida Molina, P., Saiz Jiménez, J.Á., Molina Palomares, M.P., Álvarez Valenzuela, B., 2017. Instalaciones solares fotovoltaicas de autoconsumo para pequeñas instalaciones. Aplicación a una nave industrial. 3C Tecnol. 1–14. https://doi.org/http://dx.doi.org/10.17993/3ctecno.2017.v6n1e21.1-14

Chowdhury, N., Hossain, C., Longo, M., Yaïci, W., 2018. Optimization of Solar Energy System for the Electric Vehicle at University Campus in Dhaka, Bangladesh. Energies 11, 2433. https://doi.org/10.3390/en11092433

Chowdhury, T., Chowdhury, H., Miskat, M.I., Chowdhury, P., Sait, S.M., Thirugnanasambandam, M., Saidur, R., 2020. Developing and evaluating a stand-alone hybrid energy system for Rohingya refugee community in Bangladesh. Energy 191, 116568. https://doi.org/10.1016/j.energy.2019.116568

Corporate Finance Institute, 2020. Levelized Cost of Electricity [WWW Document]. URL https://corporatefinanceinstitute.com/resources/knowledge/finance/levelized-cost-of-energy-lcoe/ (accessed 5.14.20).

Deb, S., Tammi, K., Kalita, K., Mahanta, P., 2018. Impact of Electric Vehicle Charging Station Load on Distribution Network. Energies 11, 178. https://doi.org/10.3390/en11010178

DGT, 2019. Traffic information [WWW Document]. URL http://infocar.dgt.es/etraffic/ (accessed 9.19.19).

Dijk, M., Orsato, R.J., Kemp, R., 2013. The emergence of an electric mobility trajectory. Energy Policy 52, 135–145. https://doi.org/10.1016/J.ENPOL.2012.04.024

Dino, I.G., Meral Akgül, C., 2019. Impact of climate change on the existing residential building stock in Turkey: An analysis on energy use, greenhouse gas emissions and occupant comfort. Renew. Energy 141, 828–846. https://doi.org/10.1016/j.renene.2019.03.150

Dixon, J., Bukhsh, W., Edmunds, C., Bell, K., 2020. Scheduling electric vehicle charging to minimise carbon emissions and wind curtailment. Renew. Energy 161, 1072–1091. https://doi.org/10.1016/j.renene.2020.07.017

Domínguez-Navarro, J.A., Dufo-López, R., Yusta-Loyo, J.M., Artal-Sevil, J.S., Bernal-Agustín, J.L., 2019. Design of an electric vehicle fast-charging station with integration of renewable energy and storage systems. Int. J. Electr. Power Energy Syst. 105, 46–58. https://doi.org/10.1016/j.ijepes.2018.08.001

Driscoll, Á., Lyons, S., Mariuzzo, F., Tol, R.S.J., 2013. Simulating demand for electric vehicles using revealed preference data. Energy Policy 62, 686–696. https://doi.org/10.1016/j.enpol.2013.07.061

Electric Mobility Plan [WWW Document], 2017. URL https://www.gva.es/es/inicio/area_de_prensa/not_detalle_area_prensa?id=8600

77 (accessed 7.2.20).

Galiveeti, H.R., Goswami, A.K., Dev Choudhury, N.B., 2018. Impact of plug-in electric vehicles and distributed generation on reliability of distribution systems. Eng. Sci. Technol. an Int. J. 21, 50–59. https://doi.org/10.1016/J.JESTCH.2018.01.005

GVA, 2017. Valencian Climate Change and Energy Strategy 2030 [WWW Document]. URL http://www.agroambient.gva.es/es/web/cambio-climatico/2020-2030 (accessed 7.2.20).

Hansen, J.M., Xydis, G.A., 2020. Rural electrification in Kenya: a useful case for remote areas in sub-Saharan Africa. Energy Effic. 13, 257–272. https://doi.org/10.1007/s12053-018-9756-z

Hansen, K., 2019. Decision-making based on energy costs: Comparing levelized cost of energy and energy system costs. Energy Strateg. Rev. https://doi.org/10.1016/j.esr.2019.02.003

Hidalgo Batista, E.R., Villavicencio Proenza, D.D., 2011. The reliability of stationary internal combustion diesel engines. Rev. Científica Trimest. 1–10.

HOMER, 2020. Hybrid Renewable and Distributed Generation System Design Software [WWW Document]. URL https://www.homerenergy.com/ (accessed 5.14.20).

Huang, P., Ma, Z., Xiao, L., Sun, Y., 2019. Geographic Information System-assisted optimal design of renewable powered electric vehicle charging stations in high-density cities. Appl. Energy 255, 113855. https://doi.org/10.1016/j.apenergy.2019.113855

Hurtado, E., Peñalvo-López, E., Pérez-Navarro, Á., Vargas, C., Alfonso, D., 2015. Optimization of a hybrid renewable system for high feasibility application in non-connected zones. Appl. Energy 155, 308–314. https://doi.org/10.1016/J.APENERGY.2015.05.097

IDAE, 2020b. Wind resource analyses. Wind atlas of Spain [WWW Document]. URL https://www.idae.es/uploads/documentos/documentos_11227_e4_atlas_eolico_A_9b90ff10.pdf (accessed 7.8.20).

IEA, 2017b. Data & Statistics [WWW Document]. URL https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy consumption&indicator=Oil products final consumption by sector (accessed 2.13.20).

IEA, 2016. Data and statistics [WWW Document]. URL https://www.iea.org/data-and-statistics/data-tables?country=WORLD&energy=Balances&year=2016 (accessed 12.12.19).

Karmaker, A.K., Ahmed, M.R., Hossain, M.A., Sikder, M.M., 2018. Feasibility assessment & design of hybrid renewable energy based electric vehicle charging station in Bangladesh. Sustain. Cities Soc. 39, 189–202. https://doi.org/10.1016/j.scs.2018.02.035

Kruyt, B., van Vuuren, D.P., de Vries, H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Policy 37, 2166–2181. https://doi.org/10.1016/j.enpol.2009.02.006

Li, J., Gao, S., Xu, B., Chen, H., 2019. Modeling and Controllability Evaluation of EV Charging Facilities Changed from Gas Stations with Renewable Energy Sources, in: 2019 Asia Power and Energy Engineering Conference, APEEC 2019. Institute of Electrical and Electronics Engineers Inc., pp. 269–273. https://doi.org/10.1109/APEEC.2019.8720700

Liu, Z., Wu, Q., Nielsen, A., Wang, Y., 2014. Day-Ahead Energy Planning with 100% Electric Vehicle Penetration in the Nordic Region by 2050. Energies 7, 1733–1749. https://doi.org/10.3390/en7031733

Losev, O.G., Grigor'ev, A.S., Mel'nik, D.A., Grigor'ev, S.A., 2020. Charging Station for Electric Transport Based on Renewable Power Sources. Russ. J. Electrochem. 56, 163–169. https://doi.org/10.1134/S1023193520020093

Luca de Tena, D., Pregger, T., 2018. Impact of electric vehicles on a future renewable energy-based power system in Europe with a focus on Germany. Int. J. Energy Res. 42, 2670–2685. https://doi.org/10.1002/er.4056

Manjunath, A., Gross, G., 2017. Towards a meaningful metric for the quantification of GHG emissions of electric vehicles (EVs). Energy Policy 102, 423–429. https://doi.org/10.1016/j.enpol.2016.12.003

Martínez-Lao, J., Montoya, F.G., Montoya, M.G., Manzano-Agugliaro, F., 2017. Electric vehicles in Spain: An overview of charging systems [WWW Document]. Renew. Sustain. Energy Rev. https://doi.org/10.1016/J.RSER.2016.11.239

Nizam, M., Wicaksono, F.X.R., 2019. Design and Optimization of Solar, Wind, and Distributed Energy Resource (DER) Hybrid Power Plant for Electric Vehicle (EV) Charging Station in Rural Area, in: Proceeding - 2018 5th International Conference on Electric Vehicular Technology, ICEVT 2018. Institute of Electrical and Electronics Engineers Inc., pp. 41–45. https://doi.org/10.1109/ICEVT.2018.8628341

Pérez-Navarro, A., Alfonso, D., Ariza, H.E., Cárcel, J., Correcher, A., Escrivá-Escrivá, G., Hurtado, E., Ibáñez, F., Peñalvo, E., Roig, R., Roldán, C., Sánchez, C., Segura, I., Vargas, C., 2016. Experimental verification of hybrid renewable systems as feasible energy sources. Renew. Energy 86, 384–391. https://doi.org/10.1016/J.RENENE.2015.08.030

Philipsen, R., Brell, T., Brost, W., Eickels, T., Ziefle, M., 2018. Running on empty – Users' charging behavior of electric vehicles versus traditional refueling. Transp. Res. Part F Traffic Psychol. Behav. 59, 475–492. https://doi.org/10.1016/j.trf.2018.09.024

PVGIS, 2020. Solar irradiation [WWW Document]. URL http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=es&map=europe (accessed 12.26.18).

Quddus, M.A., Kabli, M., Marufuzzaman, M., 2019. Modeling electric vehicle charging station expansion with an integration of renewable energy and Vehicle-to-Grid sources. Transp. Res. Part E Logist. Transp. Rev. 128, 251–279. https://doi.org/10.1016/j.tre.2019.06.006

Rashid, M.M., Islam Maruf, M.N., Akhtar, T., 2019. An RES-based grid connected electric vehicle charging station for Bangladesh, in: 1st International Conference on Robotics, Electrical and Signal Processing Techniques, ICREST 2019. Institute of

Electrical and Electronics Engineers Inc., pp. 205–210. https://doi.org/10.1109/ICREST.2019.8644130

REE, 2018. Electric mobility guide for local entities [WWW Document]. URL https://www.ree.es/sites/default/files/downloadable/Guia_movilidad_electrica_para_entidades_locales.pdf (accessed 7.31.19).

Ribó-Pérez, D., Bastida-Molina, P., Gómez-Navarro, T., Hurtado-Pérez, E., 2020. Hybrid assessment for a hybrid microgrid: A novel methodology to critically analyse generation technologies for hybrid microgrids. Renew. Energy 157, 874–887. https://doi.org/10.1016/j.renene.2020.05.095

Savio, D.A., Juliet, V.A., Chokkalingam, B., Padmanaban, S., Holm-Nielsen, J.B., Blaabjerg, F., 2019. Photovoltaic Integrated Hybrid Microgrid Structured Electric Vehicle Charging Station and Its Energy Management Approach. Energies 12, 168. https://doi.org/10.3390/en12010168

Sehar, F., Pipattanasomporn, M., Rahman, S., 2017. Demand management to mitigate impacts of plug-in electric vehicle fast charge in buildings with renewables. Energy 120, 642–651. https://doi.org/10.1016/J.ENERGY.2016.11.118

Singh, M., Balachandra, P., 2019. Microhybrid Electricity System for Energy Access, Livelihoods, and Empowerment. Proc. IEEE 107, 1995–2007. https://doi.org/10.1109/JPROC.2019.2910834

Sovacool, B.K., Mukherjee, I., 2011. Conceptualizing and measuring energy security: A synthesized approach. Energy 36, 5343–5355. https://doi.org/10.1016/j.energy.2011.06.043

Su, J., Lie, T.T., Zamora, R., 2019. Modelling of large-scale electric vehicles charging demand: A New Zealand case study. Electr. Power Syst. Res. 167, 171–182. https://doi.org/10.1016/J.EPSR.2018.10.030

Teixeira, A.C.R., Sodré, J.R., 2018. Impacts of replacement of engine powered vehicles by electric vehicles on energy consumption and CO2 emissions. Transp. Res. Part D Transp. Environ. 59, 375–384. https://doi.org/10.1016/J.TRD.2018.01.004

Tulpule, P.J., Marano, V., Yurkovich, S., Rizzoni, G., 2013. Economic and environmental impacts of a PV powered workplace parking garage charging station. Appl. Energy 108, 323–332. https://doi.org/10.1016/j.apenergy.2013.02.068

Vermaak, H.J., Kusakana, K., 2014. Design of a photovoltaic-wind charging station for small electric Tuk-tuk in D.R.Congo. Renew. Energy 67, 40–45. https://doi.org/10.1016/j.renene.2013.11.019

Woo, J.R., Choi, H., Ahn, J., 2017. Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: A global perspective. Transp. Res. Part D Transp. Environ. 51, 340–350. https://doi.org/10.1016/j.trd.2017.01.005

Wu, C., Gao, S., Liu, Y., Song, T.E., Han, H., 2021. A model predictive control approach in microgrid considering multi-uncertainty of electric vehicles. Renew. Energy 163, 1385–1396. https://doi.org/10.1016/j.renene.2020.08.137

Xie, R., Wei, W., Khodayar, M.E., Wang, J., Mei, S., 2018. Planning Fully Renewable

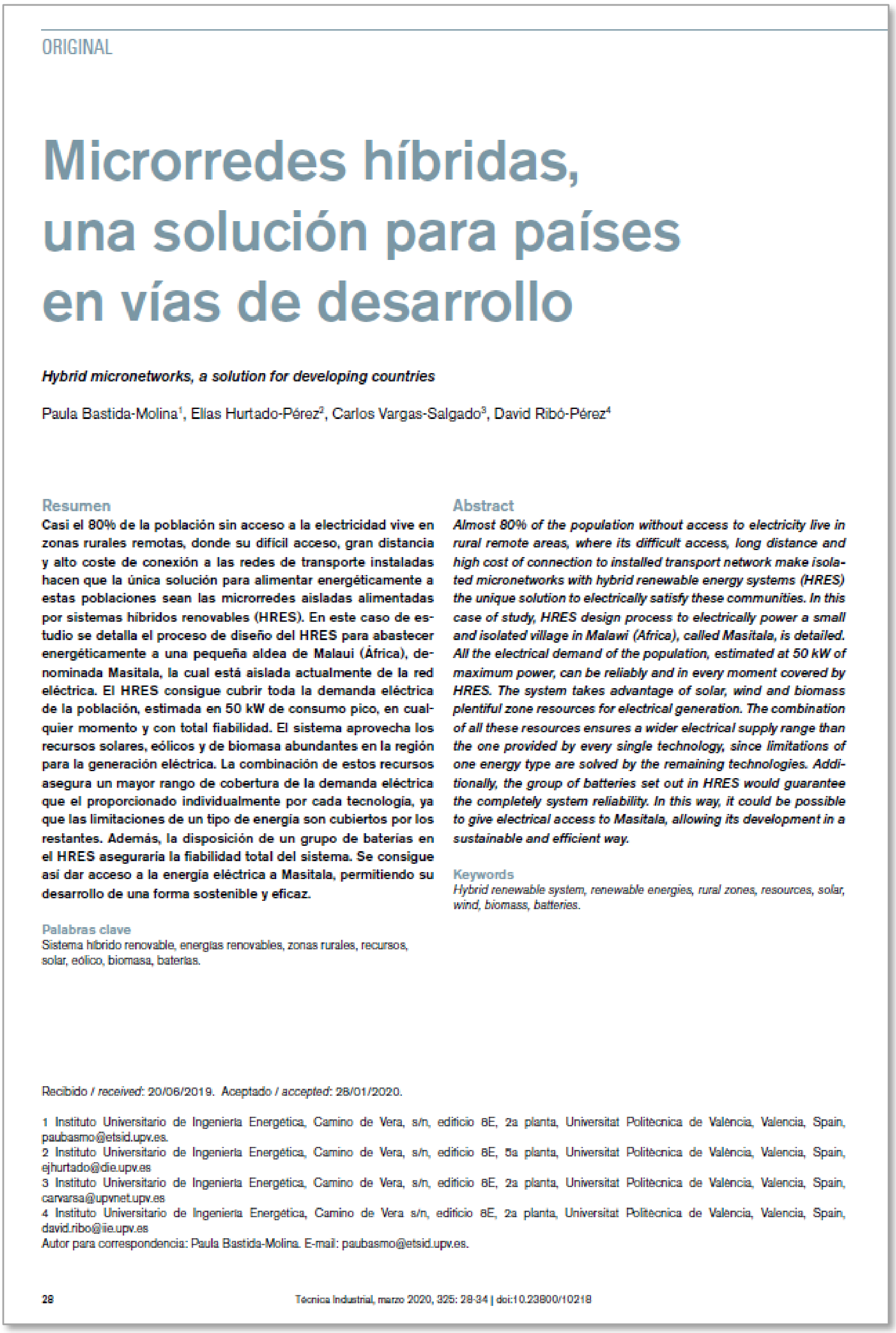
Powered Charging Stations on Highways: A Data-Driven Robust Optimization Approach. IEEE Trans. Transp. Electrif. 4, 817–830. https://doi.org/10.1109/TTE.2018.2849222

Xu, X., Hu, W., Cao, D., Huang, Q., Chen, C., Chen, Z., 2020. Optimized sizing of a standalone PV-wind-hydropower station with pumped-storage installation hybrid energy system. Renew. Energy 147, 1418–1431. https://doi.org/10.1016/j.renene.2019.09.099

Zhang, Y., Yuan, J., Zhao, C., Lyu, L., 2020. Can dispersed wind power take off in China: A technical & institutional economics analysis. J. Clean. Prod. 256, 120475. https://doi.org/10.1016/j.jclepro.2020.120475

Zheng, J., Sun, X., Jia, L., Zhou, Y., 2020. Electric passenger vehicles sales and carbon dioxide emission reduction potential in China's leading markets. J. Clean. Prod. 243, 118607. https://doi.org/10.1016/j.jclepro.2019.118607

2.4. Microrredes híbridas, una solución para países en vías de desarrollo



ORIGINAL

Microrredes híbridas, una solución para países en vías de desarrollo

Hybrid micronetworks, a solution for developing countries

Paula Bastida-Molina[1], Elías Hurtado-Pérez[2], Carlos Vargas-Salgado[3], David Ribó-Pérez[4]

Resumen

Casi el 80% de la población sin acceso a la electricidad vive en zonas rurales remotas, donde su difícil acceso, gran distancia y alto coste de conexión a las redes de transporte instaladas hacen que la única solución para alimentar energéticamente a estas poblaciones sean las microrredes aisladas alimentadas por sistemas híbridos renovables (HRES). En este caso de estudio se detalla el proceso de diseño del HRES para abastecer energéticamente a una pequeña aldea de Malaui (África), denominada Masitala, la cual está aislada actualmente de la red eléctrica. El HRES consigue cubrir toda la demanda eléctrica de la población, estimada en 50 kW de consumo pico, en cualquier momento y con total fiabilidad. El sistema aprovecha los recursos solares, eólicos y de biomasa abundantes en la región para la generación eléctrica. La combinación de estos recursos asegura un mayor rango de cobertura de la demanda eléctrica que el proporcionado individualmente por cada tecnología, ya que las limitaciones de un tipo de energía son cubiertos por los restantes. Además, la disposición de un grupo de baterías en el HRES aseguraría la fiabilidad total del sistema. Se consigue así dar acceso a la energía eléctrica a Masitala, permitiendo su desarrollo de una forma sostenible y eficaz.

Palabras clave

Sistema híbrido renovable, energías renovables, zonas rurales, recursos, solar, eólico, biomasa, baterías.

Abstract

Almost 80% of the population without access to electricity live in rural remote areas, where its difficult access, long distance and high cost of connection to installed transport network make isolated micronetworks with hybrid renewable energy systems (HRES) the unique solution to electrically satisfy these communities. In this case of study, HRES design process to electrically power a small and isolated village in Malawi (Africa), called Masitala, is detailed. All the electrical demand of the population, estimated at 50 kW of maximum power, can be reliably and in every moment covered by HRES. The system takes advantage of solar, wind and biomass plentiful zone resources for electrical generation. The combination of all these resources ensures a wider electrical supply range than the one provided by every single technology, since limitations of one energy type are solved by the remaining technologies. Additionally, the group of batteries set out in HRES would guarantee the completely system reliability. In this way, it could be possible to give electrical access to Masitala, allowing its development in a sustainable and efficient way.

Keywords

Hybrid renewable system, renewable energies, rural zones, resources, solar, wind, biomass, batteries.

Recibido / *received*: 20/06/2019. Aceptado / *accepted*: 28/01/2020.

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28 Técnica Industrial, marzo 2020, 325: 28-34 | doi:10.23800/10218

Microrredes híbridas, una solución para países en vías de desarrollo

Hybrid microgrids, a solution to developing countries

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Abstract

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Key words

Hybrid renewable system, renewable energies, rural zones, resources, solar, wind, biomass, batteries.

1. Introducción

El acceso por parte de la población a la electricidad se ha convertido en uno de los índices más importantes para el desarrollo de un país. Tal y como afirman distintas organizaciones como el Banco Mundial (WB) o Agencia Internacional de la Energía (IEA), el acceso a la electricidad proporciona a los distintos países los recursos necesarios para mejorar aspectos clave como educación, sanidad, redes de agua, comunicaciones o adaptación y mitigación al cambio climático. Sin embargo, existe aún cerca de 1 billón de personas sin acceso a la electricidad (IEA, 2018). De estas, el 80% vive en zonas rurales aisladas del África subsahariana, el sudeste asiático y Sudamérica principalmente.

Los costes de inversión que tendrían que asumir estas comunidades para poder tener acceso a la red eléctrica son muy altos, prácticamente prohibitivos. Por ello, las microrredes aisladas alimentadas por sistemas híbridos renovables (HRES, por sus siglas en inglés) se presentan como una solución que permitiría dar respuesta a esta necesidad de las comunidades aisladas de electricidad (IEA, 2017a). Estos sistemas permiten cubrir la demanda eléctrica de las poblaciones rurales utilizando recursos renovables abundantes en la región, como la energía solar, eólica, biomasa etc. El uso híbrido y combinado de los distintos tipos de tecnologías supera las restricciones de los sistemas renovables convencionales, puesto que las limitaciones de un tipo de tecnología se suplen con las características del resto de fuentes (Kartite and Cherkaoui, 2019). Además, los HRES cuentan con el respaldo de baterías o grupos electrógenos, haciéndolos así sistemas de elevada fiabilidad.

En los últimos años, se han llevado a cabo numerosos proyectos de implantación de HRES en poblaciones rurales aisladas de la red eléctrica. Algunos de ellos son el proyecto llevado a cabo en Necoclí- Colombia en 2009, Kinshasa (República Dominicana del Congo) en 2012 (Hurtado, Peñalvo-López, Pérez-Navarro, Vargas, & Alfonso, 2015) o en Choco-Colombia en 2015. Estos proyectos han verificado la idoneidad de utilizar HRES en zonas aisladas de la red eléctrica, especialmente en comunidades de África y Sudamérica, donde las horas de sol y los recursos de biomasa son abundantes.

En este artículo se plantea el diseño de una instalación que se prevé desarrollar en una pequeña aldea de Malawi, en África, denominada Masitala. Esta comunidad ha sufrido numerosos problemas agrícolas y de sequía en los últimos tiempos, lo que ha conducido a una desnutrición generalizada de la población. La actuación de William Kamkwanba en 2010 logró salvar a esta pequeña aldea de una fuerte hambruna, dando a conocer la comunidad en el mundo. Este joven, originario de Masitala, consiguió construir un molino de viento utilizando restos de chatarra, troncos de árbol, piezas de automóvil etc. viendo las imágenes de un libro en inglés que encontró en la biblioteca, sin saber él nada de inglés. Con este rudimentario molino de viento fue posible generar una pequeña cantidad de energía con la que se logró bombear agua para regar los cultivos, mitigando el hambre de los habitantes de la población (Dieterich, 2018).

Sin embargo, este pequeño molino es insuficiente y poco fiable para cubrir toda la demanda energética de la aldea. Además, tan sólo es posible utilizarlo en momentos puntuales de tiempo. Se considera así que la aldea está aislada eléctricamente.

Por ello, se pretende diseñar un sistema híbrido renovable que permita cubrir las necesidades energéticas de Masitala utilizando recursos solares, eólicos y de biomasa, utilizando como respaldo un sistema de almacenamiento en baterías.

2. Curva de consumo diaria

El primer paso para poder dimensionar un HRES es conocer la curva de consumo diaria de la población donde se instalará. Sin embargo, en este caso de estudio no es posible recopilar datos reales, ya que actualmente la población de Masitala se encuentra aislada de la red. El método que se utiliza para ello consiste en estimar cuáles serían los consumidores principales de Masitala y estimar su curva de consumo diaria para asegurar así una calidad de vida digna a sus habitantes (Bhuiyan and Ali Asgar, 2003). Para una aldea como Masitala, se establece que estos consumos serían una biblioteca, una escuela de educación infantil-primaria, una escuela de educación secundaria, un consultorio médico, las residencias de los habitantes (70 en total), la red de alumbrado público y una bomba de extracción de agua. Así, es posible obtener finalmente la curva de consumo total como el sumatorio de cada una de las curvas de consumo diario de cada consumidor establecido. La Figura 1 presenta el resultado de la estimación. En ella se puede observar que la potencia máxima estimada es de 50 kW a última hora de la noche.

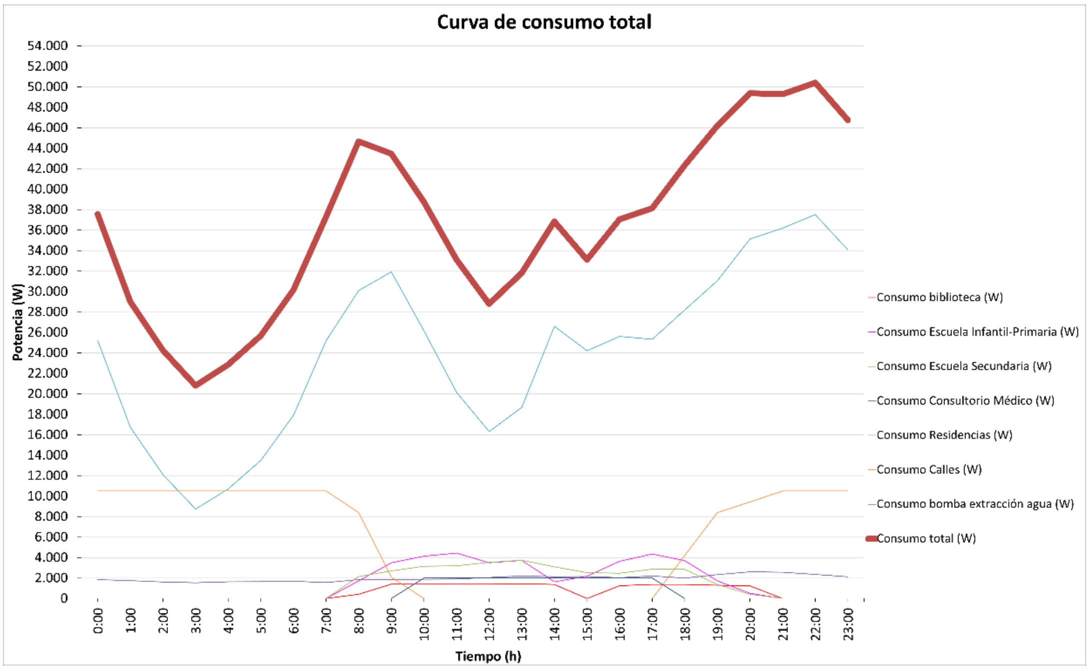


Figura 1. Curva de consumo total.

3. Elección de las distintas tecnologías

La elección de los distintas tecnologías que compondrán el HRES es un punto clave del proceso de diseño (Mandelli et al., 2016). La demanda de energía estimada para la población, la abundancia de los recursos y la viabilidad técnica y económica son los principales factores que se han tenido en cuenta para ello (Hussain et al., 2017).

El elevado número de horas solares que se dan en Masitala a lo largo del año (2362 HSP), sumado a la fácil instalación de los paneles solares fotovoltaicos y su precio competitivo hacen que la energía solar resulte idónea para el HRES. Además, se dispone de forma abierta de la herramienta PVGIS con la cual es posible obtener la curva de radiación solar en cada mes del año.

La ubicación de Masitala hace que el viento sea también un recurso abundante en la aldea. El patrón de vientos (dirección, frecuencia…) se obtiene con la herramienta Global Wind Atlas, una herramienta gratuita y de libre uso. Esto hace que la energía eólica sea una fuente de energía adecuada también para el sistema, aunque se dispondrá en menor medida que la solar por su mayor dificultad de instalación, operación y coste, ayudando al aumento de la fiabilidad del sistema, principalmente en épocas con mucha nubosidad.

En Masitala existen también especies leñosas de alto poder calorífico muy abundantes en la región. Así, la energía de la biomasa también se va se va a utilizar en el HRES. Sin embargo, va a incluirse como una tecnología secundaria, que sólo entrará en funcionamiento en momentos puntuales, ya que su funcionamiento continuado supondría graves problemas en el equipo de biomasa (obstrucción, alquitranes…).

Otros posibles tipos de energía a incluir en el HRES podrían ser la energía hidráulica o la geotérmica. Sin embargo, la gran infraestructura que necesitarían y su elevado coste hacen que estas tecnologías sean descartadas.

Como sistema de respaldo para almacenar los excedentes de energía cuando el potencial de generación supera a la demanda de energía, se decide utilizar baterías. Podría utilizarse también grupos electrógenos, por su amplia madurez tecnológica, facilidad de uso e instalación. Sin embargo, los grupos electrógenos son descartados por su elevado índice de emisiones contaminantes (Arabzadeh Saheli et al., 2019).

Tras este breve análisis, se determina que las fuentes de energía que formarán el HRES serán la energía solar, eólica y de biomasa, junto con el respaldo de un grupo de baterías.

4. Descripción del HRES

En general, el objetivo de cualquier HRES es asegurar que la demanda energética de la población se cubra con una alta fiabilidad (Pérez-Navarro et al., 2016). Para el caso de estudio, el HRES deberá cubrir la demanda eléctrica de Masitala, a partir de los recursos renovables, contando adicionalmente con el apoyo de un sistema de almacenamiento en baterías.

El inversor-cargador de batería bidireccional, “Sunny Island”, es el “cerebro” del sistema. Permite crear la red aislada de 230-400 V en corriente alterna cuando toma la energía de las baterías.

Los recursos de generación solar y eólica están conectados a esta red, así como los consumos de la población. Por otro lado, el grupo electrógeno del equipo de biomasa está directamente conectado a Sunny Island. En los momentos en que actúa la biomasa, Sunny Island es capaz de sincronizarse y conectarse con el grupo electrógeno. En esas situaciones, la red deja de estar formada por Sunny Island, será el grupo electrógeno de la biomasa el elemento que determine los parámetros de la red (Figura 2)

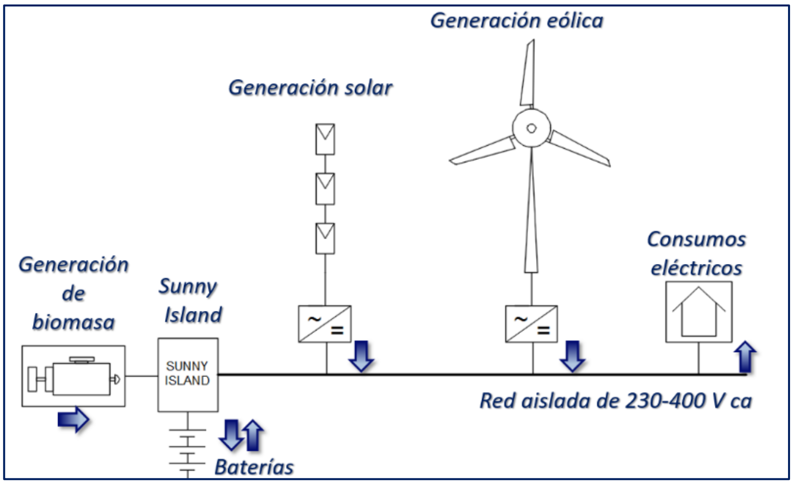


Figura 2. Configuración del HRES

Las posibles situaciones de generación-consumo son descritas a continuación y recopiladas en la Tabla 1:

- Si con la generación solar-eólica fuese posible cubrir toda la demanda eléctrica de Masitala, sin que se produjesen excedentes de energía, ni la ayuda del grupo electrógeno de la biomasa ni la de las baterías serían necesarias. No habría tampoco excedentes de energía y Sunny Island sería el encargado de establecer la red.

- En el caso de que la generación solar-eólica pudiera cubrir toda la demanda eléctrica de Masitala y además se produjeran excedentes, con los mismos sería posible cargar las baterías. En esta situación ni el grupo electrógeno ni las baterías actuarían. La red la formaría Sunny Island.
- La tercera situación que podría darse es que los recursos solares-eólicos no fueran suficientes para suplir la demanda eléctrica de Masitala. En este caso, podrían ocurrir tres nuevas situaciones:
    - La actuación del grupo electrógeno de la biomasa permitiría cubrir toda la demanda, sin necesidad de que actuaran las baterías. En este caso, sería el grupo electrógeno quien formaría la red.
    - El grupo electrógeno de la biomasa no entra en funcionamiento, sino las baterías. En este caso, Sunny Island sería el encargado de formar la red.
    - Si la demanda de energía es cubierta tanto por el grupo electrógeno de la biomasa como por las baterías, el grupo electrógeno es quien formaría la red.

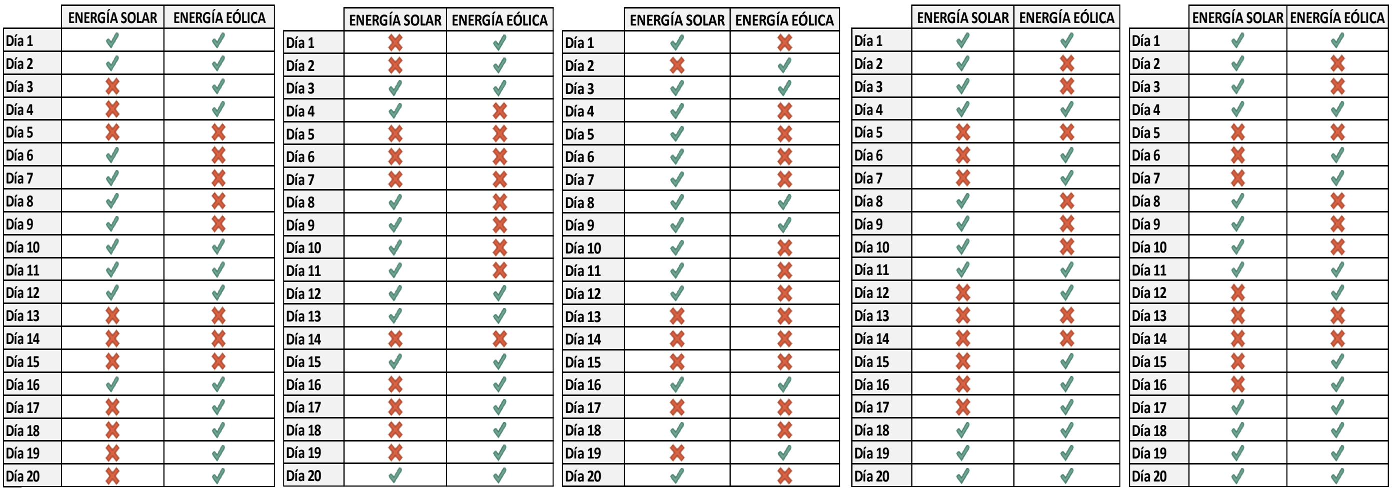
Esta secuencia de funcionamiento coincide con la descrita en la fase de estudio de selección de las distintas tecnologías que formarán el HRES. La demanda energética se cubre con los recursos solares y eólicos en primer lugar, después con los de la biomasa y, por último, con las baterías.

Tabla 1. Situaciones de funcionamiento del HRES.

SITUACIONES DE FUNCIONAMIENTO. SISTEMA HÍBRIDO RENOVABLE				
GENERACIÓN SOLAR Y/O EÓLICA	**EXCEDENTES DE ENERGÍA**	**GRUPO ELECTRÓGENO**	**BATERÍAS**	**ELEMENTO QUE FORMA LA RED**
Si, cubre la demanda energética	No	No actúa	No actúan	Sunny Island
Si, cubre la demanda energética	Si. Carga de baterías	No actúa	No actúan	Sunny Island
No cubre toda la demanda energética	No	Si actúa	No actúan	Grupo electrógeno
	No	No actúa	Si actúan	Sunny Island
	No	Si actúa	Si actúan	Grupo electrógeno

5. Dimensionado del HRES

El dimensionado del HRES se realiza siempre para el mes más desfavorable, es decir el mes con menor producción energética, para asegurar una mayor fiabilidad del sistema (Bastida Molina, 2018). Conocido este mes, es necesario realizar un extenso estudio para determinar los patrones climatológicos que podrían darse en la población en dicho mes: cuantos días suelen ser soleados, cuántos suelen ser ventosos, cuantos días suelen ser soleados y ventosos a la vez o la cantidad de días seguidos que cumplen estas características. La herramienta utilizada para ello ha sido Meteoblue. Realizando este estudio para Masitala, se establecen finalmente cinco patrones climatológicos (Figura 3).



	ENERGÍA SOLAR	ENERGÍA EÓLICA
Día 1	✓	✓
Día 2	✓	✓
Día 3	✗	✓
Día 4	✗	✓
Día 5	✗	✗
Día 6	✓	✗
Día 7	✓	✗
Día 8	✓	✗
Día 9	✓	✗
Día 10	✓	✓
Día 11	✓	✓
Día 12	✓	✓
Día 13	✗	✗
Día 14	✗	✗
Día 15	✗	✗
Día 16	✓	✓
Día 17	✗	✓
Día 18	✗	✓
Día 19	✗	✓
Día 20	✗	✓

	ENERGÍA SOLAR	ENERGÍA EÓLICA
Día 1	✗	✓
Día 2	✗	✓
Día 3	✓	✓
Día 4	✓	✗
Día 5	✗	✗
Día 6	✗	✗
Día 7	✗	✗
Día 8	✓	✗
Día 9	✓	✗
Día 10	✓	✗
Día 11	✓	✗
Día 12	✓	✓
Día 13	✓	✓
Día 14	✗	✗
Día 15	✓	✓
Día 16	✗	✓
Día 17	✗	✓
Día 18	✗	✓
Día 19	✗	✓
Día 20	✓	✓

	ENERGÍA SOLAR	ENERGÍA EÓLICA
Día 1	✓	✗
Día 2	✗	✓
Día 3	✓	✓
Día 4	✓	✗
Día 5	✓	✗
Día 6	✓	✗
Día 7	✓	✗
Día 8	✓	✓
Día 9	✓	✓
Día 10	✓	✗
Día 11	✓	✗
Día 12	✓	✗
Día 13	✗	✗
Día 14	✗	✗
Día 15	✗	✗
Día 16	✓	✓
Día 17	✗	✗
Día 18	✓	✗
Día 19	✗	✓
Día 20	✓	✗

	ENERGÍA SOLAR	ENERGÍA EÓLICA
Día 1	✓	✓
Día 2	✓	✗
Día 3	✓	✗
Día 4	✓	✓
Día 5	✗	✗
Día 6	✗	✓
Día 7	✗	✓
Día 8	✓	✗
Día 9	✓	✗
Día 10	✓	✗
Día 11	✓	✓
Día 12	✗	✓
Día 13	✗	✗
Día 14	✗	✗
Día 15	✗	✓
Día 16	✗	✓
Día 17	✗	✓
Día 18	✓	✓
Día 19	✓	✓
Día 20	✓	✓

	ENERGÍA SOLAR	ENERGÍA EÓLICA
Día 1	✓	✓
Día 2	✓	✗
Día 3	✓	✗
Día 4	✓	✓
Día 5	✗	✗
Día 6	✗	✓
Día 7	✗	✓
Día 8	✓	✗
Día 9	✓	✗
Día 10	✓	✗
Día 11	✓	✓
Día 12	✗	✓
Día 13	✗	✗
Día 14	✗	✗
Día 15	✗	✓
Día 16	✗	✓
Día 17	✓	✓
Día 18	✓	✓
Día 19	✓	✓
Día 20	✓	✓

Figura 3. Patrones climatológicos.

Para cada uno de estos patrones climatológicos (hipótesis), se calcula una curva inicial de producción solar-eólica (Figura 4). Seguidamente, en cada una de las hipótesis se añade la curva de producción de biomasa (Figura 5). Para ello, hay que tener en cuenta una serie de características, detalladas a continuación (Hurtado et al., 2015):

- La biomasa deberá actuar en los momentos en que haya déficit de energía. Para conocer esos momentos, se superponen las curvas de producción solar-eólica con la curva de consumo diario en cada hipótesis y para todos los días (Figura 6). Así, es posible conocer en qué momentos debe actuar la biomasa.
- El número de horas de funcionamiento del equipo de biomasa no es fijo, si no que variará en función del día.
- Se debe evitar siempre el funcionamiento intermitente del equipo de biomasa

El sumatorio de los tres tipos de producción (solar, eólica y biomasa) corresponde a la curva de producción total (Figura 7).

Como elemento de apoyo, se ha decidido utilizar baterías, qué actuarán cuando el resto de tecnologías no sean capaces de cubrir la demanda de energía. Es necesario superponer las curvas de producción y de consumo totales (Figura 8) para ver en qué momentos se producen excedentes o déficits de energía ya que las baterías se cargarán cuando haya excedentes de energía y actuarán (se descargarán) cuando haya déficit de energía (Figura 9).

Una vez conocida la metodología, se implementa un proceso iterativo a partir de los datos iniciales para poder dimensionar el sistema y determinar qué cantidad de recursos de generación (solar, eólica, biomasa y baterías) son necesarios. Se considera que el proceso iterativo ha finalizado cuando en las cinco hipótesis propuestas se alcanzan los requisitos que se describen a continuación:

- Todos los recursos de generación no deben ser utilizados en la misma proporción. El estudio previo acerca de las tecnologías a introducir en el HRES determinó que el recurso más abundante debía ser el solar, seguido de la energía eólica y por último biomasa. La función de apoyo de las baterías, similar a la de la biomasa, hace que estas estén en una proporción muy similar a la biomasa.
- El equipo de biomasa no puede funcionar de forma intermitente, sino que lo hace en un único periodo del día.
- Para evitar problemas de funcionamiento en las baterías, su energía almacenada nunca puede bajar por debajo del 30% de la nominal.

- La potencia cargada o descargada instantáneamente por las baterías debe ser siempre inferior al 10% de su energía nominal.

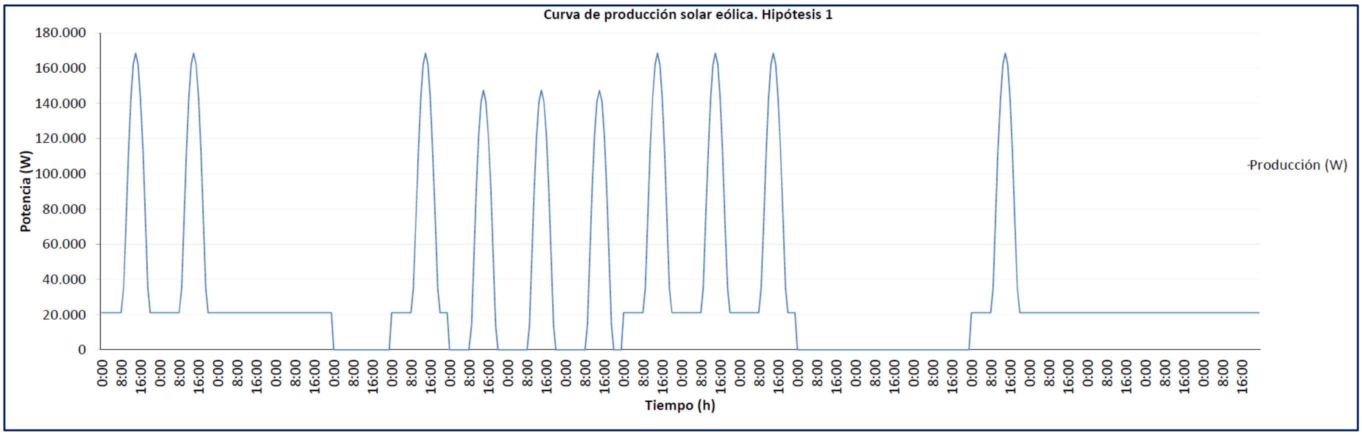


Figura 4. Curva de producción solar-eólica. Hipótesis 1.

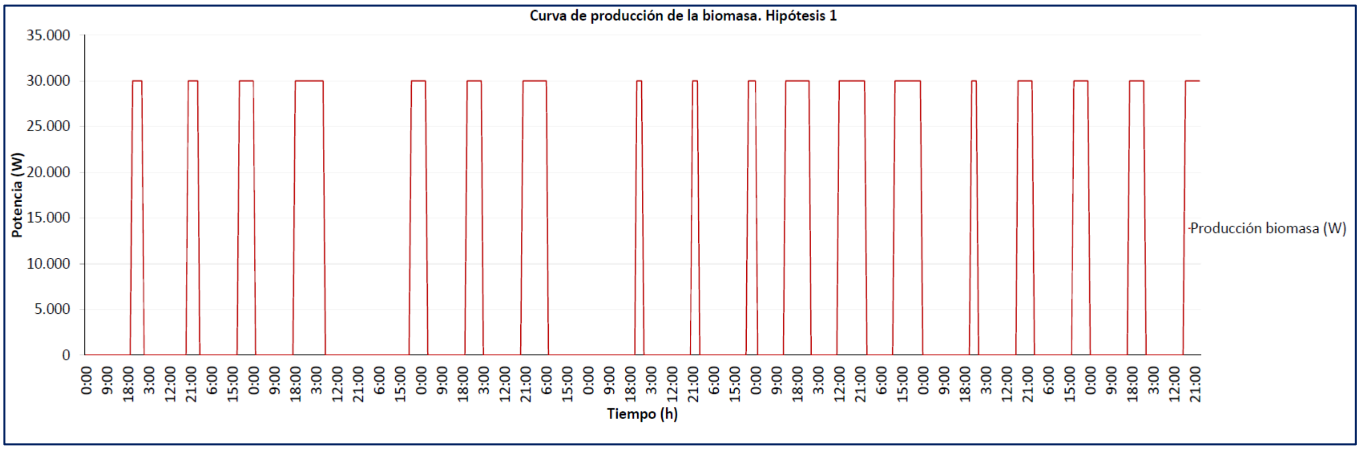


Figura 5. Curva de producción de la biomasa. Hipótesis 1.

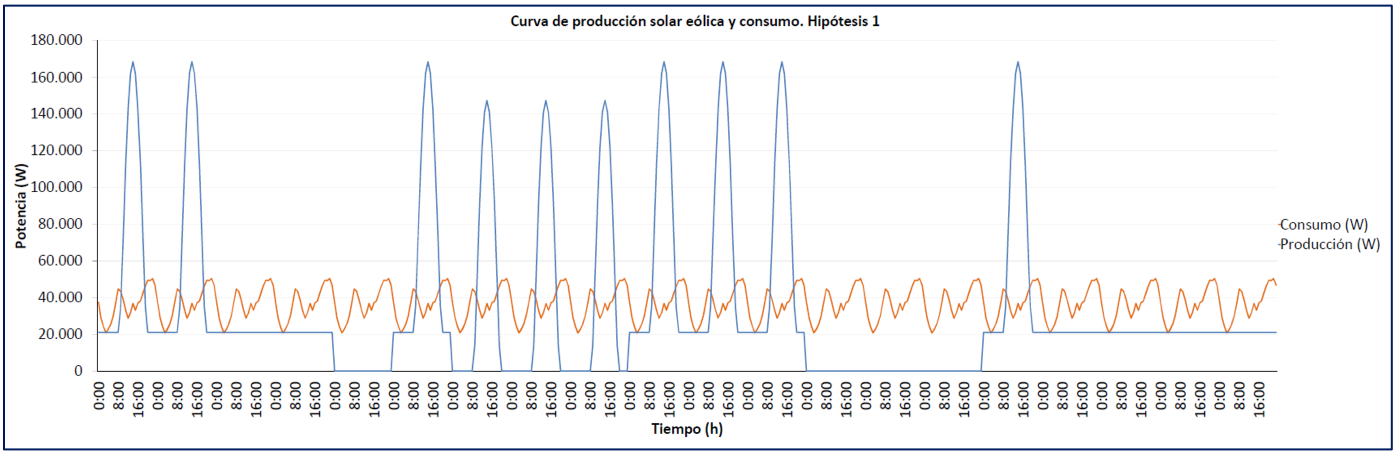


Figura 6. Curva de producción solar, eólica y consumo. Hipótesis 1.

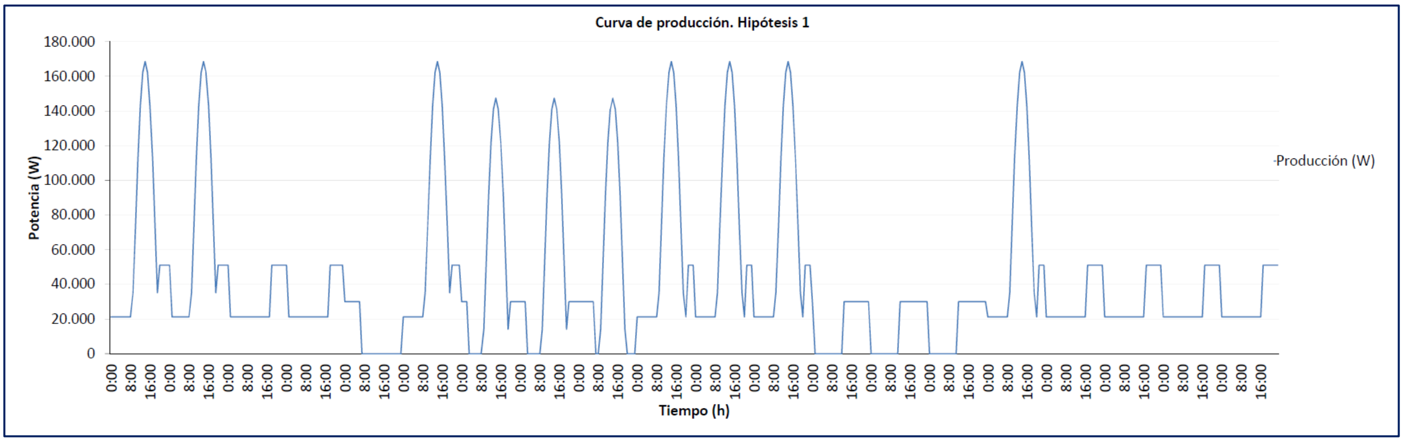


Figura 7. Curva de producción total. Hipótesis 1.

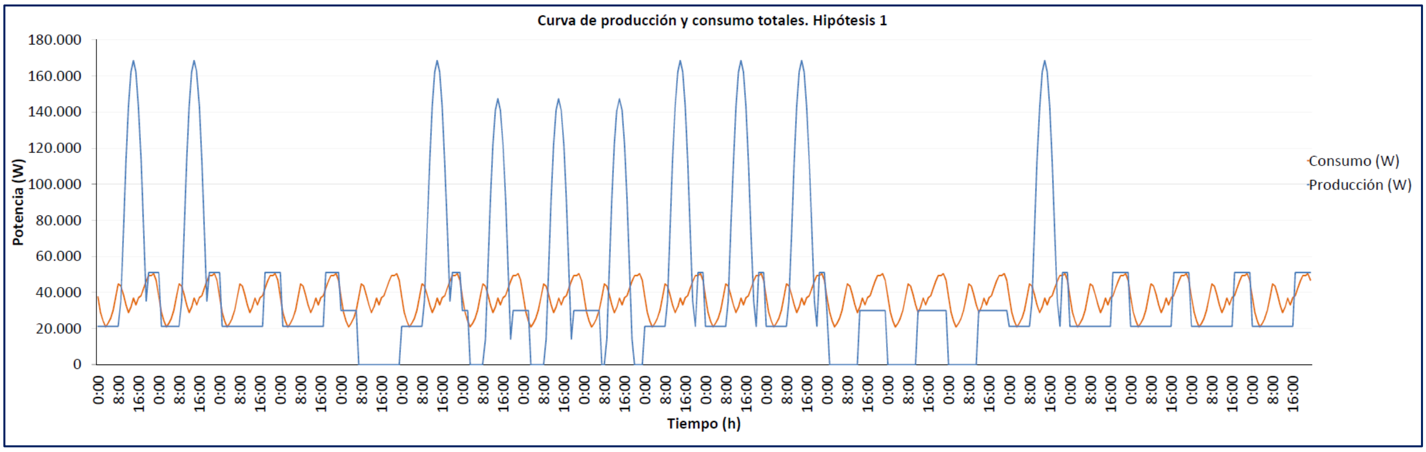


Figura 8. Curva de consumo y producción totales. Hipótesis 1.

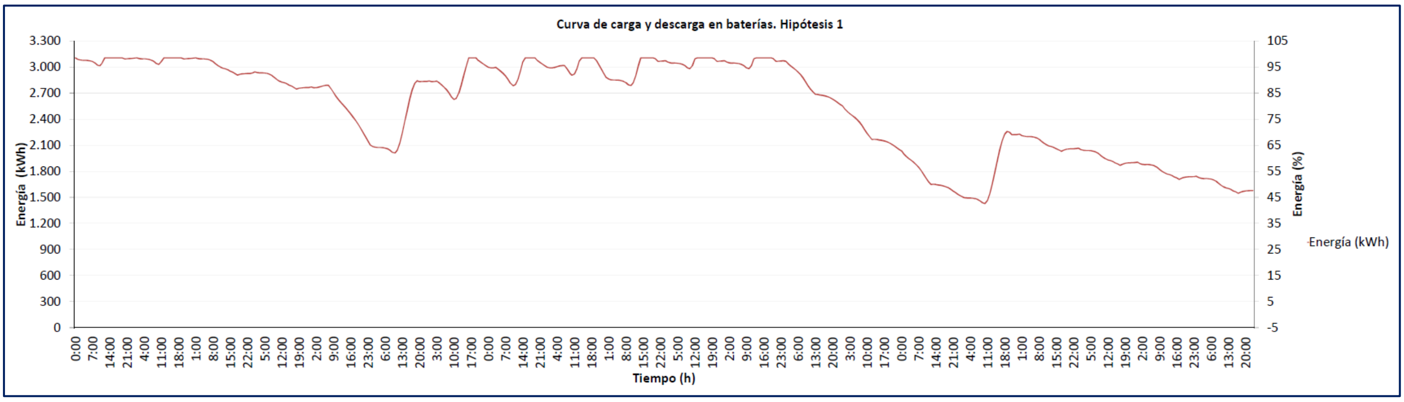


Figura 9. Curva de carga y descarga de baterías. Hipótesis 1.

Aplicando este proceso, es posible obtener la cantidad de recursos de generación y respaldo que permitirían cubrir la demanda energética de Masitala, cumpliendo los requisitos expuestos en las 5 hipótesis. De este modo, el sistema está formado por 1200 placas de 255 W_p, 8 aerogeneradores de 10 kW, un grupo electrógeno para la biomasa de 36 kW, 14 líneas en paralelo de baterías de 4620 Ah cada una y 21 Sunny Island.

Tabla 2. Diseño final del Sistema Híbrido Renovable

Diseño final del Sistema Híbrido Renovable	
Energía solar	1200 placas, de 255W_p cada placa
Energía eólica	8 aerogeneradores, de 10 kW cada uno
Energía de la biomasa	Grupo electrógeno para biomasa de 36 kW
Baterías	14 líneas en paralelo, capacidad de 4620 Ah cada batería

6. Conclusiones

El HRES objeto de estudio permitiría solucionar el principal problema que asola actualmente a Masitala: el aislamiento eléctrico. El uso de recursos renovables que se encuentran de forma muy abundante (biomasa) o de forma ilimitado (sol, viento) en la población es aprovechado para dar solución a este gravísimo problema. Los recursos son combinados de forma adecuada en el HRES dimensionado, que aseguraría la demanda energética de la población en cualquier situación, apoyándose de un grupo de baterías para una total fiabilidad. Esto supondría un gran avance tecnológico y social para la población, que verían como su nivel de vida mejora significativamente en aspectos tan diversos como sanidad, comunicaciones o educación, entre otros muchos. Además, desde el punto de vista medioambiental, se consigue alimentar toda una población con un balance de emisiones nulo durante la generación eléctrica aprovechando los recursos naturales disponibles.

Agradecimientos

Este trabajo ha sido respaldado en parte por la administración pública de Valencia bajo la beca ACIF/2018/106 y por la administración pública de España bajo la beca FPU2016/00962.

Referencias

Arabzadeh Saheli, M., Fazelpour, F., Soltani, N., Rosen, M.A., 2019. Performance analysis of a photovoltaic/wind/diesel hybrid power generation system for domestic utilization in winnipeg, manitoba, canada. Environ. Prog. Sustain. Energy 38, 548–562. https://doi.org/10.1002/ep.12939

Bastida Molina, P., 2018. Diseño de un sistema híbrido de energía para el suministro eléctrico a una comunidad aislada de 50 kW de potencia máxima a través de recursos solares, eólicos y de biomasa. RiuNET.

Bhuiyan, M.M.H., Ali Asgar, M., 2003. Sizing of a stand-alone photovoltaic power system at Dhaka. Renew. Energy 28, 929–938. https://doi.org/10.1016/S0960-1481(02)00154-4

Dieterich, M., 2018. Sustainable development as a driver for innovation and employment. Int. J. Innov. Sustain. Dev. 12, 2. https://doi.org/10.1504/IJISD.2018.10009931

Hurtado, E., Peñalvo-López, E., Pérez-Navarro, Á., Vargas, C., Alfonso, D., 2015. Optimization of a hybrid renewable system for high feasibility application in non-connected zones. Appl. Energy 155, 308–314. https://doi.org/10.1016/J.APENERGY.2015.05.097

Hussain, C.M.I., Norton, B., Duffy, A., 2017. Technological assessment of different solar-biomass systems for hybrid power generation in Europe. Renew. Sustain. Energy Rev. 68, 1115–1129. https://doi.org/10.1016/J.RSER.2016.08.016

IEA, 2018. World Energy Outlook.

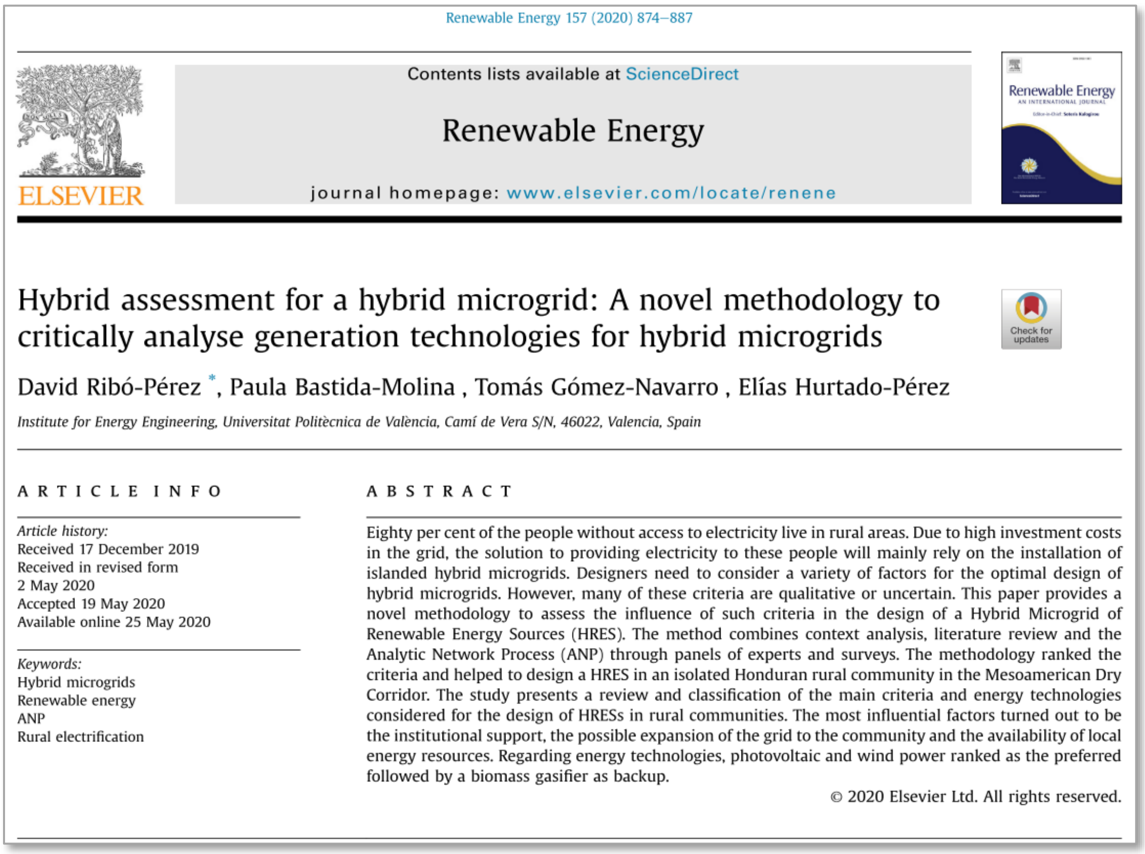
IEA, 2017a. World Energy Outlook.

Kartite, J., Cherkaoui, M., 2019. Study of the different structures of hybrid systems in renewable energies: A review. Energy Procedia 157, 323–330. https://doi.org/10.1016/J.EGYPRO.2018.11.197

Mandelli, S., Barbieri, J., Mereu, R., Colombo, E., 2016. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renew. Sustain. Energy Rev. 58, 1621–1646. https://doi.org/10.1016/J.RSER.2015.12.338

Pérez-Navarro, A., Alfonso, D., Ariza, H.E., Cárcel, J., Correcher, A., Escrivá-Escrivá, G., Hurtado, E., Ibáñez, F., Peñalvo, E., Roig, R., Roldán, C., Sánchez, C., Segura, I., Vargas, C., 2016. Experimental verification of hybrid renewable systems as feasible energy sources. Renew. Energy 86, 384–391. https://doi.org/10.1016/J.RENENE.2015.08.030

2.5. Hybrid assessment for a hybrid microgrid: A novel methodology to critically analyse generation technologies for hybrid microgrids



Renewable Energy 157 (2020) 874–887

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

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ARTICLE INFO

Article history:
Received 17 December 2019
Received in revised form
2 May 2020
Accepted 19 May 2020
Available online 25 May 2020

Keywords:
Hybrid microgrids
Renewable energy
ANP
Rural electrification

ABSTRACT

Eighty per cent of the people without access to electricity live in rural areas. Due to high investment costs in the grid, the solution to providing electricity to these people will mainly rely on the installation of islanded hybrid microgrids. Designers need to consider a variety of factors for the optimal design of hybrid microgrids. However, many of these criteria are qualitative or uncertain. This paper provides a novel methodology to assess the influence of such criteria in the design of a Hybrid Microgrid of Renewable Energy Sources (HRES). The method combines context analysis, literature review and the Analytic Network Process (ANP) through panels of experts and surveys. The methodology ranked the criteria and helped to design a HRES in an isolated Honduran rural community in the Mesoamerican Dry Corridor. The study presents a review and classification of the main criteria and energy technologies considered for the design of HRESs in rural communities. The most influential factors turned out to be the institutional support, the possible expansion of the grid to the community and the availability of local energy resources. Regarding energy technologies, photovoltaic and wind power ranked as the preferred followed by a biomass gasifier as backup.

Hybrid assessment for a hybrid microgrid: a novel methodology to critically analyse generation technologies for hybrid microgrids

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Abstract

Eighty per cent of the people without access to electricity live in rural areas. Due to high investment costs in the grid, the solution to providing electricity to these people will mainly rely on the installation of islanded hybrid microgrids. Designers need to consider a variety of factors for the optimal design of hybrid microgrids. However, many of these criteria are qualitative or uncertain. This paper provides a novel methodology to assess the influence of such criteria in the design of a Hybrid Microgrid of Renewable Energy Sources (HRES). The method combines context analysis, literature review and the Analytic Network Process (ANP) through panels of experts and surveys. The methodology ranked the criteria and helped to design a HRES in an isolated Honduran rural community in the Mesoamerican Dry Corridor. The study presents a review and classification of the main criteria and energy technologies considered for the design of HRESs in rural communities. The most influential factors turned out to be the institutional support, the possible expansion of the grid to the community and the availability of local energy resources. Regarding energy technologies, photovoltaic and wind power ranked as the preferred followed by a biomass gasifier as backup.

Keywords

Hybrid Microgrids, Renewable Energy, ANP, Rural Electrification.

1. Introduction

Access to clean electricity is a key factor in fighting energy poverty and promoting sustainable development. Organisations such as the World Bank or the International Energy Agency state that access to electricity improves socio-economic conditions such as the poverty ratio, health, education, environment and income (Kanagawa and Nakata, 2008). The UN Sustainable Development Goal 7 (Affordable and Clean Energy) plans to achieve the electrification of the world's population by 2030 (UN, 2019). However, around 0.86 billion people remain without access to it (IEA, 2018). Among them, 80% live in rural areas mainly located in sub-Saharan Africa, Southeast Asia and South America. Commonly, vast and/or, steep lands separate these rural communities from the central power grid, resulting in high investment costs to connect them. Electrification is understood to cover the basic human demands and community needs (He and Reiner, 2014; Taele et al., 2007) and this is normally beyond the supply of the common pico-solar and individual home power systems (Ahmed et al., 2014; Parajuli, 2011).This situation makes islanded microgrids an optimal solution to securely cover electrical demand (IEA, 2017a). In fact, the International Energy Agency foresees that microgrids will provide almost 50% of projected electrification worldwide (IEA, 2017a). Microgrids tend to rely on the different renewable energy sources available in the communities, supported by back-up systems (Østergaard et al., 2020). These microgrids combine several technologies and the literature refers to them as Hybrid Microgrids of Renewable Energy Sources (HRES) (Hurtado et al., 2015; Scheubel et al., 2017; Wang et al., 2019).

A broad range of studies analyse the feasibility of Hybrid Microgrids of Renewable Energy Sources (HRES) to electrify remote rural areas. Oduo *et al.* study the techno-economic viability of an HRES in a village of Benin (Odou et al., 2020). Their research shows that a hybrid solar PV system with a battery and the support of a diesel generator provides the lowest cost option. Ayodele *et al.* present an HRES optimisation model applied to a village in Nigeria. Wind and solar PV resources supported by conventional generators and batteries power the HRES (Ayodele et al., 2019). Das and Zaman show a viable performance of an HRES based on solar PV, diesel and batteries in a remote community in Bangladesh bearing in mind economic parameters such as cost of energy and net present cost (Das and Zaman, 2019).

Nowadays, experts accept the feasibility of HRESs for electrifying rural areas. Nevertheless, to our knowledge no research deals with how to optimally select the technologies prior to the design based in a diversity of both quantitative and qualitative interrelated criteria. Drivers like energy resources, climate conditions, project specific viability or energy demands condition the decision (Hussain et al., 2017). Despite the undeniable importance of these factors, basing technology selection only on these criteria jeopardises the long-term sustainability of the project, which also requires social acceptability and community appropriation of it. For instance, Ilskog proposed a set of 39 indicators for rural electrification analysis grouped into five different dimensions, which contained not only technical or economic sustainability, but also social/ethical, environmental and institutional sustainability criteria (Ilskog, 2008). Ilskog and Kjellstrom completed this study by scoring 31 of these indicators (Ilskog and Kjellström, 2008). Katre and Tozzi (Katre and Tozzi, 2018) and Purwanto and Afifah (Purwanto and Afifah, 2016) also assess the sustainability of HRES regarding these last five dimensions. The first ones proposed a list of 12 measures and 31 indicators (Katre and Tozzi, 2018). While Purwanto and Afifah (Purwanto and Afifah, 2016) highlighted the important role that rural communities play on electrification projects. Lillo *et al*. (Lillo et al., 2015) shed light on this statement, and incorporated a Human Development approach to evaluate hybrid electrification projects. This approach relies on four principles: equity and diversity, sustainability, empowerment and productivity, emphasising the importance of social and communitarian indicators. Besides, Lhendup rank ordered different criteria related to rural energy supply based on a score method (Lhendup, 2008). These studies show how non-commonly assessed factors such as institutional regulations and environmental and social aspects may largely affect HRES projects' feasibility. Among these factors, authors identify the social acceptance of the community as a critical factor to ensure the success of these projects, which cannot take acceptance for granted (Aklin et al., 2018).

Despite all this research, the way these criteria should inform the selection of HRES technologies remains unclear (Lillo et al., 2015; Petruschke et al., 2014); particularly how trade-offs among different objectives in conflict occur. These competing objectives require an assessment on how each criterion influences the selection of alternative technologies. Prioritising alternatives based on their performance on multiple criteria is the purpose of Multi Criteria Decision Making (MCDM) methods. Multi Criteria Decision Making (MCDM) have been able to successfully prioritise renewable energy alternatives at a system scale. Authors use the method ELECTRE III to select among seven energy strategies for the island of Crete (Greece) (Georgopoulou et al., 1997); or to conduct an energy resources selection in France (Siskos and Hubert, 1983). Researchers use another MCDM method, PROMETHEE II, to perform a decision-making process about four geothermal energy development scenarios for Chios island in Greece (Haralambopoulos and Polatidis, 2003); or to select from among fourteen renewable energy technologies in a German case study (Madlener and Stagl, 2005). These and other MCDM methods demand quantitative, certain and complete information. However, this is not the case of the social, institutional and other criteria influencing at the first stage of the HRES configuration previous to its design.

To overcome incompleteness, a series of MCDM methods exist to manage situations of incomplete, qualitative and uncertain information that may produce disagreements among decision makers. These MCDM have dealt with social, institutional and other criteria, although without considering quantitative data (Cherni et al., 2007). The Analytic Hierarchy Process (AHP), and its development: the Analytic Network Process (ANP) (Gómez-Navarro and Ribó-Pérez, 2018) derive ratio-scale measurements to allocate resources according to their ratio-scale priorities. Then, ratio-scale assessments, in turn, enable prioritisations based on trade-offs. Noble uses the Analytic Hierarchy Process (AHP) to decide among five energy policy scenarios in Canada (Noble, 2004); besides, Chatzimouratidis and Pilavachi apply AHP in another research to select energy technologies considering quality of life and socio-economic aspects of the beneficiaries (Chatzimouratidis and Pilavachi, 2008). The AHP drawback is the need to model the reality by means of independent factors or criteria, although social, economic and technical factors are normally mutually dependent.

ANP is a development of AHP that allows for complex inter-relationships among the factors at different decision levels. For that reason, ANP models the prioritisation problem as a network of criteria and alternatives, grouped into clusters. This provides an accurate modelling of complex settings and allows handling of the usual interdependence among elements, as in the selection of technologies for an HRES. Different studies present successful cases of ANP used to assess energy related issues. Aragonés-Beltrán *et al.* (Aragonés-Beltrán et al., 2014, 2010) present an ANP model to decide over investment variables in both solar PV and solar thermal plants. ANP methods have also ranked decisions over renewable energy planning (Polatidis et al., 2006), national renewable portfolios (Kabak and Dağdeviren, 2014), wind farm (Yeh and Huang, 2014) or solar PV locations (Alami Merrouni et al., 2018). Finally, another ANP study rank ordered the barriers to the deployment of renewable energy sources in Colombia (Gómez-Navarro and Ribó-Pérez, 2018). To the best knowledge of the authors no research has performed such a holistic approach as to consider all influential and interrelated factors, both qualitative and quantitative, of the HRES design, nor applied ANP to decide energy technologies in this context.

This paper provides a novel methodology to assess the influence of the different criteria to predesign an HRES that combines context analysis, literature review and the Analytic Network Process (ANP) through a series of panels of experts and surveys. The authors apply the methodology to a case study based on a real HRES in the Honduran rural community of El Santuario. The study presents a review and classification of the main criteria and energy technologies considered in the design of HRESs for rural communities. Moreover, the ANP proves itself as a viable tool to assess the influence of the criteria and to choose suitable technologies for the implementation of HRESs in rural contexts. Finally, the paper presents the main findings of the case study that can provide valuable conclusions to similar projects in the area.

The rest of the paper's structure is as follows. Section 2 presents the methodology. Section 3 provides the information on the case study, the stakeholders and the criteria analysis. The results and discussion arise in section 4, and section 5 concludes.

2. Methodology

The proposed methodology contains three main phases: i) a literature and context review, ii) the selection of a panel of experts and, iii) the application of the ANP method. The first two phases are part of the ANP method but require special analysis and need to be case specific. In this regard, Figure 1 presents the rest of the sub processes and outputs of the methodology, including the feedback loops with the panel of experts in several stages of the method. It is important to remark the methodology applies after the full identification of the project has been carried out. This identification sets the reference terms that will be the boundaries of the problem: beneficiaries' own resources, culture, energy demand, social structure… and most importantly, their agency. This is undergone mainly by the beneficiaries themselves and the rural development agents, with the support of other actors like policy makers or project designers. Hence, when applying the methodology to the early design of the project, each reference term must be met, or consensually changed.

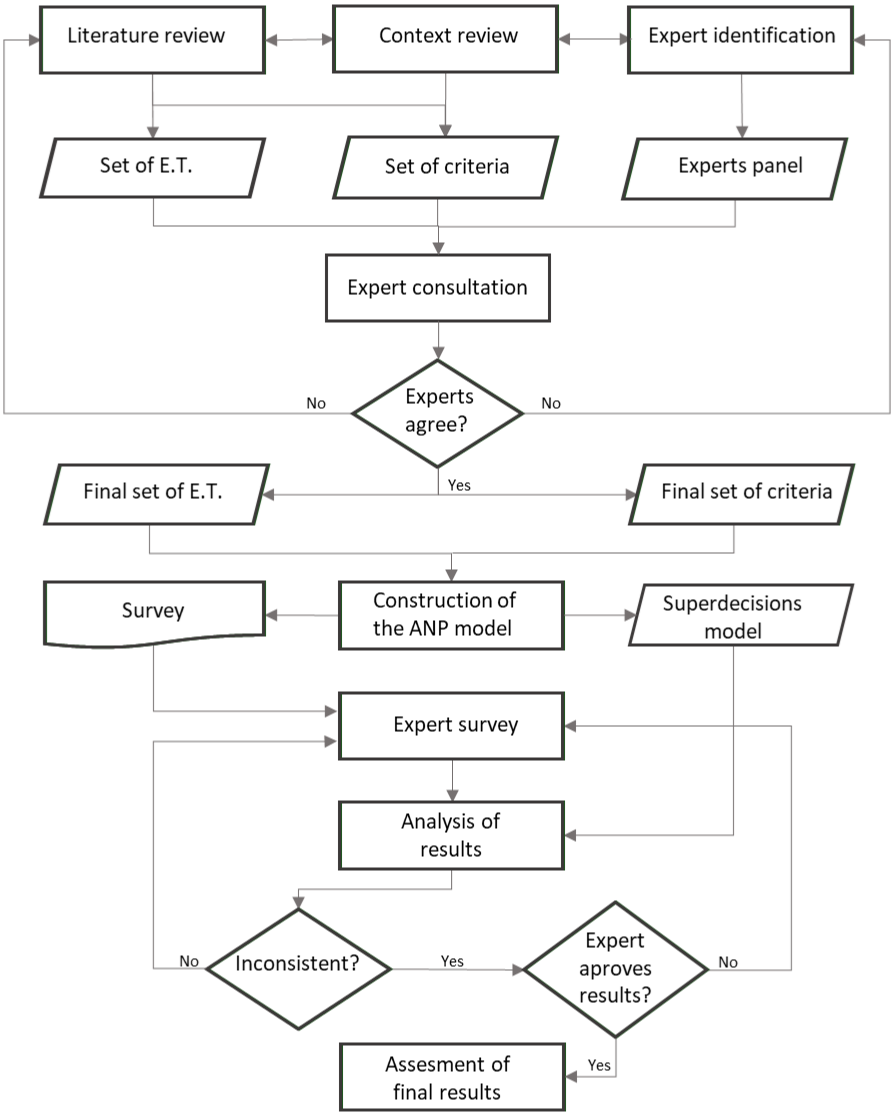

Figure 1. Methodology proposed. Note: E.T. means Energy Technologies.

2.1. Literature review and context analysis

This phase has the purpose of identifying all eligible energy technologies and all the relevant criteria for the assessment. This comprises participatory processes with the community, which hasto agree the project's terms of reference (including energy needs (GIZ, 2016)), and it will participate in the selection of the possible technologies. As introduced, different approaches exist to study the optimal design of an HRES (Erdinc and Uzunoglu, 2012). Besides, some authors have developed an extensive literature review in the field focusing on rural communities' applications (Bhattacharyya, 2012; Mandelli et al., 2016; Renewable Energy Agency, 2014; Shmelev and van den Bergh, 2016). Table 1 presents the combination of the results of these works, a starting list of 23 initial criteria and 7 different energy technologies for rural communities. Initial criteria are classified into 5 main clusters: economic, environmental, institutional, social and technical (Yaqoot et al., 2016).

Table 1. List of criteria and energy technologies.

Cluster	Criteria	Description	In final selection (see section 3.3)	Research
Economic	Investment cost	Cost associated with capital-intensive uses at the start of projects, related to materials, technologies, civil engineering, etc.	Included	(Blum et al., 2013)
	Operation and maintenance cost	Cost associated with the day-to-day management and maintenance of the installation.	Included	(Abaye and Haro, 2018)
	Levelized cost of energy (LCOE)	Power source measurement to allow comparisons among different electricity generation procedures.	Considered with the previous two	(Lai et al., 2017) (Kolhe et al., 2015)
	Institutional support	Existing public policies to subsidise installations costs or administration exemptions to accelerate projects' implementation.	Included including fiscal policies	(Mawhood and Gross, 2014) (Ranaboldo et al., 2015)
	Custom tariff	Tax of import/export components of the microgrid from one country to another.	Considered with institutional support	(Castillo-Ramírez et al., 2017)
Environmental	Greenhouse emissions	Emissions gases into the earth's atmosphere. They contribute to global warming.	Included as environment	(Dutta, 2019) (Shezan et al., 2017)
	Impact on forests	Forest disturbances due to natural phenomena or human actions	Included as local environment	(Elisa et al., 2020)
	Noise pollution	High levels of noise which disturb people and other environmental conditions.	Included as local environment	(Phuangpornpitak and Kumar, 2011)
	Visual impact	Change in the landscape due to microgrid, so it would not be in line with the environmental context anymore.	Included as local environment	(Tong et al., 2010) (Ladenburg, 2009)
	Waste	Residues produced during operation, or that remain after the main processes have finished or the main parts have been used.	Included as local environment	(Kim et al., 2019)
Institutional	Unclear legal framework	The ambiguity of policies or the absence of them regarding renewable systems.	Considered in institutional support	(Banerjee et al., 2017)
	High level of corruption	Dishonest conducts carried out by the Public Administration or private companies mainly due to bribes or extortions.	Included	(Cherni and Preston, 2007) (Rahman et al., 2013)
	Political will to expand the grid	Probability of expansion, in the short or medium term, of the electric grid up to where the microgrid will be sited.	Included	(Odou et al., 2020) (Diego

				Jiménez et al., 2017)
Social	Employment generation	Job or business opportunities creation due to the operation and maintenance tasks of the new equipment.	Included in equal distribution	(Vishnupriyan and Manoharan, 2017) (Dufo-López et al., 2016)
	Capacity building	Individual and communal knowledge and tools provided to the inhabitants in order to ensure correct system management.	Included	(O and Kim, 2019) (Dufo-López et al., 2016)
	Equal distribution of impacts	Electricity arrival should provide equal opportunities to all the inhabitants irrespective of their gender, race or age.	Included	(Smit et al., 2019) (Fernández-Baldor et al., 2014)
	Social acceptability	A proper assessment and involvement of the community should be carried out. Otherwise, people can reject the project.	Included	(Bhowmik et al., 2018) (Aklin et al., 2018)
	Cohesion to local activities	Renewable energy projects should be in line with the local activities of the community.	Included in social acceptability	(Joshi et al., 2019) (Nna et al., 2016)
Technical	Local energy resource availability	Quantity of natural resources and their electricity conversion potential such as wind speed and frequency, solar irradiation, wood availability…	Included	(Ristic et al., 2019) (Singh and Balachandra, 2019)
	Technical feasibility	Development of technical equipment and knowledge to ensure a correct and safe operation, and also long-term durability of the installations.	Included	(Hurtado et al., 2015) (Chatterjee and Rayudu, 2018)
	Total energy generation	Total energy that should be provided by the system, directly related to the community`s electricity demand.	Included	(Pérez-Navarro et al., 2016)
	Technological maturity	Widely proven technologies, whose initial problems have been solved.	Included	(Lai and McCulloch, 2017)
	Security of supply	Guarantee of electric supply due to the different combination of renewable sources and back-up systems.	Included in total energy	(Khare et al., 2016) (Domenech et al., 2015)
Energy Technologies	Batteries	Back-up technology that allows electric power storage due to a chemical process.	Included	(Jyothy et al., 2017) (Muh and Tabet, 2019)

Biomass digestor	Renewable technology used to generate biogas from anaerobic digestion (breakdown of organic materials in the absence of oxygen). This gas is then utilised as combustible in power generators.	Discarded	(Rasheed et al., 2016)
Biomass gasifier	Renewable technology used to generate synthesis gas from dry biomass gasification. This gas is then used as combustible in power generators	Included	(Kamble et al., 2019) (Deb et al., 2016)
Diesel	Traditional power generators that use diesel petroleum derivate as combustible. Although it is not a renewable source of energy, designers occasionally use it as a backup system in HRES.	Included	(Yetano Roche et al., 2019) (Salisu et al., 2019)
Small hydro	Renewable technology that uses water potential energy to generate electricity.	Discarded	(Rasheed et al., 2016) (Bekele and Tadesse, 2012)
Solar PV	Renewable technology that uses solar radiation to generate electricity.	Included	(Moner-Girona et al., 2018) (Akikur et al., 2013)
Wind	Renewable technology that uses wind to generate electricity.	Included	(Hailu Kebede and Bekele Beyene, 2018)(Muh and Tabet, 2019)

2.2. Panel of experts

Once the boundaries of the problem are set by the community and the rural development agents, the method involves the collaboration of a panel of experts who represent different approaches to the problem to prioritise the selection of technologies. As ANP is a semi-qualitative technique, and in view of to the available kind of information, the quality of experts is mandatory and more important than the number of them. ANP is not a survey that requires large sample sizes as discussed in [24] and the results from different experts provide different and valuable viewpoints. The methodology demands three main rules, starting by the selection of experts based on their broad experience in the model issues, their personal research on the topic and their involvement as a specific type of key actor. This leads normally to indirectly include the community representatives in the panel, i.e. to ask the rural development agents who work with them to speak on their behalf (consulting them if need be). Normally, in cooperation projects, the beneficiaries lack the specific knowledge on many of the model's criteria, and neither the schedule, nor the budget, allow to train them on these in the early stages of the project's design.

The second rule is feasible inclusivity. i.e. an as complete and balanced as possible panel of experts. Based on the literature and the authors' experience, normally three key actors with holistic views exist in the supply of electricity by means of off-grid HRES to isolated energy-poor rural communities: project designers, rural development agents (promoters and managers) and policy makers. Representatives of the beneficiaries must be added to the panel if they have the required expertise. Other stakeholders only relate partially or indirectly to the HRES design and deployment. Anyhow, above-mentioned key actors know other stakeholders' views and can reflect them in the process. Furthermore, each experts' group can include one or more different profiles and one type of profile can be part of different groups. For instance, local or regional public institutions can either act as policy makers or rural development agents. Non-Profit Organisations (NPO) normally act as development agents but, in particular, public universities can also design microgrids or provide regulatory or strategic advice. Private companies tend to play the role of project designers but can also be rural development agents, etc. For a complete and balanced design of the experts' panel, all those roles and profiles must be studied and considered in the panel.

The third rules is to avoid unidentified bias. For this, it is recommended to involve more than one expert by type, in order to contrast their opinions [24]. Finally, the method relies critically in the expert knowledge and commitment to the project of the participants, which needs to be reviewed periodically. Due to this, the stage can be said to be the most difficult of the methodology, although not the most laborious, which is the literature review.

2.3. Analytic Network Process

ANP is a method proposed by Saaty (Saaty, 2001) that enables a framework for decision making under complex contexts. In (Saaty, 2005), Saaty provides the main characteristics and its mathematical formulation. ANP performs the ranking of elements by deriving ratio-scale measurements based on their ratio-scale priorities, which enable trade-off considerations.

These network comparisons among elements grouped in clusters provide an accurate modelling among interdependent elements. The main steps of the ANP are the following:

1. Identification of the elements of the network and their relationships.

2. Pairwise comparisons of both clusters and elements using Saaty's 1-to-9 scale.

3. Construction of the unweighted supermatrix, which represents the interrelationships of all elements in the network.

4. Construction of the weighted supermatrix, which considers the cluster comparison to weigh the elements.

5. Obtention of the limit supermatrix by raising the weighted matrix to limiting powers until the matrix converges.

6. Obtention of the prioritisations of the elements given by the limit supermatrix.

7. Interpretation of the results.

The importance of each element is a non-dimensional value. According to the questions made to feed in the method, the ANP considers the influence of the criteria on the other criteria and on the energy technologies.

3. Case study

This section presents the case study in which we applied the proposed methodology. The section explores the context of the selected rural community, the criteria and the technologies considered in the proposed method and the ANP model obtained.

3.1. A rural community in the MesoAmerican Dry Corridor

The rural community of El Santuario is in the department of Choluteca at the south west of Honduras. This region is part of the Mesoamerican Dry Corridor, which covers large parts of central America from Mexico to Panama. The area experiences the El Niño-Southern Oscillation (ENSO), which causes extreme drought periods followed by heavy rains and floods. The frequency of these events has increased due to the effects of climate change, worsening the socio economic vulnerability of the area (FAO, 2017). FAO recognised these conditions and designated the area as one of the most affected by the effects of climate change, which generate major climate migration movements (FAO, 2016).

El Santuario has a topography characterised by steep slopes and it is surrounded by a dry forest of pines and oaks. The main water sources are streams running during approximately six months of the year and water wells during the rest of the year. Temperatures and sunlight are stable due to its equatorial location. However, rainfall concentrates in the wet season. The community has a population of approximately five hundred people that inhabit eighty houses. Economic activity is predominantly based on subsistence agriculture with almost no production surplus and the inhabitants migrate to nearby areas to occasionally work in agriculture. Just like 30% of the Honduran rural population (IEA, 2017a), El Santuario does not have access to electricity. The community is fifty kilometres away from the state's capital, but a complex set of valleys and mountain trails hinder most communications. As with many other communities, the government has no projects to build power line infrastructures to connect the community with the main grid in the coming years and the electricity access of these communities will mainly come from HRESs.

3.2. ANP experts' profile

As previously discussed, three profiles normally represent the key stakeholders in the development of HRESs for rural development; project designers, rural development agents and policy makers. The first ones are key to understand the robustness of the preferred solution and the demand needs of the community as well as fulfilling the national energy policy. Rural development agents are the main intermediaries between the project and the community. Their main objective is to help the community's agency ensuring the long-term sustainability of the project by transferring the necessary knowledge to use the system. Policy makers have expertise in the system as a whole and promote policies to diminish the lack of modern energy, understanding budgets needs and program designs. For the case of El Santuario, and based on the stakeholders' project analysis, three experts per category formed a panel of 9 experts. In order to prevent biasing the results, the same number of experts formed each group. All the experts know the community and the project, some rural development agents indeed performed the previous participatory processes with the community, and all fulfil the expected requirements. Finally and, just as important, they all are willing to participate in the research. Actors that did not meet all the requirements were not selected as the method relies critically in their expert knowledge. Acknowledging the inherent uncertainty of such a decision, based on their performance, this paper research authors believe the panel was sufficiently complete and balanced.

As for the sub profiles that play a key role in this project, they are listed in Table 2, alongside a small description of them.

Table 2. List of stakeholders.

ID	Affiliation	Stakeholder group
PD1	Associate professor with vast experience in designing isolated microgrids	Project Designer
PD2	Researcher specialised in hybrid renewable systems	Project Designer
PD3	Engineer in a private utility company with experience of rural microgrids	Project Designer
RD1	Director of an energy research institute with experience in rural electrification projects	Development agent
RD2	Project coordinator of rural electrification projects	Development agent
RD3	Technician in a cooperation and development agency	Development agent
PM1	Energy consultant in a public international organisation	Policy Maker
PM2	Former environment secretary of state and project officer in a public international organisation	Policy Maker
PM3	Researcher specialised in energy policy	Policy Maker

The research team played the role of the ANP facilitators during the decision-making process; that is, assisting the experts in the evaluation and discussion of results throughout the entire procedure.

3.3. Selection of criteria

A literature review nourished the first set of criteria and energy technologies presented in Table 1. This set of criteria acts as a starting set of factors and energy technologies to consider in all projects of rural electrification, mainly in energy poor communities, by means of islanded HRESs.

The field work for this specific project determined which of the selected criteria were not influential. Thus, the panel of experts, in coordination with the research team, reduced the criteria from the initial set of 23 to a set of 14 criteria grouped in 5 different clusters: economic, environmental, institutional, social and technical (see Table 3). This process aimed to avoid repetition of criteria, which are directly or partly included in another criteria or group of them. For instance, the levelized cost of energy criteria depends on T4. Total energy, as well as on Ec1. Investment cost and Ec2. Operation and maintenance criteria (Aldersey-Williams and Rubert, 2019). Cohesion to local activities directly depends on S3. Social acceptability criteria as only the projects in line with local activities of a community could achieve from their social acceptance (Joshi et al., 2019).

Furthermore, the panel eliminated two of the seven initially selected energy technologies. Since mini hydro and biomass digestors need considerable water inputs, experts excluded these energy technologies as inviable solutions in a region characterised by a six-month dry season and growing indicators of water stress and droughts. Table 3 presents the final selection of both criteria and energy technologies for the analysis.

Table 3. List of criteria.

Cluster	**Criteria**	**Description**
Economic	Ec1. Investment cost	[a]
	Ec2. Operation and maintenance cost	[a]
	Ec3. Institutional support	Existing public policies to subsidise installation costs or administration exemptions to accelerate projects' implementation.
Environmental	En1. Global environment	Impacts perceived at a global scale, mainly related with climate change.
	En2. Local environment	Impacts perceived at a local scale such as noise, fuel spills, land use change, waste generation, deforestation or visual impact.
Institutional	I1. Expansion of grid	[a]
	I2. High level of corruption	[a]
Social	S1. Capacity building	[a]
	S2. Equal distribution	[a]
	S3. Social acceptability	[a]
Technical	T1. Local resources	[a]
	T2. Technical feasibility	[a]
	T3. Technological maturity	[a]
	T4. Total energy	[a]
Energy technologies	A1. Batteries	[a]
	A2. Biomass gasifier	[a]
	A3. Diesel	[a]
	A4. Solar PV	[a]
	A5. Wind	[a]

[a]: As previously described at Table 1.

3.4. ANP model

Once the experts agree on the clusters of criteria and alternatives, the panel fills in the unweighted supermatrix to represent the interrelationships of all the elements in the network. This phase is divided into two sub steps. First, the dependence matrix shows the model elements in rows and columns. Later the criteria's relationships fill in the matrix with data (a_{mn}) that can be 0 or 1. If $a_{mn} = 1$ the criterion in the row m influences the criterion in the column n. Otherwise, there is no influence. For this, the Pareto Principle was applied to identify the small set of relationships that accumulate the biggest influence. Experts were asked if variations of one criterion would influence the performance of another, pairwise analysis, and only those cases were there was a clear agreement on the existence of an influence, were included in the matrix. Secondly, each expert answers a questionnaire to determine the level of influence that each element has on the rest of the elements that it is related to. The matrix below presented shows a series of key aspects regarding the influences among criteria. On the one hand, Ec3. Institutional support influences most criteria from other clusters while Ec1 and Ec2 do not. En 2 Local environment and I1 Expansion of the grid influence all three economic criteria. On the other hand, En1 Global environment, T1 Local resources and T4 Total energy have low dependencies as they are only related to the alternatives and one or none criteria. Finally, in contrast to what was expected from the literature review S3: Social acceptability was not a very influential criterion. The ANP results show that the social cluster was found not to be very influential in the model and thus, S3 was not influential either. We assume this contradiction with the literature since the community acceptance of all alternatives is almost guaranteed with the previous participatory process and the agreed reference terms, diminishing the possibility to social unacceptability. Regarding the alternatives, they influence and are influenced by all criteria, but normally do not influence each other, according to the methodology presented by Saaty (Saaty, 2005).

Table 4. Dependence matrix of all elements of the network.

	Ec1	**Ec2**	**Ec3**	**En1**	**En2**	**I1**	**I2**	**S1**	**S2**	**S3**	**T1**	**T2**	**T3**	**T4**	**A1**	**A2**	**A3**	**A4**	**A5**
Ec1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1
Ec2	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	1	1	1	1
Ec3	1	1	0	0	1	0	1	1	1	1	0	0	1	0	1	1	1	1	1
En1	1	0	1	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1
En2	1	1	1	0	0	0	1	0	0	1	0	0	0	0	1	1	1	1	1
I1	1	1	1	0	0	0	1	0	0	1	0	0	0	0	1	1	1	1	1
I2	1	0	1	1	0	1	0	0	1	1	0	0	1	0	1	1	1	1	1
S1	0	1	1	0	1	0	0	0	1	1	0	0	1	0	1	1	1	1	1
S2	0	0	1	0	0	0	0	1	0	1	0	0	1	0	1	1	1	1	1
S3	0	0	1	0	0	1	0	1	1	0	0	0	1	0	1	1	1	1	1
T1	1	1	0	0	0	0	1	0	0	0	0	1	1	0	1	1	1	1	1
T2	1	1	1	0	1	0	0	0	0	1	0	0	1	1	1	1	1	1	1
T3	1	1	0	0	0	0	0	1	1	1	0	0	0	0	1	1	1	1	1
T4	1	1	1	0	0	0	0	0	0	1	0	1	1	0	1	1	1	1	1
A1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
A2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
A3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
A4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
A5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0

Figure 2 shows the ANP model obtained from the dependence matrix. The software Superdecision® serves as a tool to include the dependences among elements and clusters in the ANP model. Clusters containing criteria and energy technologies represent the model. These relate with each other through arrows that represent the dependencies among elements of the model. An arrow represents that an element of a cluster exerts influence over one or more elements in another cluster. Bidirectional arrows express influences among criteria in both directions and feedback arrows indicate influences between elements of the same cluster.

The model serves afterwards to include the expert's pairwise comparison and calculate the ANP results for each of them. The software also provides the inconsistency ratio of each group of judgments and the unweighted, weighted and limit supermatrices associated with the model.

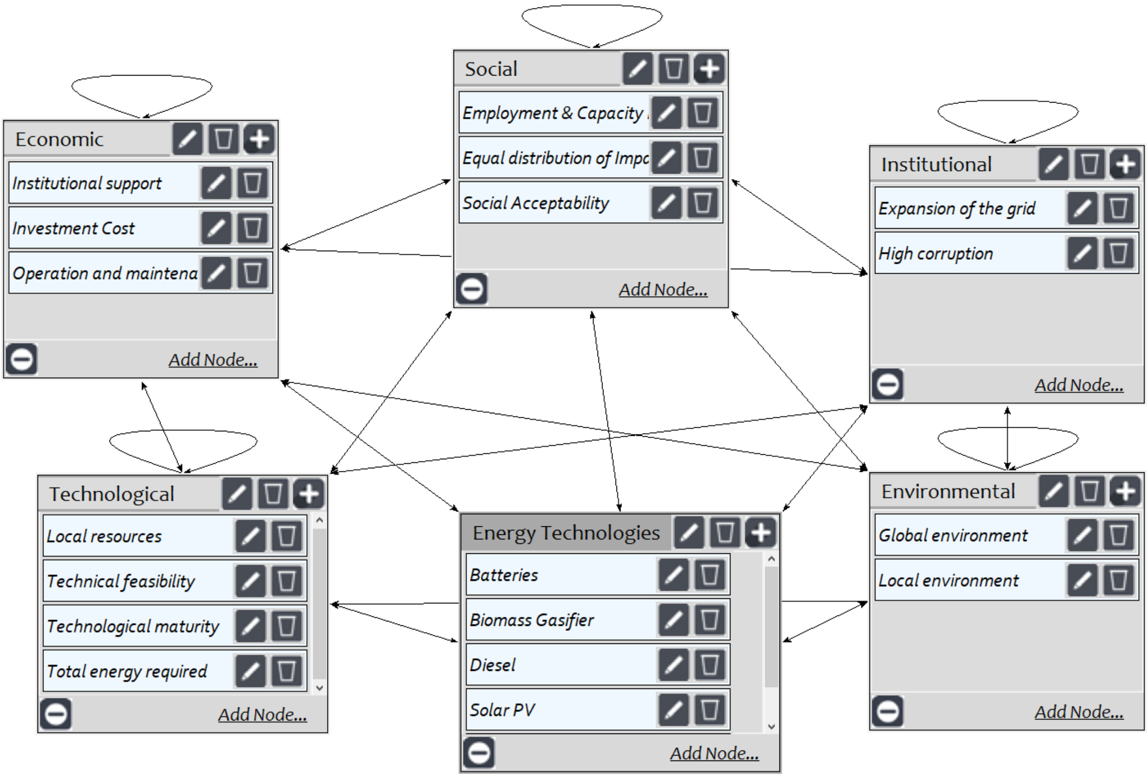

Figure 2. ANP network of the case study obtained by means of the software Superdecisions®

4. Results and discussion

The first result of the research is the list of the various influential factors that a project should analyse prior to the design of HRESs for energy poor rural communities (see Table 1). On the one hand, this list applies to all such projects regardless of the region or the size or the promoters. The same applies to the methodology, which is also universal. On the other hand, the particular application is specific in the field-work and social assessments of each project. Thus, the project stakeholders should trim the list of criteria discarding those factors that are not influential. The eligible technologies are also site specific and different from one project to another. The experts will vary consistent with the stakeholders' analysis of the project and, finally, the relationships among the elements of the model may be different, and also their influences.

4.1. Influential factors for the assessment of technologies in an HRES

After the selection of the influential factors, the assessment criteria, and their arrangement in an ANP network, experts compare the importance of the various elements by means of an ANP questionnaire that is introduced in Superdecisions® to obtain the different Matrices of the method. The ANP procedure captures these judgements and the Limit matrix gives the results of Figures 3, 4, 5 and 6 following the procedure developed by Saaty (Saaty, 2005). The figures place the factors with axis values and grouped by clusters. The levels show the relative importance of each criterion given by the experts; for example, all the criteria add one for one expert.

The study groups experts by their role and, logically, they tend to agree on their judgments, although they present some significant differences. Figure 3 shows how project designers tend to consider as most important criteria I1: Expansion of the grid, Ec1: Institutional support, T1: Local resources and En2: Local environment. In contrast, criteria Ec2: Investment costs, Ec3: Costs of operation and maintenance and T4: Total energy are the least influential.

The latter may come as a surprise because those factors are normally among the first criteria a project designer considers. However, during the feedback loops the experts considered energy supply to be a strategic business sector subject to extensive regulation with a large control by the public institutions. Besides, economies of scale do apply for energy supply and small installations cannot be economically affordable for energy poor communities without public support. Therefore, the Honduran project and the alike greatly rely on public funding and support. Finally, ANP makes comparisons among elements of the same cluster. And based on the judgments it assigns a greater or lower fraction of the weight of the cluster to its elements. When reviewing the answers by the experts, they gave more influence to follow the requirements and preferences of the public administration supporting the project (in this case the foreign affairs ministry of Spain) than to optimising the capital expenditure (Ec2.) or the operational expenditure (Ec3.).

Based on the discussion of results with the experts, factor T1: Local resources contribute more to prioritising one energy technology over another than T2: Technical feasibility or T3: Technical maturity, and hence their lower influence. Asked about T4: Total energy demanded by the community, the experts explained its low importance was due to that, whichever the alternative, the early design will cover the basic energy needs according to the project's terms of reference agreed with the community. All stakeholders consider a dramatic change to move from no energy to the agreed energy. Therefore, variations on the total amount of energy did not help to prioritise among technologies as much as variations of local energy resources. Local energy resources are critical to ensure the endogenous and autonomous development of the community and accumulated most of the preferences of the Technical cluster.

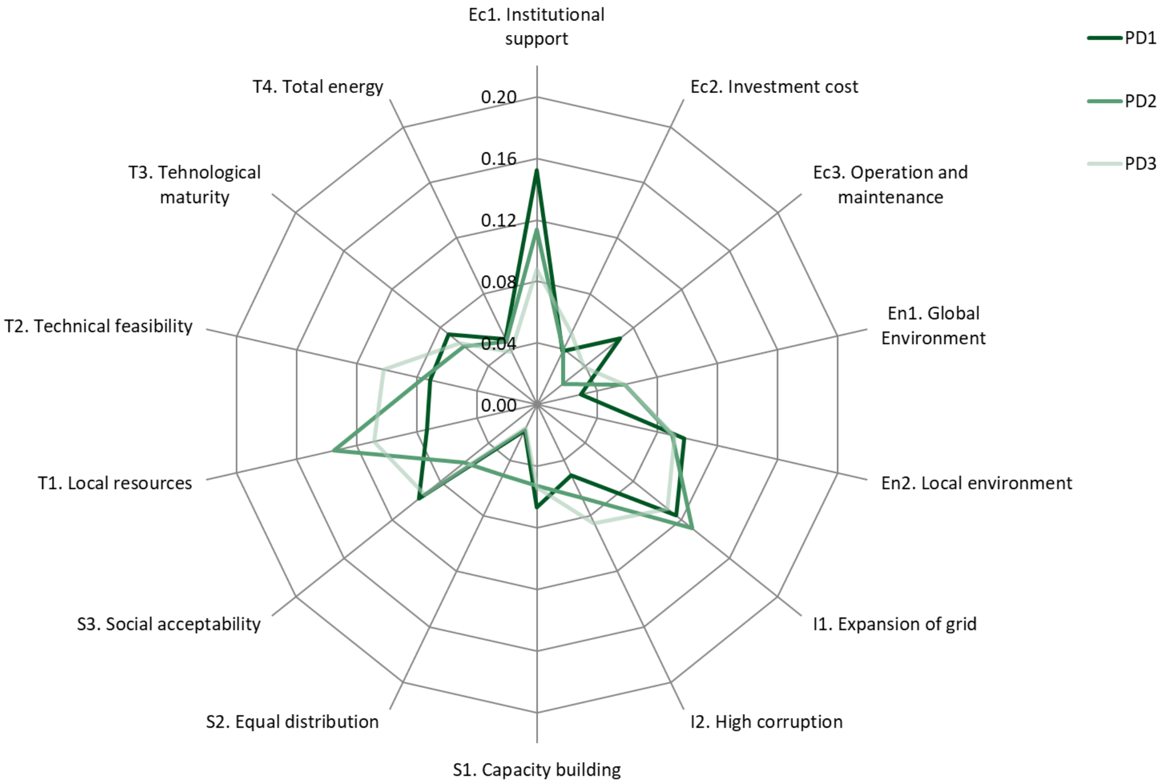

Figure 3. Relative importance of the criteria for the project designers

Figure 4 shows that rural development agents present a similar profile to project designers, with higher importance assigned to criteria T1: Local resources, I1: Expansion of the grid, Ec1: Institutional support, and En2: Local environment. According to the development agents, in this project the least influential criteria are Ec3: Operation and Maintenance costs, S2: Equal distribution, and T3: Technological maturity. Besides, overall, agents showed more agreement on the influence of the criteria than project designers.

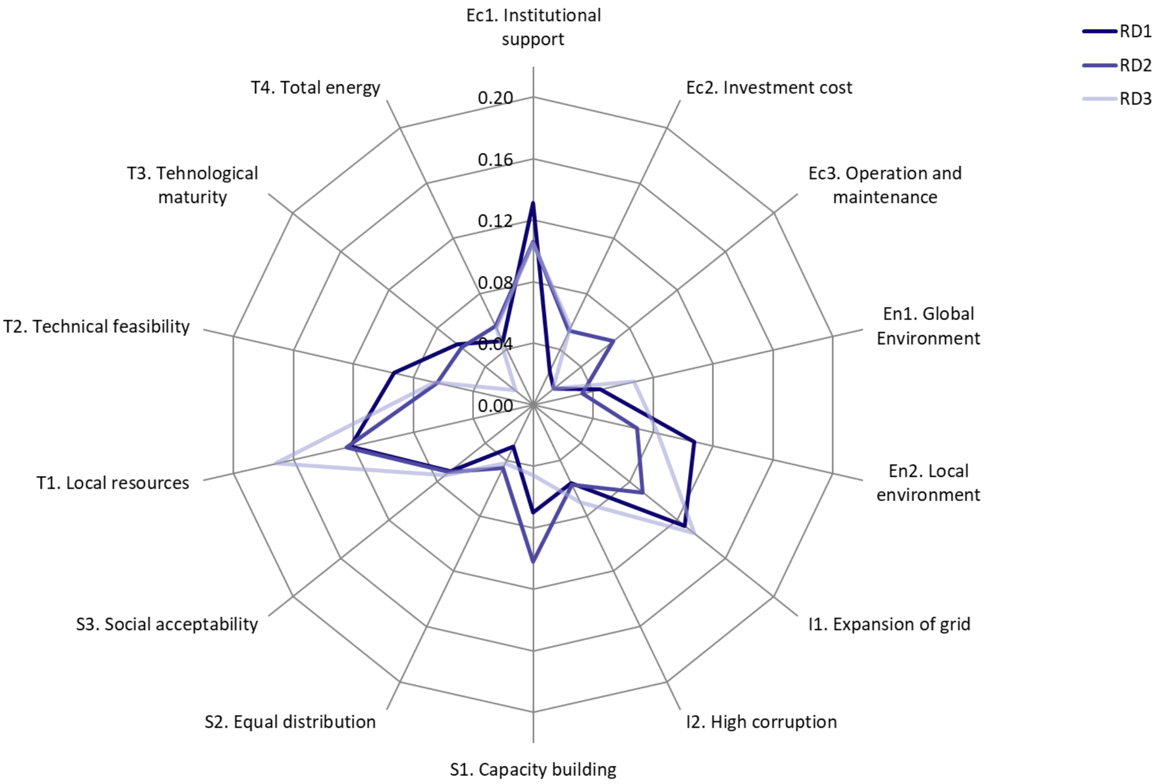

Figure 4. Relative importance of the criteria for rural development agents

Again, it is interesting to discuss why development agents gave such little importance to the social factors, which could be a priority for them. Actually, all experts have considered social aspects to be more related to the distribution of the electricity than to the generation of the electricity. The decision problem of this case study was mainly the generation and backup technologies, while grid topology did not change in any case. Therefore, rural development agents considered the cluster of social criteria less influential than the other clusters; and its elements have less influence to share.

Policy makers in Figure 5 also rank order Ec1: Institutional support and I1: Expansion of the grid and T1: Local resources as the most influential, but they clearly value the rest of criteria less. Again, S2: Equal distribution and Ec3: Costs of operation and maintenance have less importance in El Santuario project. In this group, one of the experts presented significant differences from the others, both in the criteria and the alternatives. Later, differences among alternatives are discussed.

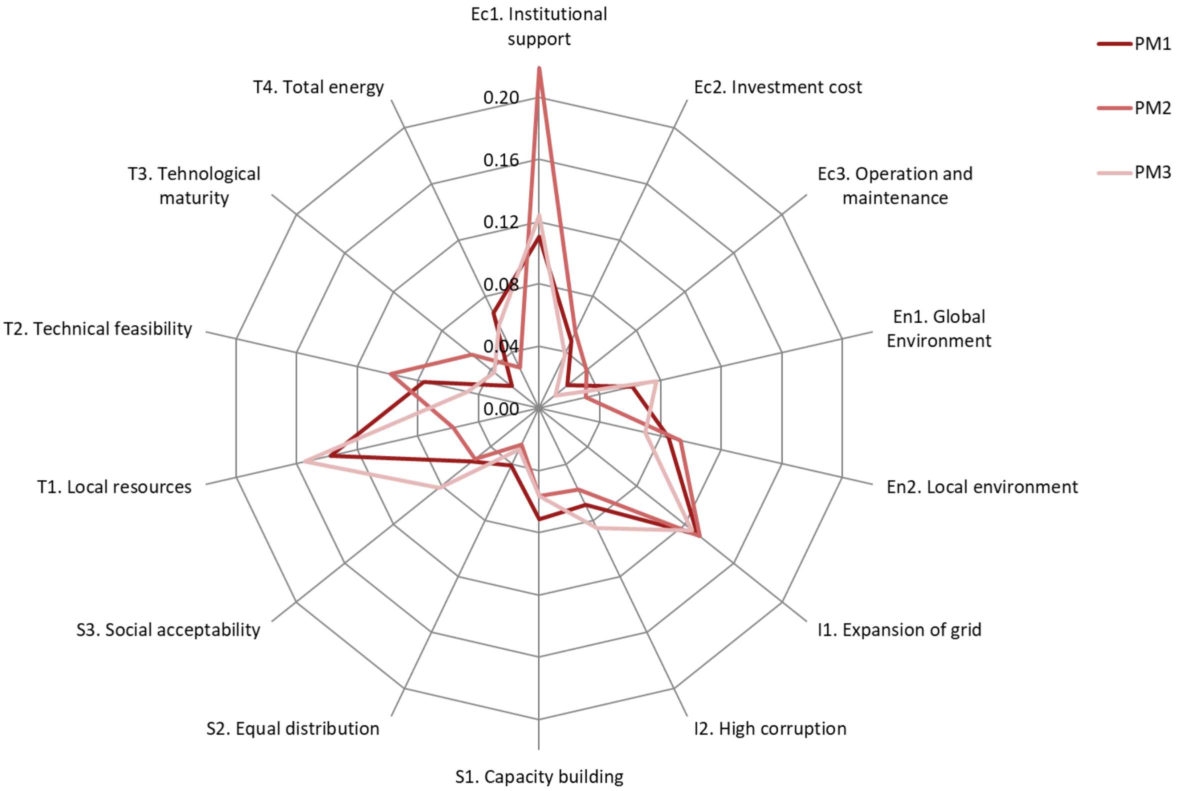

Figure 5. Relative importance of the criteria for the policy makers

When asked why the institutional factor I1: Expansion of the grid was so influential, the experts argued similarly for the importance of criterion Ec1. The institutional decisions are relevant for the prioritisation of the alternatives. And then, between the probability of the expansion of the grid up to the community and the possibility of corrupt public officers, the former contributed clearly more than the latter to prefer some technologies over the others.

Also, the comparison between the elements of the cluster Environment yields some interesting discussion. The project presents alternatives that are respectful with the environment, with the exception of the diesel generator, and the project is sensitive to the local community. In this context, all experts agreed on assigning more influence to the combination of local environmental impacts (En2.) than to the combination of global environmental impacts (En1.), even if the latter included the worrying Climate Change. Indeed, almost all technologies have low global environmental impacts, but they potentially have different local environmental impacts that establish clear differences among them. For example, diesel generators produce noise and emissions while photovoltaic panels pressurise land availability.

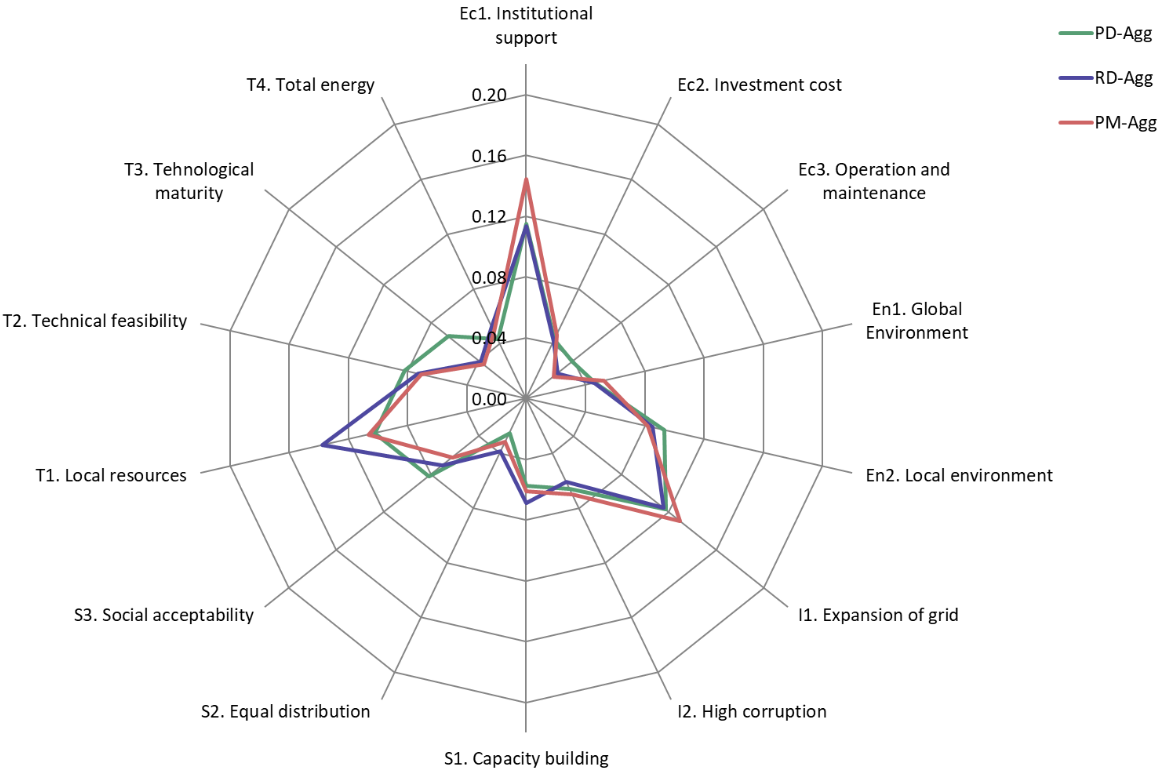

Figure 6. Aggregated relative importance of the criteria by stakeholders' group

To end this section, Figure 6 shows the results of entering in the ANP calculations the aggregation of the judgements of all experts of each role. For that, aggregation uses the Geometric Mean as prescribed by Saaty (Saaty, 2005). The differences among experts compensate and the average numbers are more moderate. Besides, the profile of the three groups coincide considerably, and this is not usual, and we associate it with the particular characteristics of the project.

4.2. Prioritisation of the energy technologies.

Figure 7 shows the preferences for alternatives after aggregating all the experts' judgments. Therefore, in the HRESs for El Santuario, Honduras, the preferred energy technology is solar PV, followed by wind generation and the gasification of biomass. All three clearly differentiated in preference. For the dispatchable technology in the HRESs, the biomass gasifier is preferred to the diesel generator and the batteries, which both score similarly.

Indeed, the final solution opts for Solar PV as the main energy source against wind, selecting among the two non-dispatchable technologies. Batteries accompanied with a biomass gasifier as the preferred back up since they provide emissions free electricity compared with the diesel generator. Moreover, and in agreement with the community, the low preference of batteries lead to a design were the gasifier plays a more active role than a mere back up. The community prefers to rely on a sustainable consumption of local dry biomass to an intensive use of batteries that will shorten their lifespan, or to devote a higher share of the investment to such a sensitive asset.

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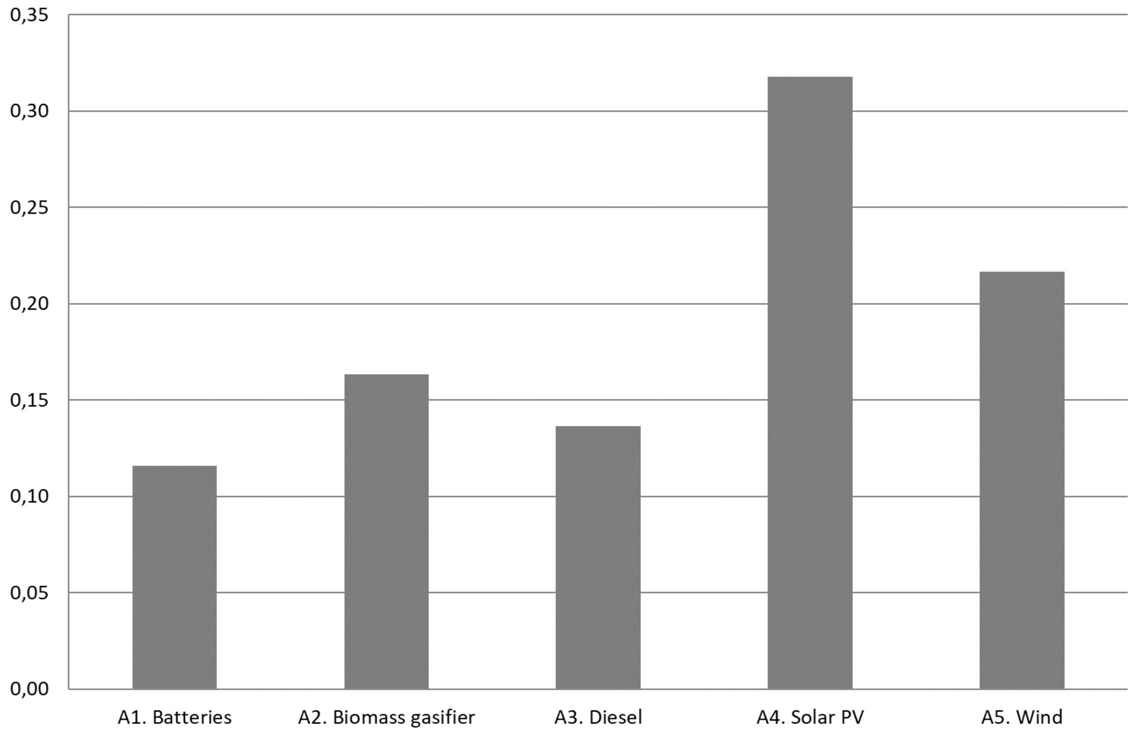


Figure 7. Aggregated relative importance of the energy technologies

Figure 8 shows the rank order of alternatives by expert, again grouped by role. The bars show the relative importance of each alternative, all the values add one for a particular expert. Again, experts tend to agree with their group members, but there is a policy maker that clearly disagrees. This is due to the great difference among the profiles of policy makers. While two of them have a wide experience with biomass systems and have supported them in the past, the other has mainly worked with solar PV plants and he presents bias towards this option. In conclusion, an adequate panel of experts must include not only representatives of all the important stakeholders, but also experts of the different profiles and disciplines involved. The discrepancies among all representatives of a certain stakeholder are relevant, as figure 8 shows.

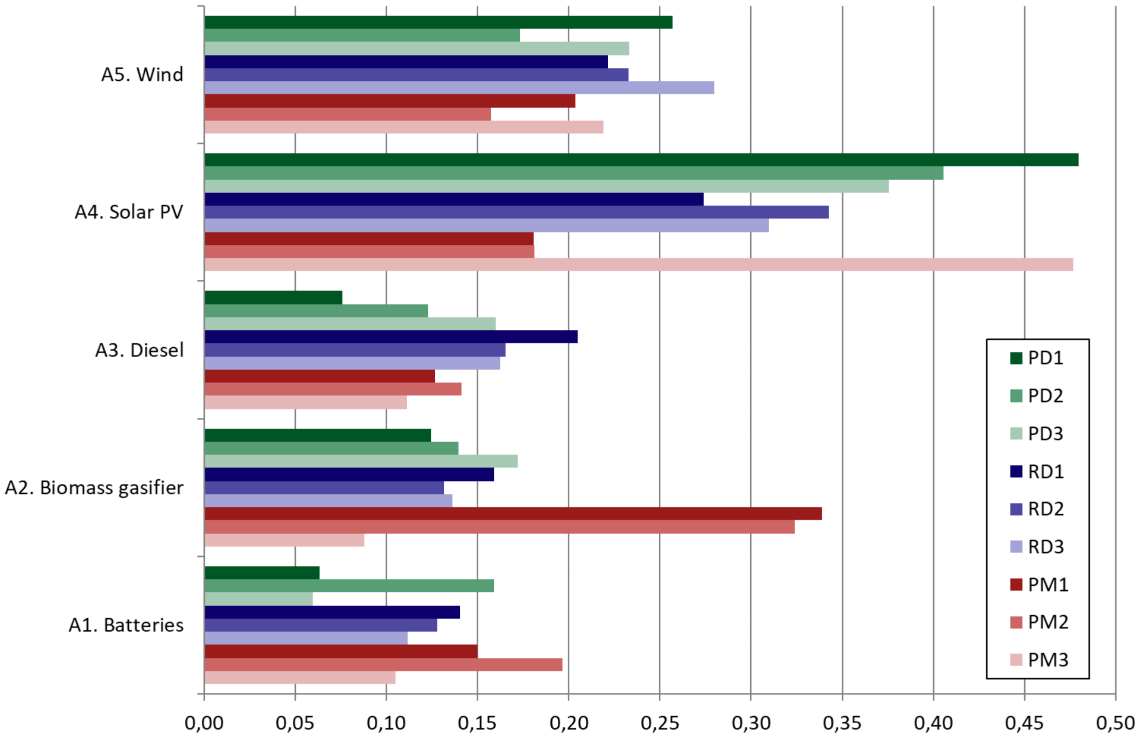


Figure 8. Relative importance of the energy technologies

4.3. Partial analysis. Influence of the criteria on the alternatives.

ANP also allows partial studies, for example how the criteria influence each alternative. Figure 9 shows the weighted supermatrix of the procedure, which presents these influences. For the analysis, again the ANP procedure introduces the aggregation of the experts' judgments. This partial analysis allows us to understand the general results better. Starting with what Figure 9 shows, Ec3: Operation and Maintenance costs are very influential for Diesel Generators, En2: Local environmental impacts is very influential in the case of the biomass gasifier, Batteries are the most expensive technology by investment (Ec1), and factor T1: Local resources have little influence on batteries and the diesel generator.

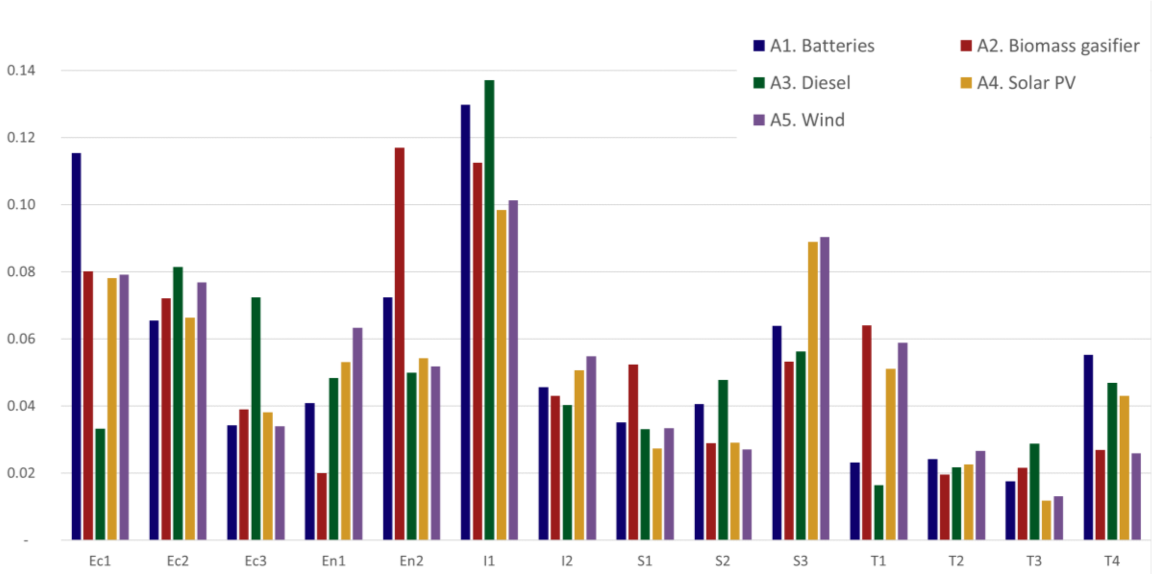


Figure 9. Relative importance of criteria by energy technologies

However, it came as a surprise that factor S3: Social acceptability shows a higher influence on alternatives than the importance experts gave this factor. When we checked the influences among factors in the weighted supermatrix, S3 may be influential as regards alternatives, but itself is a factor with little influence on the others. The contrary happens with T1: Local resources, that shows a somehow lower than expected overall influence on alternatives, although it influences many other criteria.

Figure 10 shows another ANP partial analysis, how experts rank ordered alternatives by criterion. If applied to the more influential criteria, it shows what are the preferred alternatives for those criteria and contributes to their assessment.

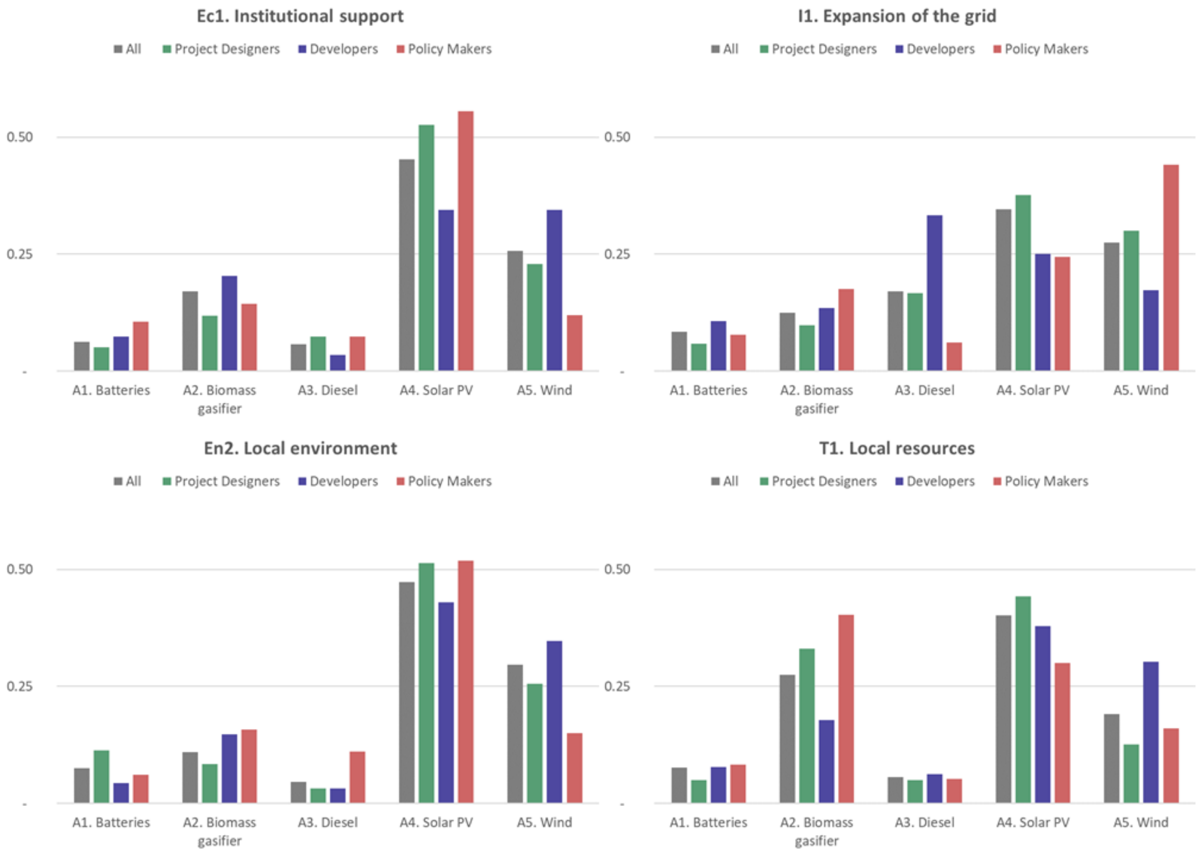


Figure 10. Relative importance of energy technologies by most relevant criteria

As expected, experts generally prefer the solar photovoltaic to the others for each influential criterion. Wind generators follow, except from the point of view of the availability and use of local resources, where the gasifier scores higher. Criteria Ec1., En2. and T1. penalise the diesel generator, which becomes interesting for experts only if the institutions plan to develop the electric grid to reach the community in the short term.

5. Conclusion

To fulfil the UN's Sustainable Development Goal 7 by 2030, millions of inhabitants of isolated rural areas will likely opt for islanded microgrids. Furthermore, these microgrids must be sustainable and for that, they should rely on local renewable energy resources. A combination of different dispatchable and non-dispatchable energy technologies can ensure a reliable continuous supply of energy. This complex technical design must be combined with a thorough social analysis. However, the outcomes of such work are normally qualitative, may be uncertain and frequently debatable without agreement among the stakeholders. This work proposed a methodology to bridge and combine the two realms. By means of ANP and the expert knowledge of representatives of the main stakeholders, the technical and social factors can be combined, informing the selection of technologies before the detailed design of the HRESs.

On the one hand, ANP is a valid methodology for decision making in situations of qualitative and uncertain information, where variables relate to each other. Nevertheless, to the knowledge of the authors, no research has applied ANP to designing the configuration of an HRES. On the other hand, it remains unclear how designers combine the two realms of information in their HRES design. Too often, technical and economic factors are the only influential ones and designers overlook social or institutional factors. Hence, this research aims to strengthen HRES design practice, mainly in its first and critical steps. ANP also allows us to carry out partial analysis to better understand experts' judgements. These analyses include the partial influence of criteria on Alternatives, the influence among criteria or the scores of alternatives for certain criteria. This information feeds a discussion about the particularities of the outcomes with experts.

The first and general findings of the research are the following. First, a complete list of 23 influential criteria for the configuration of an HRES to deliver electricity to poor communities based on an extensive literature review. Experts and stakeholders of these projects should initially consider these factors. However, they must be adapted to each case. Second, the proposed methodology explained in Figure 1, which experts may use with the necessary adaptation to each project and context.

To illustrate the viability of the methodology and the need to adapt it to each context, the article presents a case study of an energy poor community in the Honduran Mesoamerican Dry Corridor. The methodology guides the decision over the design of an islanded HRES to supply electricity. Three panels of experts, one per each main project-design stakeholder group provided, their opinions throughout the project. Each panel itself, included three experts with the same role but different profiles. In our case, experts mainly agreed on their conclusions. However, in other cases this might not happen and a decision must be taken about which experts' opinion should be followed. Based on the initial list and the field work, the experts agreed on a final list of 14 influential criteria grouped in 5 clusters: economic, environmental, institutional, social and technical. The number of viable energy technologies was 5, which formed a new cluster of the ANP model. The outcomes of the method state that the most influential criteria by order of importance are institutional support, the possible expansion of the grid and local energy resources. The preferred energy technologies in the case of El Santuario are Solar PV, wind power and a biomass gasifier.

Currently, the HRES for El Santuario includes a solar PV power plant as large as the energy demand, the local sun radiation and the foreseen budget allow. To combine it with a dispatchable energy technology, a biomass gasifier that will use the local biomass resource is also part of the system. The wind power alternative and the diesel generator have been discarded in accordance with the outcomes of the method in favour of Solar PV and a Biomass gasifier. Finally, a bank of batteries will also be added as the gasifier needs an electric supply to be turned on and off. Batteries will be as reduced as possible based on the case study results.

Acknowledgements

We really appreciate the help of our four experts in the field. Without them, we could not have carried out the research.

This is an extended and updated version of a paper originally presented at the 14th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES 2019) held in Dubrovnik, Croatia over the period 1st to 6th October 2019 (denoted then as paper SDEWES2019.0565 - Choosing the best configuration for a hybrid microgrid of renewable energy sources by means of the analytic network process).This work was supported in part by the Spanish public administration under grant FPU2016/00962, by the regional public administration of Valencia under grant ACIF/2018/106, by the Food and Agriculture Organisation under the Letter of Agreement (PO number: 332412). And finally, by the Cátedra de Transición Energética Urbana (Las Naves-UPV).

References

Abaye, A.E., Haro, R.D., 2018. Assessment of resource potential and feasibility study of standalone PV - Wind-biogas hybrid system for rural electrification, in: 2018 2nd International Conference on Electronics, Materials Engineering and Nano-Technology, IEMENTech 2018. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/IEMENTECH.2018.8465317

Ahmed, S., Islam, M.T., Karim, M.A., Karim, N.M., 2014. Exploitation of renewable energy for sustainable development and overcoming power crisis in Bangladesh. Renew. Energy. https://doi.org/10.1016/j.renene.2014.07.003

Akikur, R.K., Saidur, R., Ping, H.W., Ullah, K.R., 2013. Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.06.043

Aklin, M., Cheng, C.-Y., Urpelainen, J., 2018. Social acceptance of new energy technology in developing countries: A framing experiment in rural India. Energy Policy 113, 466–477. https://doi.org/10.1016/J.ENPOL.2017.10.059

Alami Merrouni, A., Elwali Elalaoui, F., Mezrhab, Ahmed, Mezrhab, Abdelhamid, Ghennioui, A., 2018. Large scale PV sites selection by combining GIS and Analytical Hierarchy Process. Case study: Eastern Morocco. Renew. Energy 119, 863–873. https://doi.org/10.1016/j.renene.2017.10.044

Aldersey-Williams, J., Rubert, T., 2019. Levelised cost of energy – A theoretical justification and critical assessment. Energy Policy 124, 169–179. https://doi.org/10.1016/j.enpol.2018.10.004

Aragonés-Beltrán, P., Chaparro-González, F., Pastor-Ferrando, J.P., Pla-Rubio, A., 2014. An AHP (Analytic Hierarchy Process)/ANP (Analytic Network Process)-based multi-criteria decision approach for the selection of solar-thermal power plant investment projects. Energy 66, 222–238. https://doi.org/10.1016/j.energy.2013.12.016

Aragonés-Beltrán, P., Chaparro-González, F., Pastor-Ferrando, J.P., Rodríguez-Pozo, F., 2010. An ANP-based approach for the selection of photovoltaic solar power plant investment projects. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2009.07.012

Ayodele, E., Misra, S., Damasevicius, R., Maskeliunas, R., 2019. Hybrid microgrid for microfinance institutions in rural areas – A field demonstration in West Africa. Sustain. Energy Technol. Assessments 35, 89–97. https://doi.org/10.1016/j.seta.2019.06.009

Banerjee, S.G., Moreno, F.A., Sinton, J.E., Primiani, T., Seong, J., 2017. Regulatory indicators for sustainable energy : a global scorecard for policy makers.

Bekele, G., Tadesse, G., 2012. Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia. Appl. Energy 97, 5–15. https://doi.org/10.1016/j.apenergy.2011.11.059

Bhattacharyya, S.C., 2012. Review of alternative methodologies for analysing off-grid electricity supply. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2011.08.033

Bhowmik, C., Bhowmik, S., Ray, A., 2018. Social acceptance of green energy determinants using principal component analysis. Energy 160, 1030–1046.

https://doi.org/10.1016/j.energy.2018.07.093

Blum, N.U., Sryantoro Wakeling, R., Schmidt, T.S., 2013. Rural electrification through village grids—Assessing the cost competitiveness of isolated renewable energy technologies in Indonesia. Renew. Sustain. Energy Rev. 22, 482–496. https://doi.org/10.1016/J.RSER.2013.01.049

Castillo-Ramírez, A., Mejía-Giraldo, D., Molina-Castro, J.D., 2017. Fiscal incentives impact for RETs investments in Colombia. Energy Sources, Part B Econ. Planning, Policy 12, 759–764. https://doi.org/10.1080/15567249.2016.1276648

Chatterjee, A., Rayudu, R., 2018. Techno-economic analysis of hybrid renewable energy system for rural electrification in India, in: 2017 IEEE Innovative Smart Grid Technologies - Asia: Smart Grid for Smart Community, ISGT-Asia 2017. Institute of Electrical and Electronics Engineers Inc., pp. 1–5. https://doi.org/10.1109/ISGT-Asia.2017.8378470

Chatzimouratidis, A.I., Pilavachi, P.A., 2008. Sensitivity analysis of the evaluation of power plants impact on the living standard using the analytic hierarchy process. Energy Convers. Manag. 49, 3599–3611. https://doi.org/10.1016/j.enconman.2008.07.009

Cherni, J.A., Dyner, I., Henao, F., Jaramillo, P., Smith, R., Font, R.O., 2007. Energy supply for sustainable rural livelihoods. A multi-criteria decision-support system. Energy Policy 35, 1493–1504. https://doi.org/10.1016/j.enpol.2006.03.026

Cherni, J.A., Preston, F., 2007. Rural electrification under liberal reforms: the case of Peru. J. Clean. Prod. 15, 143–152. https://doi.org/10.1016/j.jclepro.2006.01.029

Das, B.K., Zaman, F., 2019. Performance analysis of a PV/Diesel hybrid system for a remote area in Bangladesh: Effects of dispatch strategies, batteries, and generator selection. Energy 169, 263–276. https://doi.org/10.1016/j.energy.2018.12.014

Deb, P., Mahapatra, S., Rajbongshi, R., Dasappa, S., 2016. BIOMASS GASIFIER BASED HYBRID ENERGY SYSTEM OPTIMIZATION FOR ENERGY ACCESS BY USING HOMER.

Diego Jiménez, J., Maria Vives, S., Guillermo Jiménez, E., Patricio Mendoza, A., 2017. Development of a methodology for planning and design of microgrids for rural electrification, in: 2017 CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies, CHILECON 2017 - Proceedings. Institute of Electrical and Electronics Engineers Inc., pp. 1–6. https://doi.org/10.1109/CHILECON.2017.8229558

Domenech, B., Ferrer-Martí, L., Pastor, R., 2015. Including management and security of supply constraints for designing stand-alone electrification systems in developing countries. Renew. Energy 80, 359–369. https://doi.org/10.1016/j.renene.2015.02.033

Dufo-López, R., Cristóbal-Monreal, I.R., Yusta, J.M., 2016. Optimisation of PV-wind-diesel-battery stand-alone systems to minimise cost and maximise human development index and job creation. Renew. Energy 94, 280–293. https://doi.org/10.1016/j.renene.2016.03.065

Dutta, R., 2019. Use of Clean, Renewable and Alternative Energies in Mitigation of Greenhouse Gases, in: Reference Module in Materials Science and Materials Engineering. Elsevier. https://doi.org/10.1016/b978-0-12-803581-8.11048-3

Elisa, P., Alessandro, P., Andrea, A., Silvia, B., Mathis, P., Dominik, P., Manuela, R., Francesca, T., Voglar, G.E., Tine, G., Nike, K., Thomas, S., 2020. Environmental and climate change impacts of eighteen biomass-based plants in the alpine region: A comparative analysis. J. Clean. Prod. 242. https://doi.org/10.1016/j.jclepro.2019.118449

Erdinc, O., Uzunoglu, M., 2012. Optimum design of hybrid renewable energy systems: Overview of different approaches. Renew. Sustain. Energy Rev. 16, 1412–1425. https://doi.org/10.1016/J.RSER.2011.11.011

FAO, 2017. Dry Corridor Central America. Situation Report.

FAO, 2016. Dry Corridor Central America. Situation Report.

Fernández-Baldor, Á., Boni, A., Lillo, P., Hueso, A., 2014. Are technological projects reducing social inequalities and improving people’s well-being? A capability approach analysis of renewable energy-based electrification projects in Cajamarca, Peru. J. Hum. Dev. Capab. 15, 13–27. https://doi.org/10.1080/19452829.2013.837035

Georgopoulou, E., Lalas, D., Papagiannakis, L., 1997. A Multicriteria Decision Aid approach for energy planning problems: The case of renewable energy option. Eur. J. Oper. Res. 103, 38–54. https://doi.org/10.1016/S0377-2217(96)00263-9

GIZ, 2016. What size shall it be? A guide to mini-grid sizing and demand forecasting.

Gómez-Navarro, T., Ribó-Pérez, D., 2018. Assessing the obstacles to the participation of renewable energy sources in the electricity market of Colombia. Renew. Sustain. Energy Rev. 90, 131–141. https://doi.org/10.1016/j.rser.2018.03.015

Hailu Kebede, M., Bekele Beyene, G., 2018. Feasibility Study of PV-Wind-Fuel Cell Hybrid Power System for Electrification of a Rural Village in Ethiopia. J. Electr. Comput. Eng. 2018. https://doi.org/10.1155/2018/4015354

Haralambopoulos, D.A., Polatidis, H., 2003. Renewable energy projects: Structuring a multi-criteria group decision-making framework. Renew. Energy 28, 961–973. https://doi.org/10.1016/S0960-1481(02)00072-1

He, X.., Reiner, D., 2014. Electricity Demand and Basic Needs: Empirical Evidence from China's Households. Cambridge Work. Pap. Econ. https://doi.org/10.17863/CAM.5834

Hurtado, E., Peñalvo-López, E., Pérez-Navarro, Á., Vargas, C., Alfonso, D., 2015. Optimization of a hybrid renewable system for high feasibility application in non-connected zones. Appl. Energy 155, 308–314. https://doi.org/10.1016/J.APENERGY.2015.05.097

Hussain, C.M.I., Norton, B., Duffy, A., 2017. Technological assessment of different solar-biomass systems for hybrid power generation in Europe. Renew. Sustain. Energy Rev. 68, 1115–1129. https://doi.org/10.1016/J.RSER.2016.08.016

IEA, 2018. World Energy Outlook.

IEA, 2017a. World Energy Outlook.

Ilskog, E., 2008. Indicators for assessment of rural electrification-An approach for the comparison of apples and pears. Energy Policy 36, 2665–2673. https://doi.org/10.1016/j.enpol.2008.03.023

Ilskog, E., Kjellström, B., 2008. And then they lived sustainably ever after?-Assessment of rural electrification cases by means of indicators. Energy Policy 36, 2674–2684. https://doi.org/10.1016/j.enpol.2008.03.022

Joshi, L., Choudhary, D., Kumar, P., Venkateswaran, J., Solanki, C.S., 2019. Does involvement of local community ensure sustained energy access? A critical review of a solar PV technology intervention in rural India. World Dev. 122, 272–281. https://doi.org/10.1016/j.worlddev.2019.05.028

Jyothy, K.R., Raju, C.P., Srinivasarao, R., 2017. Simulation studies on WTG-FC-battery hybrid energy system, in: IEEE International Conference on Innovative Mechanisms for Industry Applications, ICIMIA 2017 - Proceedings. Institute of Electrical and Electronics Engineers Inc., pp. 710–716. https://doi.org/10.1109/ICIMIA.2017.7975557

Kabak, M., Dağdeviren, M., 2014. Prioritization of renewable energy sources for Turkey by using a hybrid MCDM methodology. Energy Convers. Manag. 79, 25–33. https://doi.org/http://dx.doi.org/10.1016/j.enconman.2013.11.036

Kamble, P., Khan, Z., Gillespie, M., Farooq, M., McCalmont, J., Donnison, I., Watson, I., 2019. Biomass gasification of hybrid seed Miscanthus in Glasgow's downdraft gasifier testbed system, in: Energy Procedia. Elsevier Ltd, pp. 1174–1181. https://doi.org/10.1016/j.egypro.2019.01.303

Kanagawa, M., Nakata, T., 2008. Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries. Energy Policy 36, 2016–2029. https://doi.org/10.1016/j.enpol.2008.01.041

Katre, A., Tozzi, A., 2018. Assessing the Sustainability of Decentralized Renewable Energy Systems: A Comprehensive Framework with Analytical Methods. Sustainability 10, 1058. https://doi.org/10.3390/su10041058

Khare, V., Nema, S., Baredar, P., 2016. Solar–wind hybrid renewable energy system: A review. Renew. Sustain. Energy Rev. 58, 23–33. https://doi.org/10.1016/J.RSER.2015.12.223

Kim, B., Azzaro-Pantel, C., Pietrzak-David, M., Maussion, P., 2019. Life cycle assessment for a solar energy system based on reuse components for developing countries. J. Clean. Prod. 208, 1459–1468. https://doi.org/10.1016/J.JCLEPRO.2018.10.169

Kolhe, M.L., Ranaweera, K.M.I.U., Gunawardana, A.G.B.S., 2015. Techno-economic sizing of off-grid hybrid renewable energy system for rural electrification in Sri Lanka. Sustain. Energy Technol. Assessments 11, 53–64. https://doi.org/10.1016/j.seta.2015.03.008

Ladenburg, J., 2009. Visual impact assessment of offshore wind farms and prior experience. Appl. Energy. https://doi.org/10.1016/j.apenergy.2008.05.005

Lai, C.S., Jia, Y., Xu, Z., Lai, L.L., Li, X., Cao, J., McCulloch, M.D., 2017. Levelized cost of electricity for photovoltaic/biogas power plant hybrid system with electrical energy storage degradation costs. Energy Convers. Manag. 153, 34–47. https://doi.org/10.1016/j.enconman.2017.09.076

Lai, C.S., McCulloch, M.D., 2017. Levelized cost of electricity for solar photovoltaic and electrical energy storage. Appl. Energy 190, 191–203. https://doi.org/10.1016/j.apenergy.2016.12.153

Lhendup, T., 2008. Rural electrification in Bhutan and a methodology for evaluation of distributed generation system as an alternative option for rural electrification. Energy Sustain. Dev. 12, 13–24. https://doi.org/10.1016/S0973-0826(08)60434-2

Lillo, P., Ferrer-Martí, L., Boni, A., Fernández-Baldor, Á., 2015. Assessing management models for off-grid renewable energy electrification projects using the Human Development approach: Case study in Peru. Energy Sustain. Dev. 25, 17–26. https://doi.org/10.1016/j.esd.2014.11.003

Madlener, R., Stagl, S., 2005. Sustainability-guided promotion of renewable electricity generation. Ecol. Econ. 53, 147–167. https://doi.org/10.1016/j.ecolecon.2004.12.016

Mandelli, S., Barbieri, J., Mereu, R., Colombo, E., 2016. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renew. Sustain. Energy Rev. 58, 1621–1646. https://doi.org/10.1016/J.RSER.2015.12.338

Mawhood, R., Gross, R., 2014. Institutional barriers to a ‘perfect’ policy: A case study of the Senegalese Rural Electrification Plan. Energy Policy 73, 480–490. https://doi.org/10.1016/J.ENPOL.2014.05.047

Moner-Girona, M., Solano-Peralta, M., Lazopoulou, M., Ackom, E.K., Vallve, X., Szabó, S., 2018. Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: Reducing the gap between current business models and on-site experience. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2018.04.018

Muh, E., Tabet, F., 2019. Comparative analysis of hybrid renewable energy systems for off-grid applications in Southern Cameroons. Renew. Energy 135, 41–54. https://doi.org/10.1016/J.RENENE.2018.11.105

Nna, C.D., Gbadegesin, A.O., Lawal, K.O., 2016. A decentralized, renewable-energy-powered business hub for rural areas: A case study of Ilakan community, Nigeria, in: Clemson University Power Systems Conference, PSC 2016. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/PSC.2016.7462814

Noble, B.F., 2004. A multi-criteria analysis of Canadian electricity supply futures. Can. Geogr. 48, 11–28. https://doi.org/10.1111/j.1085-9489.2004.002b16.x

O, N.C., Kim, H., 2019. Towards the 2 °C goal: Achieving Sustainable Development Goal (SDG) 7 in DPR Korea. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2019.104412

Odou, O.D.T., Bhandari, R., Adamou, R., 2020. Hybrid off-grid renewable power system for sustainable rural electrification in Benin. Renew. Energy 145, 1266–1279. https://doi.org/10.1016/j.renene.2019.06.032

Østergaard, P.A., Duic, N., Noorollahi, Y., Mikulcic, H., Kalogirou, S., 2020. Sustainable development using renewable energy technology. Renew. Energy.

https://doi.org/10.1016/j.renene.2019.08.094

Parajuli, R., 2011. Access to energy in Mid/Far west region-Nepal from the perspective of energy poverty. Renew. Energy. https://doi.org/10.1016/j.renene.2011.01.014

Pérez-Navarro, A., Alfonso, D., Ariza, H.E., Cárcel, J., Correcher, A., Escrivá-Escrivá, G., Hurtado, E., Ibáñez, F., Peñalvo, E., Roig, R., Roldán, C., Sánchez, C., Segura, I., Vargas, C., 2016. Experimental verification of hybrid renewable systems as feasible energy sources. Renew. Energy 86, 384–391. https://doi.org/10.1016/J.RENENE.2015.08.030

Petruschke, P., Gasparovic, G., Voll, P., Krajačić, G., Duić, N., Bardow, A., 2014. A hybrid approach for the efficient synthesis of renewable energy systems. Appl. Energy 135, 625–633. https://doi.org/10.1016/j.apenergy.2014.03.051

Phuangpornpitak, N., Kumar, S., 2011. User acceptance of diesel/PV hybrid system in an island community. Renew. Energy 36, 125–131. https://doi.org/10.1016/j.renene.2010.06.007

Polatidis, H., Haralambopoulos, D.A., Munda, G., Vreeker, R., 2006. Selecting an Appropriate Multi-Criteria Decision Analysis Technique for Renewable Energy Planning. Energy Sources, Part B Econ. Planning, Policy 1, 181–193. https://doi.org/10.1080/009083190881607

Purwanto, W.W., Afifah, N., 2016. Assessing the impact of techno socioeconomic factors on sustainability indicators of microhydro power projects in Indonesia: A comparative study. Renew. Energy 93, 312–322. https://doi.org/10.1016/j.renene.2016.02.071

Rahman, M.M., Paatero, J. V., Poudyal, A., Lahdelma, R., 2013. Driving and hindering factors for rural electrification in developing countries: Lessons from Bangladesh. Energy Policy 61, 840–851. https://doi.org/10.1016/j.enpol.2013.06.100

Ranaboldo, M., Domenech, B., Reyes, G.A., Ferrer-Martí, L., Pastor Moreno, R., García-Villoria, A., 2015. Off-grid community electrification projects based on wind and solar energies: A case study in Nicaragua. Sol. Energy 117, 268–281. https://doi.org/10.1016/j.solener.2015.05.005

Rasheed, R., Khan, N., Yasar, A., Su, Y., Tabinda, A.B., 2016. Design and cost-benefit analysis of a novel anaerobic industrial bioenergy plant in Pakistan. Renew. Energy 90, 242–247. https://doi.org/10.1016/j.renene.2016.01.008

Renewable Energy Agency, I., 2014. Evaluating Renewable Energy Policy: A Review of Criteria and Indicators for Assessment Acknowledgements About IRENA.

Ristic, B., Mahlooji, M., Gaudard, L., Madani, K., 2019. The relative aggregate footprint of electricity generation technologies in the European Union (EU): A system of systems approach. Resour. Conserv. Recycl. 143, 282–290. https://doi.org/10.1016/J.RESCONREC.2018.12.010

Saaty, T.L., 2005. Theory and Applications of the Analytic Network Process. RWS Publications, Pittsburgh, PA.

Saaty, T.L., 2001. The Analytic Network Process: Decision Making with Dependence and Feedback. RWS Publications.

Salisu, S., Mustafa, W., Mohammed, O.O., Mustapha, M., Jumani, A., 2019. Techno-Economic Feasibility Analysis of an Off-grid Hybrid Energy System for Rural Electrification in Nigeria.

Scheubel, C., Zipperle, T., Tzscheutschler, P., 2017. Modeling of industrial-scale hybrid renewable energy systems (HRES) – The profitability of decentralized supply for industry. Renew. Energy 108, 52–63. https://doi.org/10.1016/j.renene.2017.02.038

Shezan, S.K.A., Das, N., Mahmudul, H., 2017. Techno-economic Analysis of a Smart-grid Hybrid Renewable Energy System for Brisbane of Australia, in: Energy Procedia. Elsevier Ltd, pp. 340–345. https://doi.org/10.1016/j.egypro.2017.03.150

Shmelev, S.E., van den Bergh, J.C.J.M., 2016. Optimal diversity of renewable energy alternatives under multiple criteria: An application to the UK. Renew. Sustain. Energy Rev. 60, 679–691. https://doi.org/10.1016/J.RSER.2016.01.100

Singh, M., Balachandra, P., 2019. Microhybrid Electricity System for Energy Access, Livelihoods, and Empowerment. Proc. IEEE 107, 1995–2007. https://doi.org/10.1109/JPROC.2019.2910834

Siskos, J., Hubert, P., 1983. Multi-criteria analysis of the impacts of energy alternatives: A survey and a new comparative approach. Eur. J. Oper. Res. 13, 278–299. https://doi.org/10.1016/0377-2217(83)90057-7

Smit, S., Musango, J.K., Brent, A.C., 2019. Understanding electricity legitimacy dynamics in an urban informal settlement in South Africa: A Community Based System Dynamics approach. Energy Sustain. Dev. 49, 39–52. https://doi.org/10.1016/j.esd.2019.01.004

Taele, B.M., Gopinathan, K.K., Mokhuts'oane, L., 2007. The potential of renewable energy technologies for rural development in Lesotho. Renew. Energy 32, 609–622. https://doi.org/10.1016/j.renene.2006.02.014

Tong, C.W., Zainon, M.Z., Chew, P.S., Kui, S.C., Keong, W.S., Chen, P.K., 2010. Innovative power-augmentation-guide-vane design of wind-solar hybrid renewable energy harvester for urban high rise application, in: AIP Conference Proceedings. pp. 507–521. https://doi.org/10.1063/1.3464898

UN, 2019. Sustainable Development Goals [WWW Document]. URL https://sdgs.un.org/es/goals (accessed 4.15.19).

Vishnupriyan, J., Manoharan, P.S., 2017. Demand side management approach to rural electrification of different climate zones in Indian state of Tamil Nadu. Energy 138, 799–815. https://doi.org/10.1016/j.energy.2017.07.140

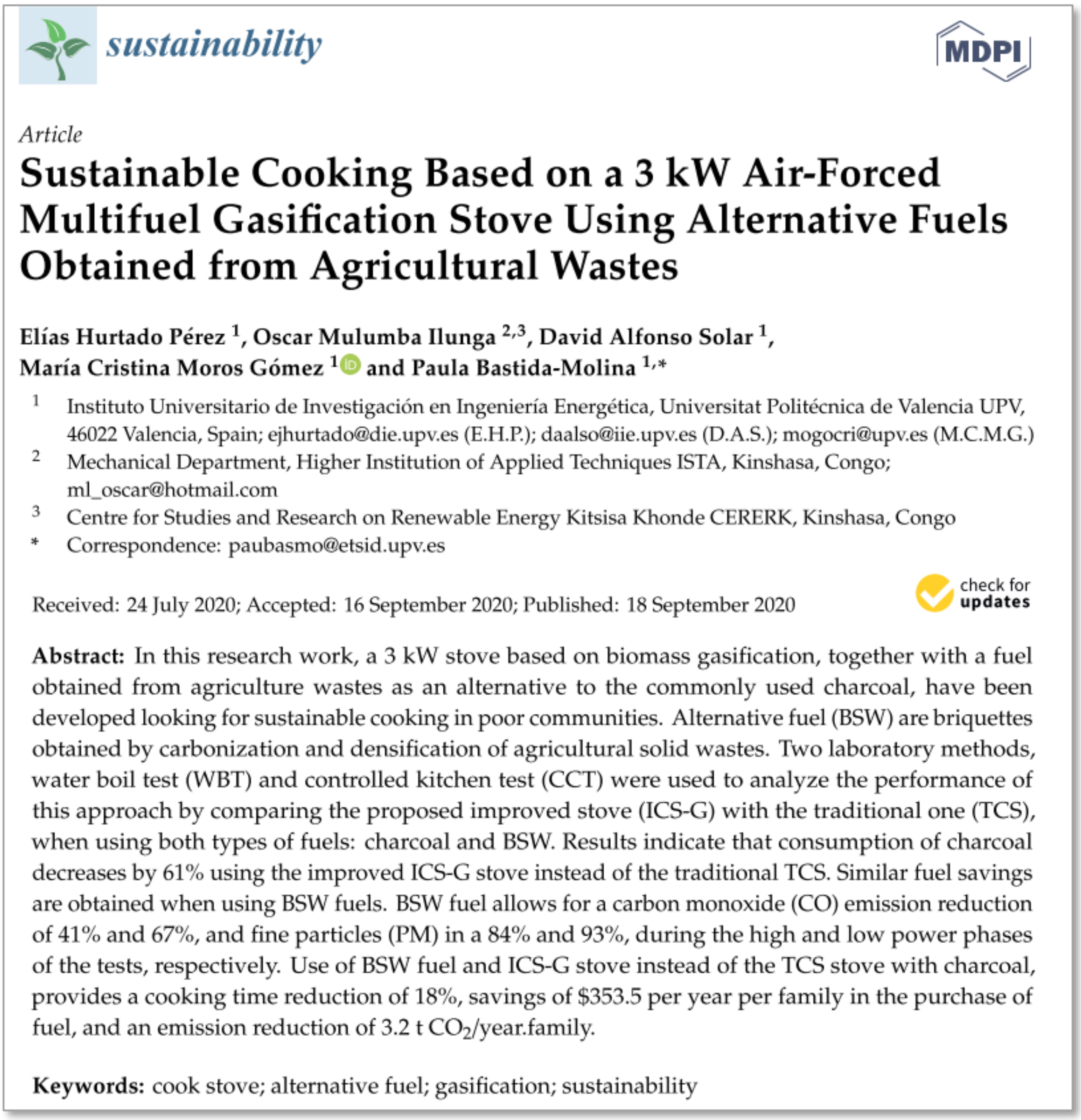
Wang, R., Xiong, J., He, M., Gao, L., Wang, L., 2019. Multi-objective optimal design of hybrid renewable energy system under multiple scenarios. Renew. Energy. https://doi.org/10.1016/j.renene.2019.11.015

Yaqoot, M., Diwan, P., Kandpal, T.C., 2016. Review of barriers to the dissemination of decentralized renewable energy systems. Renew. Sustain. Energy Rev. 58, 477–490. https://doi.org/10.1016/J.RSER.2015.12.224

Yeh, T.-M., Huang, Y.-L., 2014. Factors in determining wind farm location: Integrating GQM, fuzzy DEMATEL, and ANP. Renew. Energy 66, 159–169. https://doi.org/http://dx.doi.org/10.1016/j.renene.2013.12.003

Yetano Roche, M., Verolme, H., Agbaegbu, C., Binnington, T., Fischedick, M., Oladipo, E.O., 2019. Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways. Clim. Policy. https://doi.org/10.1080/14693062.2019.1661818

2.6. Sustainable Cooking Based on a 3 kW Air-Forced Multifuel Gasification Stove Using Alternative Fuels Obtained from Agricultural Wastes



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Article

Sustainable Cooking Based on a 3 kW Air-Forced Multifuel Gasification Stove Using Alternative Fuels Obtained from Agricultural Wastes

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Received: 24 July 2020; Accepted: 16 September 2020; Published: 18 September 2020

Abstract: In this research work, a 3 kW stove based on biomass gasification, together with a fuel obtained from agriculture wastes as an alternative to the commonly used charcoal, have been developed looking for sustainable cooking in poor communities. Alternative fuel (BSW) are briquettes obtained by carbonization and densification of agricultural solid wastes. Two laboratory methods, water boil test (WBT) and controlled kitchen test (CCT) were used to analyze the performance of this approach by comparing the proposed improved stove (ICS-G) with the traditional one (TCS), when using both types of fuels: charcoal and BSW. Results indicate that consumption of charcoal decreases by 61% using the improved ICS-G stove instead of the traditional TCS. Similar fuel savings are obtained when using BSW fuels. BSW fuel allows for a carbon monoxide (CO) emission reduction of 41% and 67%, and fine particles (PM) in a 84% and 93%, during the high and low power phases of the tests, respectively. Use of BSW fuel and ICS-G stove instead of the TCS stove with charcoal, provides a cooking time reduction of 18%, savings of $353.5 per year per family in the purchase of fuel, and an emission reduction of 3.2 t CO_2/year.family.

Keywords: cook stove; alternative fuel; gasification; sustainability

Sustainable Cooking Based on a 3 KW Air-Forced Multifuel Gasification Stove Using Alternative Fuels Obtained from Agricultural Wastes

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Abstract

In this research work, a 3 kW stove based on biomass gasification, together with a fuel obtained from agriculture wastes as an alternative to the commonly used charcoal, have been developed looking for a sustainable cooking in poor communities. Alternative fuel (BSW) are briquettes obtained by carbonization and densification of agricultural solid wastes. Two laboratory methods, water boil test (WBT) and controlled kitchen test (CCT) were used to analyze the performance of this approach by comparing the proposed improved stove (ICS-G) with the traditional one (TCS), when using both types of fuels: charcoal and BSW. Results indicate that consumption of charcoal decreases by 61% using the improved ICS-G stove instead of the traditional TCS. Similar fuel savings are obtained when using BSW fuels. BSW fuel allows for a carbon monoxide (CO) emission reduction of 41% and 67%, and fine particles (PM) in a 84% and 93%, during the high and low power phases of the tests, respectively. Use of BSW fuel and ICS-G stove instead of the TCS stove with charcoal, provides a cooking time reduction in a 18%, savings of $353.5 per year and family in the purchase of fuel and an emission reduction of 3.2 t CO_2/year.family.

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1. Introduction

In recent decades, the demand for primary energy resources has considerably increased due to the high growths, both in world population and demand, while renewable resources, such as firewood, are often poorly managed in this scenario of increasing demand.

Consequently, the proper use of these resources becomes mandatory for a sustainable development (Bhutto et al., 2019). Currently, in the world about three billion people depend on solid fuels, such as firewood and charcoal, for cooking food and heating, without having access to clean cooking methods (IEA, 2017a; Maes and Verbist, 2012; Zhang et al., 2018; Zongxi et al., 2017). Solid fuels are the main source of energy used for heating and cooking in many urban and suburban communities in sub-Saharan African countries, representing more than 80% of the primary energy supply of these areas (Chiteculo et al., 2018; Jones et al., 2016; Mwampamba et al., 2013). The traditional cooking system most used in these communities is based on burning coal or firewood on stoves with the pots placed on top, resulting in a process of very low thermal efficiency and, therefore, in an excessive fuel consumption with the consequent environmental damage (Barbieri et al., 2018; IEA, 2018; Lynch, 2002), including excessive CO_2 emissions, thus contributing to global warming and climate change (Ramanathan and Carmichael, 2008). Significant efforts are in progress to improve cooking stoves and limit the above-mentioned drawbacks. It has been found that fan-assisted cookstoves produced both lower concentrations of flue gases and particulate matter (Ndindeng et al., 2019). Positive experience in Rwanda promoting biomass pellets and a fan micro-gasification improved cookstove as a clean cooking alternative to charcoal has been obtained (Jagger and Das, 2018). Gasifier Cookstove using biochar improves energy efficiency and air quality (Gitau et al., 2019) and investigation on the gas production from a gasifier cookstove indicates the importance of primary air to reduce tars and increases combustion (Kirch et al., 2020). This paper addresses all these aspects: gasifier implementation, energy efficiency, air quality, pellets use, etc., looking for the improvement of cook stove both in the technical and economical aspects with special emphasis in the use of agriculture wastes to reduce the environmental impact of cooking in under-developed countries.

Although agriculture and timber industry are considered as the main responsible for large-scale deforestation, energy supply for food cooking (Dresen et al., 2014) has also an important contribution to deforestation and land degradation. The collection of firewood and the production of charcoal for cooking can have a significant impact on local ecosystems, particularly in overpopulated areas (Barbieri et al., 2017; Tucho and Nonhebel, 2015). Due to the fight against the climate change and the search for energy security, biomass resources are becoming more important than ever, given they can be considered as renewable and sustainable source of energy, neutral for climate impact (Smith et al., 2000) and socially viable. This is possible if: (i) they are collected in sustainably managed forests, where each cut tree is replanted directly; and, (ii) the wood is burned using appropriate technologies to maximize energy efficiency and minimize harmful emissions inside the house (CO and PM) and to the atmosphere (CO_2) (FAO and UNEP, 2020). In sub-Sahara African countries, burning agricultural wastes (including stems, herbs and leaves) is the easiest and most economical way to eliminate the volume of those wastes. Outdoors incineration allows for a fast elimination of previous crops wastes, as well as the pruning and cleaning of the crop area. It is estimated that burning biomass, such as wood, leaves, trees and pastures, including agricultural wastes, is responsible for a 40% of carbon dioxide (CO_2), 32% of carbon monoxide (CO), 20% of suspended fine particles (PM) and 8% of others emissions to the atmosphere (CCA, 2014; Ministry of Agriculture, 2012) of these areas. These biomass wastes could be instead used in cooking stoves, using a biomass gasification technology, and thus be an important part of solving these emissions problems (Bhojvaid et al., 2014; Loo et al., 2016). The amount of peanut shell waste produced annually in the Democratic Republic of the Congo is estimated at 114,000 tons and that of rice husk is around 133,200 t / year (CARD, 2013; FAO, 2015). The province of Bandundu, to which the present study is applied, being a province totally dedicated to agriculture, represents almost 20% of the production of agricultural residues in the DRC. Using improved gasification stoves, energy efficiencies can easily reach values greater than 60%, compared to 30-40% of the current ones (Panwar et al., 2009; Panwar and Rathore, 2008). Most of the technologies currently in use consist of enhanced direct combustion ICS with a ceramic combustion chamber. This approach simply involves directing much of the combustion energy to the pot. In this system, it is difficult to improve the quality of combustion because the air supply is naturally ventilated and therefore difficult to regulate, which leads to incomplete combustion with a direct negative consequence on energy efficiency and polluting emissions. In order to reduce the consumption of firewood and CO_2 emissions in cooking activities, a 3 kW power stove has been optimized using the biomass micro-gasification principle. Additionally, to reduce the consumption of forest biomass, an alternative fuel to charcoal consisting of briquettes produced by carbonization and densification of agricultural solid wastes (peanut husk and rice husk, mainly) has been developed. To verify these improvement approaches, two laboratory test methods: the boiling water test (WBT) and the controlled cooking test (CCT), have been applied to the traditional stove (TCS) and the new one we are proposing (ICS-G) , using in both cases charcoal and BSW briquettes as fuels.

2. Materials and Methods

2.1. Study case

The study was conducted in the city of Bandundu located 409 km from the DRC capital Kinshasa and in an essentially agricultural region. The population size is estimated at 3,673,000 inhabitants and 90% of the population is considered dependent on biomass-firewood for cooking food. The average family size is six people and the eating habits are such that only one large meal is served daily.

2.2. Fuels

The fuel currently used for food cooking in sub-Saharan Africa countries is charcoal. We have deduced its main characteristics by application of standards biomass characterization techniques (AENOR, 2020). Obtained results are detailed in table 1.

There are many different solid biomass residues from agricultural activities in the Democratic Republic of the Congo (DRC). In this work, we have selected as sources for fuel for cooking activities those with the better thermo-physical properties. The proposed fuel (BSW) for cooking are briquettes with a cylindrical shape of 2 cm in diameter and 3.5 cm in length (figure 1), so they are well adjusted to the typical cooking stoves. The briquettes are made from solid agricultural wastes, such as peanut shells and rice husks. Manufacturing of briquettes follows the following steps:

1st) Carbonization: carried out in a traditional furnace composed of a cylindrical metal barrel 80cm in diameter and 120cm high. The metal barrel has about thirty vent holes. 3cm at its lower base. The removable upper base has a 10cm diameter and 100cm high chimney. Char waste is introduced from the top with a quantity of 20 kg of solid waste (rice husks or peanuts). The fire is lit from the top of this furnace. The carbonization system is endothermic in oxygen, evolving at temperatures between 250-500ºC for 2 to 3 hours. After this, holes in the lower base are covered and the lid is closed until cooled, which can last 3 to 4 hours. The carbonization yield varies between 18-20%.

2nd) Grinding: the char waste is placed in a mortar with an artisanal pestle to convert the charred waste into a fine powder with a grain size of 1 mm.

3rd) Binding: the resulting powder, combined with a binder biomass (paper pulp and cassava fibers), is mixed properly up to have a good homogenization.

4th) Densification: this mixture is manually densified to form the briquettes; and

5th) Drying: the briquettes are dried in the sun for three days before their use.

Three types of briquettes were manufactured with the dosages detailed in Table 2. Their elemental composition and the different thermo-physical properties of these briquettes, respectively, are shown at tables 3 and 4. These values were obtained following current regulations for this type of characterization (AENOR, 2020). From the cooking tests carried out summarized in table 4, it results that BSW3 structure is the most adequate to be used, given its higher calorific value.

Table 1. Thermo-physical characteristics of traditional charcoal.

Bulk density [kg.m^{-3}]	**Moisture content**	**Volatile matter**	**Ash content**	**Fixed Carbon**	**HHV [MJ.kg^{-1}]**	**LHV [MJ.kg^{-1}]**
365	7%	13%	2%	85%	30,2	29,8

Table 2. Composition of the different types of briquettes [% mass].

Type	**E1**	**E2**	**E3**	**E4**	**E5**
BSW 1	50%	-	20%	15%	15%
BSW 2	-	50%	30%	10%	10%
BSW 3	-	20%	50%	15%	15%

(E1 = biochar rice, E2 = biochar peanut, E3 = sawdust, E4 = paper paste, E5 = cassava xilema fiber)

Table 3. BSW elemental composition

Type	C	H	N	O	S
BSW 1	51,70%	2,40%	0,70%	45,20%	0,00%
BSW 2	52,50%	3,20%	0,70%	43,60%	0,00%
BSW 3	50,70%	2,70%	0,60%	46,00%	0,00%

Table 4. BSW thermo-physical characteristics.

	Bulk density [kg.m^{-3}]	Moisture content	Volatile matter	Ash content	Fixed carbon	HHV [MJ.kg^{-1}]	LHV [MJ.kg^{-1}]
BSW 1	520	7,50%	34,30%	24,50%	33,70%	18,2	17,7
BSW 2	550	10,20%	36,00%	25,80%	28,00%	18,4	17,7
BSW 3	560	10,30%	38,80%	19,00%	32,90%	19	18,3

Figure 1. BSW briquettes.

2.3. Stoves

Figure 2a illustrates the traditional stove (TCS), currently used in DRC, taken as the reference for our study. It consists of a cylindrical combustion chamber, 100 mm deep and 280 mm in diameter, with holes, 10 to 12 mm in diameter, both in the base and the lateral side (Hurtado Pérez et al., 2017).

Our improved gasification stove (ICS-G), shown in Figure 2b, generates combustion through two consecutive stages with a stoichiometric proportion of 6 kg of air per 1 kg of biomass to ensure total biomass combustion. The fraction of air that is introduced into the lower part of the reactor (ε), respect to the total one used by the stove, is fixed to 0.3 - 0.4, with the purpose to gasify solid biomass into a gaseous element (syngas). The remaining quantity of air, known as secondary air, is introduced at the top of the reactor, and has the function to ensure a complete combustion of the biomass. The number of holes and, therefore, the primary and secondary air inlet sections, are such that they ensure these air proportions. The different components of this ICS-G are shown at the diagrams in the figure 3.

(**a**) (**b**)

Figure 2. Cooking stoves**. a**) Traditional cookstove, TCS. b) Improved Cookstove Gasifier, ICS-G

Calculation of the improved ICS-G stove dimensions takes into account different aspects (Belonio, 2005; Kumar et al., 2008; Mukunda, 2009; Ojolo et al., 2012; Panwar, 2009); in particular, the amount of energy needed to cook a meal for a six-persons household was estimated to be around Q = 15.8 MJ (Belonio, 2005; Kumar et al., 2008; Panwar and Rathore, 2008). Therefore, the minimum power requirement to cook food for a meal for a family of six persons with a burning time in the range 1.0 to 1.5 h (Ojolo et al., 2012) is about 3 kW. The rest of this stove design parameters are detailed in table 5.

Table 5. ICS-G design parameters.

Parameter	Symbol	Value
Power	P	3 kW
Stequiometric air	SA	6 kg air/kg biomass
Equivalence ratio	ε	0.33
Air density	ρ_a	1.25 kg.m^{-3}
Thermal efficiency	η_{th}	60%
Cooking time	Δt	1 h
Specific biomass weight	ρ_f	560 kg.m^{-3}
Air holes diameter	d_e	2 mm
Specific gasification rate	SGR	110 kg.m^{-2}.h^{-1}

The following ICS-G characteristics are deduced:

a) Fuel Consumption Rate (FCR): amount of biomass fuel to be used by the stove to provide the required energy, it is deduced by using the relationship (1).

$$FCR = \frac{P*3600}{LCV*\eta_{th}} \tag{1}$$

Where LCV represents the fuel low specific calorific power, η_{th} accounts for the gasifier thermal efficiency and P is the power reactor. For this gasifier, the thermal efficiency was initially assumed as 60-70% (Belonio, 2005; Panwar, 2009; Panwar and Rathore, 2008).

b) Reactor Diameter (Kumar et al., 2008; Mukunda, 2009; Ojolo et al., 2012; Panwar, 2009).

The reactor diameter is a function of the fuel consumption rate and the specific gasification rate (SGR), this one defined as the amount of fuel used per unit of time and per unit of area in the reactor. (110-210 kg·m^{-2}·h^{-1}) The diameter can be determined using expression (2).

$$D = \left(\frac{4 \ * \ FCR}{SGR \ * \ \pi}\right)^{0.5}$$
(2)

c) Reactor Height: The height of the reactor determines the operation time of the combustion chamber once the fuel is loaded. It is deduced by using equation (3) (Kumar et al., 2008; Mukunda, 2009; Ojolo et al., 2012; Panwar, 2009).

$$H = \frac{SGR \ * \ \Delta t}{\rho_f}$$
(3)

Being SGR the specific gasification rate; Δt is the estimated reactor operation time, and ρ_f is the fuel density.

d) Amount of air needed for gasification (Q_{PA}): This magnitude refers to the air flow rate needed to gasify the fuel and it is given by equation (4).

$$Q_{PA} = \frac{\varepsilon * FCR * SA}{\rho_a} \tag{4}$$

Where Q_{PA} is the airflow rate; ε is the gasification equivalence ratio (0.3 to 0.4), FCR is the fuel consumption rate; SA is the stoichiometric amount of air required by unit of biomass (6 kg air per kg biomass) (Belonio, 2005), and ρ_a is the air density.

The total amount of air needed for total combustion in the stove is deduced from the above mentioned Q_{PA}, by dividing it by the equivalence ratio ε.

The deduced parameters of a 3 kW stove are deduced using the abovementioned equations and are detailed in table 6.

Table 6. Parameters of a 3 kW reactor.

D [cm]	H [cm]	FCR [kg·h^{-1}]	Q_{PA} [m^3·h^{-1}]	QAT[m^3·h^{-1}]
12	19	0,906	1.304	4,34

Air is introduced in the combustion chamber (figure 3 a) through the inputs A1 (primary air for gasification) and A2 (secondary air for total combustion). The total air flux A_{ST} is guaranteed by a 3 W fan at 12 V DC. A small speed controller allows for the regulation of the airflow in the reactor. A lithium-ion battery (12V; 9Ah) and a solar panel (5W) provide the necessary power for the system. The primary air enters through 10 small holes of 2 mm in diameter located 10 mm from the bottom of the reactor. The secondary air enters the reactor through 20 small holes 2 mm in diameter at the top of the stove (figure 3b).

ICS-G stove includes the following components (figure 3c):

a. Reactor: it is cylindrical, 12cm internal diameter and 19cm deep, and surrounded by a 1cm layer of clay.

b. Secondary Air Duct Tunnel: Another 16cm cylinder surrounds the reactor, so a 1mm gap allows secondary air to rise, sweeping through the reactor body. This allows preheating of the secondary air.

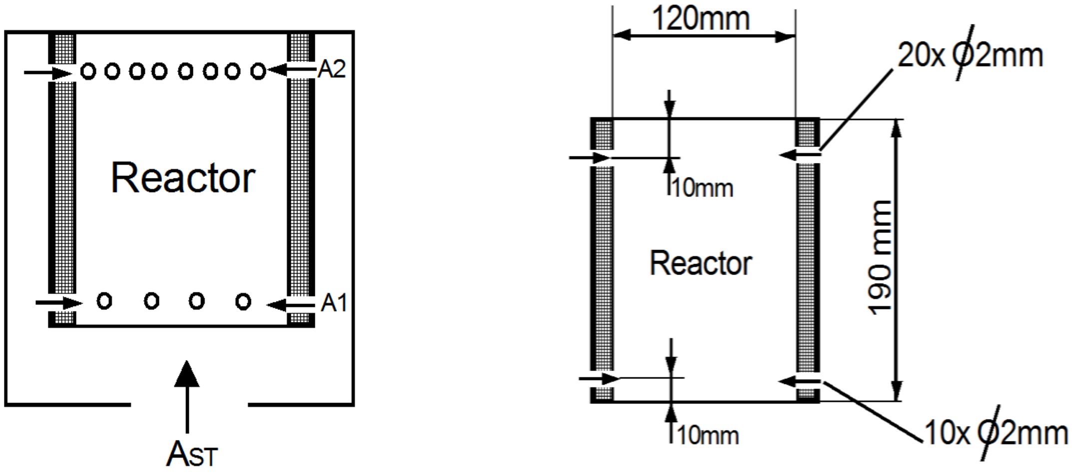
c. Thermal insulation: a 4cm layer of rock wool

d. Fan: A small 3W-12V DC motor provides the primary and secondary air supply.

e. Power supply: a small 5W solar panel that charges a 9Ah-12V lithium battery.

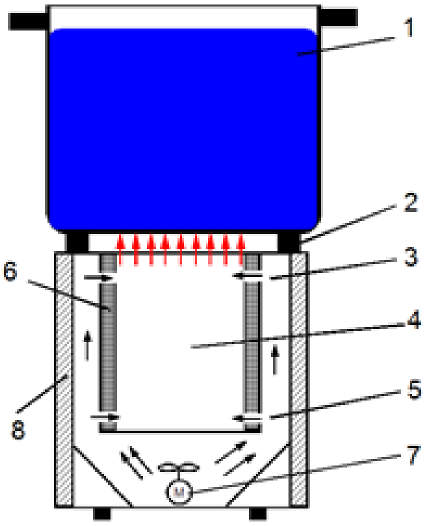
f. Regulation: a potentiometric circuit allows varying the supply voltage of the small motor, to control the primary and secondary airflows.

g. Outer shell: it is a24cm cube made of 1mm thick sheet metal. The lower base is perforated to allow the motor to inject ambient air



(a)

(b)



(c)

Figure 3. Improved Cookstove Gasifier, ICS-G **(a:** air flows; b: dimensions; c: components)

2.4. Instrumentation

The equipment used to characterize the proposed fuel and stove includes:

- Balance OHAUS V11P6 with a 6 kg capacity and 0.1g accuracy. Used to determine the amount of fuel used in the WBT and CCT test.
- Balance OHAUS NVL 20000/2 with a 20 kg capacity and 1 g accuracy. This scale was used to measure the amount of water to boil during the WBT test and the amount of dry and cooked meal during the CCT test.
- Balance Mettler AB304-S / FACT with a 320 g capacity and 0.1 mg accuracy. It was used for the characterization of briquettes
- Select Muffle Furnace SELECT-HORN, Capacity 9 liters. Power 3000 W. Maximum temperature 1100 ºC. This muffle was used for the thermo-physical characterization of briquettes
- Combustion calorimeter CAL2K/1. Resolution 0.001 MJ/kg and 0.000001 ºC. To allow for the determination of the calorific value of the briquettes

A Portable Emission Monitoring System (PEMS) was used for the determination of the polluting emissions of CO and PM during the Water Boiling Test, WBT (Fig. 4). This system consists of a bell (a1), inside which the stove to be tested (a2) is placed; an extractor (a3) absorbs all the polluting emissions and takes a sample of the emission gases to take them to the sensor box (a4). Finally, an interface with a data acquisition system, allows for the data storage in a computer (a5).

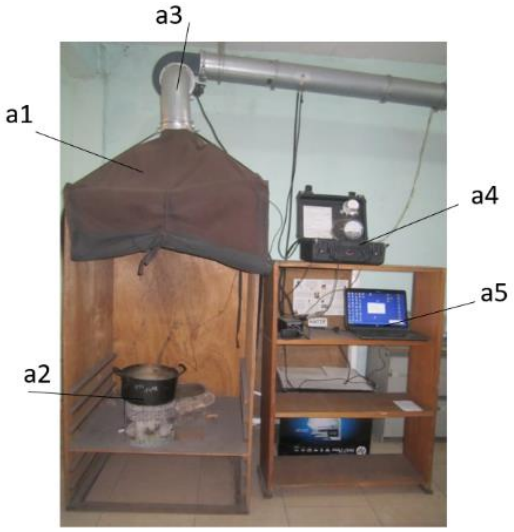


Figure 4. Portable Emission Monitoring System (PEMS).

2.5. Methods

a) Laboratory tests

Performance of the ICS-G and the TCS stoves were evaluated by using the WBT 4.2.3 (GACC, 2014) and CCT v.2 (Bailis, 2004) laboratory methods. WBT 4.2.3 protocol is a laboratory simulation of the energy efficiency of the cooking process using water in three sequential phases, as detailed in figure 5. The first phase, High Power Cold Start (HPCS), begins by heating the stove, filled with water from room temperature, up to reach the water boiling point. In the second phase, High Power High Start (HPHS), with the stove already hot from the previous phase, a new refill with fresh water is made and heating starts up to reach again the water boiling temperature. In the third phase, Low Power (LP), the water is maintained for 45 minutes at a temperature close to the boiling point. In the three phases the amount of fuel used for each process is carefully measured. Performance analyzes have been performed in order to compare the traditional stove TCS with the improved ICS-G stove using the new BSW3 fuel. The performance indicators used to compare the stoves are those officially recognized by the IWA, in order to ensure consistency of the selection with the ISO/IWA11:2012 guidelines (Technical Management Board, 2012).

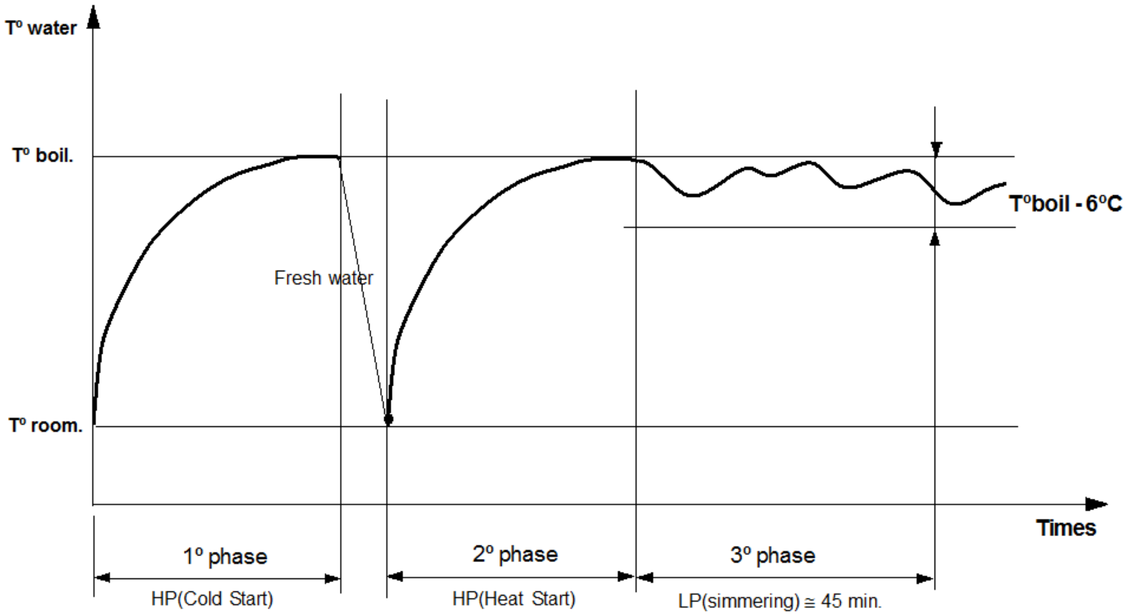


Figure 5. Sequential steps in the WBT Protocol (Jetter and Kariher, 2009).

Many studies and researchers suggest that WBT laboratory tests do not necessarily predict the performance of stoves in real domestic kitchens (Bailis et al., 2007; Baldwin, 1987; Berrueta et al., 2008; Jetter and Kariher, 2009; Smith et al., 2007). For these reasons, in this investigation the WBT tests were complemented by the CCT tests in which real meals were prepared. In these CCT tests the cooking of a real meal commonly consumed by the population of the area under study is carried out under strict controlled conditions. During the CCT process, three kitcheners prepared the same meal under identical conditions and with the same amounts of ingredients and water. Total needed time and the amount of fuel used for the food cooking are measured. To allow for the reproducibility of the results and to minimize the margin of error, all the pots used for these tests have the same characteristics and dimensions (Lombardi et al., 2018, 2017; MacCarty et al., 2008), and the cooks prepared six times the same amount of food (n = 6). The ingredients used in the tests are shown in Table 7. Each test is based on a total of 12.45 kg of raw material, including cooking water. Final weight after cooking should be 6.58 kg (Standard deviation, SD=0.10).

Table 7. Raw material for a CCT test.

	Quantity [g]
Fish (6)	1.370
Flour (corn + cassava)	2.010
Peanut paste	180
Vegetables	1.150
Other ingredients (tomatoes, salt, onion, garlic)	390
Olive oil	350
Water	7.000

This test provides reliable performance indicators of the behavior of the cooking stove when used on the field. These performance indicators are the specific fuel consumption (SFC) and the total cooking time. SFC represents the amount of fuel needed to cook the quantity of food needed for usual meal and it is calculated by:

$$SFC = \frac{W_{fuel}}{W_f} \tag{5}$$

Where $W_{fuel}$is the mass of fuel used for cooking the meal and W_f is the cooked meal mass.

b) Estimates of CO_2 Emission Reduction (ER-CO_2) for the ICS-G stove.

The calculations of the ER-CO_2 resulting from the use of non-renewable wood in kitchens are carried out using the AMS-II methodology (UN, 2021) according to the United Nations Convention on Climate Change (UNFCC). These emissions savings are given by:

$$ER = B_{Savings} * f_{NRB} * NCV_{biomass} * EF \tag{6}$$

Where: $B_{Savings}$ is the amount of woody biomass, in tons, used by the ICS-G during the year; f_{NBR} is the fraction of non-renewable biomass (it can be obtained from some study results or government data, default value for DRC is 90%); $NCV_{biomass}$ is the low specific heat value of the non-renewable woody biomass that is been replaced (in the case of wood, this value is 0.015 TJ/t, using the gross weight of the air dried wood), and *EF* is the fossil fuel emission factor that is expected to be used for the replacement of non-renewable woody biomass with other commonly available fossil fuels, its value is 63.7 t CO_2/TJ. When charcoal is used as fuel by the reference TCS stove or by the new ICS-G stove, the amount of woody biomass will be determined using a conversion factor of 5 kg of wood (wet) per 1 kg of charcoal (dry base). All these values are obtained from (UN, 2021).

$B_{Savings}$ can be determined from the results of the CCT tests by using the following relationship:

$$B_{savings} = B_{olds} * (1 - \frac{SFC_{New}}{SFC_{olds}}) \tag{7}$$

Where: SFC_{olds} and *SFCnew* are the specific fuel consumption for the TCS and the ICS-G stoves, respectively.

3. Results and discussion

3.1. Performance Analysis Using the WBT Method

Tables 8 shows the results from the WBT tests for both types of stoves when using charcoal as a fuel. Table 9 details the results when the used fuel is BSW3. All these values have been obtained directly from the PEMS system. In both cases, a significant improvement in energy efficiency of 134% and 153%, respectively, is obtained by using the ICS-G stove, together with a very significant reduction of CO and PM emissions. Comparing the TCS stove using charcoal with the new ICS-G stove using BSW3 briquettes, (Table 10), there was a 150% increase in energy efficiency, saving in fuel of about 67% and CO emission reductions of 41% and 67% during the high and low power test phases, while PM particle emission reduction reaches 84% and 93%, respectively. Therefore, a significant decrease of pollutants and an increase in performance due mainly to the new design of the stove and the new fuel is observed. In a recent study done in a Kenyan village on the impact of a gasifier on improving energy efficiency and reducing polluting emissions, Gitau, J.K. et al. (Gitau et al., 2019) underlines a reduction in CO and PM emissions of 57% and 79%, respectively, when compared with the traditional model. Our improved performance of the ICS-G is mainly due to the improved combustion quality due to the adjustment of the stoichiometric air quantity, which leads to an almost complete combustion of the solid biomass. Forced ventilation (ICS-G) always results in better combustion than natural ventilation (TCS), all other things being equal. In addition, the ICS-G combustion chamber is thermally insulated, this prevents heat loss on the sides of the ICS-G stove and therefore concentrates all the heat produced and directs it towards the pot with the movement of forced air. Natural ventilation does not ensure perfect combustion because its random nature and high dependence on the external atmospheric conditions, as the combustion chamber is not closed, heat losses are uncontrolled and widespread.

Table 8. Results from WBT test using charcoal as fuel.

IWA PERFORMANCE METRICS	UNITS	TCS	ICS-G	ICS-G.vs,TCS (%)
High Power Thermal efficiency	%	22 ± 1,0	51.6 ± 1.5	134 ± 13
Low Power Specific Fuel Consumption	kJ/(s.l)	0.64 ± 0.05	0.32 ± 0.07	-50.0 ± 11.6
High Power CO emissions	g/MJ	16.3 ± 3.8	5.1 ± 0.2	-68.7 ± 7.4
Low Power CO emissions	g/(s.l)*1e-3	5.00 ± 0.67	1.33 ± 0.08	-73.3 ± 3.9
High Power PM emissions	g/MJ*1e-3	116 ± 10.7	38.1 ± 2.4	-67.2 ± 9.5
Low Power PM emissions	g/(s·l)*1e-6	35.0 ± 0.33	20.0 ± 0.4	-42.9 ± 1.1

Table 9. Results from the WBT tests using briquettes BSW3 as fuel.

IWA PERFORMANCE METRICS	UNITS	TCS	ICS-G	ICS-G.vs,TCS (%)
High Power Thermal efficiency	%	21.8 ± 1.2	55.1 ± 0.03	153 ± 14
Low Power Specific Fuel Consumption	kJ/(s·l)	0.57 ± 0.05	0.19 ± 0.02	-66.7 ± 4.4
High Power CO	g/MJ	16.3 ± 3,8	6.9 ± 0.4	-41.0 ± 3.4
Low Power CO	g/(s·l)*1e-3	4.83 ± 0.17	1.50 ± 0.17	-66.9 ± 3.7
High Power PM	g/MJ*1e-3	83.3 ± 6.4	13.5 ± 3.1	-83.8 ± 3.9
Low Power PM	g/(s.l)*1e-6	20.7 ± 2.3	1.5 ± 0.4	-92.8 ± 1.8

Table 10. Comparison TCS/charcoal vs ICS-G/BSW3.

IWA PERFORMANCE METRICS	UNITS	TCS	ICS-G	ICS-G.vs,TCS (%)
High Power Thermal efficiency	%	22 ± 1,0	55.1 ± 0,03	150 ± 11
Low Power Specific Fuel Consumption	kJ/(s·l)	0.64 ± 0.05	0.19 ± 0.02	-70.3 ± 3.9
High Power CO	g/MJ	11.7 ± 0.07	6.9 ± 0.4	-41,0 ± 3,4
Low Power CO	g/(s·l)*1e-3	5.00 ± 0.67	1.50 ± 0.17	-70.0 ± 5.3
High Power PM	g/MJ*1e-3	116 ± 10.7	13.5 ± 3.1	-88.4 ± 3.9
Low Power PM	g/(s.l)*1e-6	35.0 ± 0.33	1.5 ± 0.4	-95.7 ± 1.1

Obtained improvement in emissions are in agreement with the results published in [16], where at lower air supply rates, low emissions of both PM and CO are achieved.

3.2. Results from the CCT analysis

Tables 11 and 12 show the results of the CCT tests carried out in the preparation of the typical meal consumed in the city of Bandundu. Table 11 summarizes the comparison between the ICS-G and TCS stoves using charcoal as fuel. A fuel saving of 61% is observed as well as a 20% decrease in the time used for cooking when the improved ICS-G stove is used. This is an improvement on the 40% fuel economy reported in (Gitau et al., 2019) for a natural air gasifier. Table 12 shows the test results using BSW3 as fuel. In this case, ICS-G has very similar fuel savings in relation to the TCS independent of the type of fuel: charcoal or BSW3 than in the previous case, 61%. Similarly, cooking time saving is almost the same for the two kind of fuel: 18% compared to the traditional system. However, BSW3 main advantage comes from the fact that this fuel is obtained from agricultural residues, so no cutting down of trees as in the use of charcoal is needed. Besides, there is a saving in fuel consumption mainly due to the fact that in an ICS-G the firepower can be fully controlled; i.e.: during the simmering phase of the food, the power is reduced with the corresponding fuel saving. For a TCS, it is impossible to vary the fire power during the different phases of the cooking process, given it is based on natural ventilation. Besides, the ICS-G includes a greater thermal insulation, especially in the lateral surface.

Table 11. CCT results (Charcoal as fuel, n=6).

	TCS	ICS-G	ICS-G.vs,TCS (%)
Fuel [g]	2063 ± 119	805 ± 80	-61.0 ± 4.5
Cooking Time [s]	15120 ± 960	12160 ± 612	-20.2 ± 6.5
SFC [g charcoal /kg cooked meal]	313 ± 16.5	123 ± 11.2	-60.7 ± 4.1
SEC[MJ /kg cooked meal]	9.3 ± 0.5	3.7 ± 0.3	-60.2 ± 3.9

Table 12. CCT results (BSW3 briquettes as fuel n=6).

	TCS	ICS-G	ICS-G/TCS[%]
Fuel [g]	3327 ± 210	1270 ± 95	-61.8 ± 3.7

Cooking Time [s]	15960 ± 432	13080 ± 654	-18.0 ± 4.7
SFC [g charcoal /kg cooked meal]	506 ± 27	194 ± 13.0	-61.7 ± 3.3
SEC[MJ /kg cooked meal]	9.3 ± 0.5	3.5 ± 0.2	-62.4 ± 2.9

3.3. Environmental analysis

By using data from the results in tables 11 and 12, we can deduce that the fuel savings by the introduction of the ICS-G stove instead the TCS is 1.21 kg when using charcoal, and 2.06 kg when using BSW3 briquettes. CO_2 emissions reductions have been calculated according to the AMS-II methodology [51]. Table 13 indicates the annual reduction in wood consumption and CO_2 emissions for a household and for the entire city of Bandundu, where around 90% depend on biomass for cooking food. We are considering that 1 kg of charcoal is equivalent to 5 kg of firewood.

Table 13. Bsavings and ER-CO_2 for ICS-G.

Fuel	Bsaving (t/year) Household	Bsaving (t/year) Bandundu City	ER- CO_2 (t/year) Household	ER-CO_2 (t/year) Bandundu City
Charcoal	2.288	1,248.194	1.97	1,073,384
BWS3	3.766	2,054,480	3.24	1,766,751

3.4. Socioeconomic analysis

The use of ICS-G with BSW3 fuel will provide significant economic benefits to the households in developing countries. The price of one kilogram of charcoal is estimated at 0.6 $/kg in Bandundu and the price of BSW3 could be around 0.2 US$/kg. In accordance with the fuel consumptions deduced in the CTT tests, the daily fuel purchases under current conditions, TCS stove using charcoal, reaches 1.23 US$/family.day, that would be reduced to 0.48 US$/family.day when using the ICS-G stove with charcoal and up to 0.25 US$/family.day if the fuel for this stove would be BSW3. Therefore, monthly savings of US$ 22.6 will be obtained by the introduction of ICS-G stoves using charcoal and US$ 29.4 when the fuel used will be BSW3. Taking into account that the purchase price of this ICS-G stove is in the order of 50 US$, the return periods are 2.2 and 1.7 months, respectively. Therefore, the savings for the first year are US$ 222 and US$ 303.5 for the both cases of ICS-G under consideration.

4. Conclusions

The causes of deforestation and greenhouse gas emissions and pollutants in developing countries, such as those in sub-Saharan Africa, are diverse, but they include in a high percentage the use in cooking activities of traditional fuels with low energy efficiency stoves. A possible solution to reduce deforestation and the rate of polluting and greenhouse gases emissions would require the improvement of the stoves and the fuels used for those cooking activities. In this work, an improved stove based on gasification and a new fuel obtained from agricultural wastes have been designed and built to address these goals. Results using standard protocols, such as BWT and CCT, indicates fuel savings up to 61% and cooking time reduction of 18% by the introduction of these improvements in stove and fuel. Environmental impact remediation is obtained by wood savings of 2.05 Mt/year, from the substitution of this wood by agricultural wastes, and 1.9 Mt CO_2/year emissions in the case of the Bandundu City in the DRC. Economic improvement is also obtained with these new elements, reaching, for a standard family with 6 members, annual savings up to US$303 by the introduction of ICS-G stoves with BSW3 fuel and a return period for the investment in the new stove below 2 months

Author contributions: Conceptualization: OMI and EHP. Methodology, OMI. Software, EHP. Validation: OMI, EHP and DA. Formal analysis: DA, MCMG and PBM. Investigation: OMI and EHP. Resources: OMI and EHP. Data: DA, OMI and MCMG. Writing (original draft preparation): OMI. Writing (review and editing): EHP and MCMG. Visualization: PBM, DA. Supervision: PBM, DA and MCMG. Project administration: MCMG, PBM and EHP. Results interpretation: all authors. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BC: Black carbon

BSW: solid fuel briquettes

CCT: cooking controlled test

ER-CO_2: Carbon dioxide emission reduction

FCR: Fuel consumption rate

HP: High power WBT phase

ICS-G: improved gasification stove

LP: low power WBT phase

PM: particle matter

PEMS: portable emissions measurement system

DRC: Democratic Republic of Congo

SA: Stequiometric air

SFC: specific fuel consumption

SEC: specific energy consumption

SGR: specific gasification rate

TCS: traditional stove

WBT: water boiling test

Acknowledgment

This work was supported in part by the regional public administration of Valencia under the grant ACIF/2018/106.

References

AENOR, 2020. UNE standars [WWW Document]. URL https://www.aenor.com/normas-y-libros/buscador-de-normas?k=(i:7516040) (accessed 3.21.20).

Bailis, R., 2004. Controlled Cooking Test (CCT).

Bailis, R., Berrueta, V., Chengappa, C., Dutta, K., Edwards, R., Masera, O., Still, D., Smith, K.R., 2007. Performance testing for monitoring improved biomass stove interventions: experiences of the Household Energy and Health Project This paper is one of six describing work done as part of the Household Energy and Health (HEH) Project. Energy Sustain. Dev. 11, 57–70. https://doi.org/10.1016/S0973-0826(08)60400-7

Baldwin, S.F., 1987. Biomass stoves: engineering design, development, and dissemmination.

Barbieri, J., Parigi, F., Riva, F., Colombo, E., 2018. Laboratory Testing of the Innovative Low-Cost Mewar Angithi Insert for Improving Energy Efficiency of Cooking Tasks on Three-Stone Fires in Critical Contexts. Energies 11, 3463. https://doi.org/10.3390/en11123463

Barbieri, J., Riva, F., Colombo, E., 2017. Cooking in refugee camps and informal settlements: A review of available technologies and impacts on the socio-economic and environmental perspective. Sustain. Energy Technol. Assessments 22, 194–207. https://doi.org/10.1016/j.seta.2017.02.007

Belonio, A.T., 2005. Rice Husk Gas Stove Handbook.

Berrueta, V.M., Edwards, R.D., Masera, O.R., 2008. Energy performance of wood-burning cookstoves in Michoacan, Mexico. Renew. Energy 33, 859–870. https://doi.org/10.1016/j.renene.2007.04.016

Bhojvaid, V., Jeuland, M., Kar, A., Lewis, J., Pattanayak, S., Ramanathan, N., Ramanathan, V., Rehman, I., 2014. How do People in Rural India Perceive Improved Stoves and Clean Fuel? Evidence from Uttar Pradesh and Uttarakhand. Int. J. Environ. Res. Public Health 11, 1341–1358. https://doi.org/10.3390/ijerph110201341

Bhutto, A.W., Bazmi, A.A., Karim, S., Abro, R., Mazari, S.A., Nizamuddin, S., 2019. Promoting sustainability of use of biomass as energy resource: Pakistan’s perspective. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-019-06179-7

CARD, 2013. National Rice Development Strategy.

CCA, 2014. Burning of agricultural waste [WWW Document]. URL http://www3.cec.org/islandora/es/item/11405-la-quema-de-residuos-agr-colas-es-una-fuente-de-dioxinas-es.pdf (accessed 3.21.20).

Chiteculo, V., Lojka, B., Surový, P., Verner, V., Panagiotidis, D., Woitsch, J., 2018. Value Chain of Charcoal Production and Implications for Forest Degradation: Case Study of Bié Province, Angola. Environments 5, 113. https://doi.org/10.3390/environments5110113

Dresen, E., DeVries, B., Herold, M., Verchot, L., Müller, R., 2014. Fuelwood Savings and Carbon Emission Reductions by the Use of Improved Cooking Stoves in an Afromontane Forest, Ethiopia. Land 3, 1137–1157. https://doi.org/10.3390/land3031137

FAO, 2015. World food production [WWW Document]. URL https://perspective.usherbrooke.ca/bilan/servlet/BMTendanceStatPays?codeTheme=5&codeStat=RS.NUT.PROD.PP.MT&codePays=COD&optionsPeriodes=Aucune&codeTheme2=5&codeStat2=RSA.FAO.RicePaddy&codePays2=COD&optionsDetPeriodes=avecNomP&langue=fr (accessed 8.7.20).

FAO and UNEP, 2020. The State of the World's Forests 2020. https://doi.org/10.4060/ca8642en

GACC, 2014. The Water Boiling Test.

Gitau, J.K., Sundberg, C., Mendum, R., Mutune, J., Njenga, M., 2019. Use of Biochar-Producing Gasifier Cookstove Improves Energy Use Efficiency and Indoor Air Quality in Rural Households. Energies 12, 4285. https://doi.org/10.3390/en12224285

Hurtado Pérez, E.J., Mulumba Ilunga, O., Moros Gómez, M.C., Vargas Salgado, C., 2017. Analyse des impacts économico-environnementaux du changement d'usage d'un foyer de cuisson traditionnel par un foyer de cuisson amélioré optimisé à charbon de bois dans les ménages de la ville de Kinshasa. Déchets, Sci. Tech. https://doi.org/10.4267/dechets-sciences-techniques.3714

IEA, 2018. World Energy Outlook.

IEA, 2017a. World Energy Outlook.

Jagger, P., Das, I., 2018. Implementation and scale-up of a biomass pellet and improved cookstove enterprise in Rwanda. Energy Sustain. Dev. 46, 32–41. https://doi.org/10.1016/j.esd.2018.06.005

Jetter, J.J., Kariher, P., 2009. Solid-fuel household cook stoves: Characterization of performance and emissions. Biomass and Bioenergy 33, 294–305. https://doi.org/10.1016/j.biombioe.2008.05.014

Jones, D., Ryan, C.M., Fisher, J., 2016. Charcoal as a diversification strategy: The flexible role of charcoal production in the livelihoods of smallholders in central Mozambique. Energy Sustain. Dev. 32, 14–21. https://doi.org/10.1016/j.esd.2016.02.009

Kirch, T., Medwell, P.R., Birzer, C.H., van Eyk, P.J., 2020. Feedstock Dependence of Emissions from a Reverse-Downdraft Gasifier Cookstove. Energy Sustain. Dev. 56, 42–50. https://doi.org/10.1016/j.esd.2020.02.008

Kumar, S.S., Pitchandi, K., Natarajan, E., 2008. Modeling and simulation of down draft wood gasifier. J. Appl. Sci. 8, 271–279. https://doi.org/10.3923/jas.2008.271.279

Lombardi, F., Riva, F., Bonamini, G., Barbieri, J., Colombo, E., 2017. Laboratory protocols for testing of Improved Cooking Stoves (ICSs): A review of state-of-the-art and further developments. Biomass and Bioenergy. https://doi.org/10.1016/j.biombioe.2017.02.005

Lombardi, F., Riva, F., Colombo, E., 2018. Dealing with small sets of laboratory test replicates for Improved Cooking Stoves (ICSs): Insights for a robust statistical analysis of results. Biomass and Bioenergy 115, 27–34. https://doi.org/10.1016/j.biombioe.2018.04.004

Loo, J., Hyseni, L., Ouda, R., Koske, S., Nyagol, R., Sadumah, I., Bashin, M., Sage, M., Bruce, N., Pilishvili, T., Stanistreet, D., 2016. User Perspectives of Characteristics of Improved Cookstoves from a Field Evaluation in Western Kenya. Int. J. Environ. Res. Public Health 13, 167. https://doi.org/10.3390/ijerph13020167

Lynch, M., 2002. Reducing Environmental Damage Caused by the Collection of Cooking Fuel by Refugees. Refug. Canada’s J. Refug. 18–27. https://doi.org/10.25071/1920-7336.21280

MacCarty, N., Ogle, D., Still, D., Bond, T., Roden, C., 2008. A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. Energy Sustain. Dev. 12, 56–65. https://doi.org/10.1016/S0973-0826(08)60429-9

Maes, W.H., Verbist, B., 2012. Increasing the sustainability of household cooking in developing countries: Policy implications. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2012.03.031

Ministry of Agriculture, 2012. Production, sustainable consumption and agricultural waste [WWW Document]. URL https://www.miteco.gob.es/images/es/Residuos agrarios_tcm30-193059.pdf (accessed 3.21.20).

Mukunda, H., 2009. Understanding Combustion, 2nd ed. Universities Press.

Mwampamba, T.H., Ghilardi, A., Sander, K., Chaix, K.J., 2013. Dispelling common misconceptions to improve attitudes and policy outlook on charcoal in developing countries. Energy Sustain. Dev. https://doi.org/10.1016/j.esd.2013.01.001

Ndindeng, S.A., Wopereis, M., Sanyang, S., Futakuchi, K., 2019. Evaluation of fan-assisted rice husk fuelled gasifier cookstoves for application in sub-Sahara Africa. Renew. Energy 139, 924–935. https://doi.org/10.1016/j.renene.2019.02.132

Ojolo, S.J., Abolarin, S.M., Adegbenro, O., 2012. Development of a Laboratory Scale Updraft Gasifier. Int. J. Manuf. Syst. 2, 21–42. https://doi.org/10.3923/ijmsaj.2012.21.42

Panwar, N.L., 2009. Design and performance evaluation of energy efficient biomass gasifier based cookstove on multi fuels. Mitig. Adapt. Strateg. Glob. Chang. 14, 627–633. https://doi.org/10.1007/s11027-009-9187-4

Panwar, N.L., Kurchania, A.K., Rathore, N.S., 2009. Mitigation of greenhouse gases by adoption of improved biomass cookstoves. Mitig. Adapt. Strateg. Glob. Chang. 14, 569–578.

https://doi.org/10.1007/s11027-009-9184-7

Panwar, N.L., Rathore, N.S., 2008. Design and performance evaluation of a 5 kW producer gas stove. Biomass and Bioenergy 32, 1349–1352. https://doi.org/10.1016/j.biombioe.2008.04.007

Ramanathan, V., Carmichael, G., 2008. Global and regional climate changes due to black carbon. Nat. Geosci. https://doi.org/10.1038/ngeo156

Smith, K.R., Dutta, K., Chengappa, C., Gusain, P.P.S., Berrueta, O.M. and V., Edwards, R., Bailis, R., Shields, K.N., 2007. Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: conclusions from the Household Energy and Health Project. Energy Sustain. Dev. 11, 5–18. https://doi.org/10.1016/S0973-0826(08)60396-8

Smith, K.R., Uma, R., Kishore, V.V.N., Zhang, J., Joshi, V., Khalil, M.A.K., 2000. Greenhouse Implications of Household Stoves: An Analysis for India. Annu. Rev. Energy Environ. 25, 741–763. https://doi.org/10.1146/annurev.energy.25.1.741

Technical Management Board, 2012. Guidelines for evaluating cookstove performance [WWW Document]. URL https://www.iso.org/standard/61975.html (accessed 3.21.20).

Tucho, G., Nonhebel, S., 2015. Bio-Wastes as an Alternative Household Cooking Energy Source in Ethiopia. Energies 8, 9565–9583. https://doi.org/10.3390/en8099565

UN, 2021. Small-Scale Methodology: Energy Efficiency Measures in Thermal Applications ofNon-Renewable Biomass [WWW Document]. URL https://cdm.unfccc.int/methodologies/DB/ZI2M2X5P7ZLRGFO37YBVDYOW62UHQP (accessed 12.9.19).

Zhang, Y., Zhang, Z., Zhou, Y., Dong, R., 2018. The Influences of Various Testing Conditions on the Evaluation of Household Biomass Pellet Fuel Combustion. Energies 11, 1131. https://doi.org/10.3390/en11051131

Zongxi, Z., Zhenfeng, S., Yinghua, Z., Hongyan, D., Yuguang, Z., Yixiang, Z., Ahmad, R., Pemberton-Pigott, C., Renjie, D., 2017. Effects of biomass pellet composition on the thermal and emissions performances of a TLUD cooking stove. Int. J. Agric. Biol. Eng. 10, 189–197. https://doi.org/10.25165/j.ijabe.20171004.2963

Chapter 3.
General discussion of the results

This chapter presents a general discussion of the results obtained in the thesis, namely about the ones presented in the previously scientific publications (chapter 2).

On the one hand, scientific publications 1, 2 and 3 addressed the use of advanced renewable systems to approach the main energetic issue in developed countries: negative environmental impact of traditional transport sector, whose results are now discussed.

The first publication proposed EVs as an environmental solution for transport sector in developed countries, as long as their introduction is accompanied by a decarbonization of the electricity generation system. Thus, the paper presented a methodology to verify the suitability of urban transport electrification. By means of the tool WtW, it calculated and compared total CO_2 emissions of equivalent fleets of ICEVs and EVs. Then, the method searched for a certain level of emissions reduction by an iterative introduction of renewable sources to the electricity generation system. The study was applied to the case study of Spain by the mid-term future, since its policies forecast a high penetration of EVs and a progressive introduction of renewable sources into the electricity mix for such period. Two scenarios for this application were studied: one in which only a net emissions balance was looked for and another one in which also a particular sustainability degree in terms of emissions reductions was searched, both regarding the introduction of EVs in the urban fleet. Referring to the first scenario, results revealed that the current Spanish electricity mix (318 gCO_2/kWh) ensures a net emissions introduction of EVs. In this scenario, the highest reduction was forecasted by 2040 and corresponded to 56 CO_2 million tons compared to ICEVs (58%). Regarding the second scenario, the CI of the electricity mix decreased progressively with the introduction of renewable sources until 59 g CO_2/kWh in 2040 (82% reduction). Hence, the contribution to CO_2 emissions of BEVs and PHEVS decreased to 82% and 26% due to their complete and partial electrical behavior, respectively. Finally, the highest emission reduction in this scenario was expected again by 2040, and corresponded to 74 CO_2 million tons (77%).

As publication 1 indicates, the introduction of EVs is expected to happen in large-scale for developed countries by the mid-term future. Such massive penetration would create negative impacts on the electricity grid. Therefore, the second publication handled this question and presented a methodology to shift the load increase due to the expected introduction of EVs making use of the temporal valleys in electricity demand curves and searching for a flat demand profile. For this issue, the method contemplated three different recharging strategies according to the place and type of recharge: at home, at public buildings or at EVCS. Following suitability reasons explained above for publication 1, this paper contemplated again the case study of Spain by the mid-term future. In this case, three levels of penetration (25%, 50% and 75%) together with three scenarios of EVs growth (low, medium and high) were analyzed. Results indicated that it is possible to maintain the current Spanish peak load of 37.8 GW and achieve an almost flat demand profile of 0.972. Only in the cases of the medium growth scenario with a 75% introduction of EVs and in the high growth scenario with a 50% and 75% of EVs was it obligatory to increase the peak value up to 5%, 7% and 11.4%, respectively. However, in all these three cases an almost flat profile, higher than 0.95, was achieved. Moreover, home recharge strategy arose as the dominant option, with an average share of 50%, mainly concentrated in peak hours.

The third publication presented HRES for EVCS as a solution to cope with the two questions presented in publications 1 and 2: the necessary decarbonization of the electric transport and the negative impact of a massive introduction of such vehicles in the grid. To this issue, paper 3 presented a novel weighted multicriteria methodology based on environmental, economic and technical criteria, to design optimal HRES for EVCS. Furthermore, the method included an experimental stage to verify the design derived from the multicriteria phase. The method was applied to Valencia (Spain), which is immersed in a deep transition towards a sustainable mobility. Simulation results pointed to an off-grid HRES with solar PV, wind and batteries as the most suitable configuration, followed by another off-grid HRES with the same energy resources and a diesel generator back-up. The third highest scored configuration was an on grid HRES with the same renewable resources. These three selected options were experimentally tested in the Laboratory of Distributed Energy Resources at the Polytechnic University of Valencia (Spain) with a scale factor of 1:250. Outcomes demonstrated that the demand was covered with all the configurations, with maximum power losses of 4.5% and SOC of batteries between 35% and 100%.

On the other hand, scientific publications 4, 5 and 6 addressed the use of advanced renewable systems to approach the main energetic issue in developing countries: energy poverty (inaccessibility to electricity and clean cooking), whose results are now discussed.

The fourth publication presented an easily applicable methodology to calculate the best design for off grid HRES in remote areas. The method was based on technical requirements such as renewable resources availability, security of supply, power losses… The methodology was applied to a specific case study: the rural village of Masitala, in Malawi (Africa). Results pointed to a HRES with solar PV, wind and biomass resources supported by a group of batteries as the ideal off grid HRES for Masitala. Solar PV technology contributed the most to the energy generation, followed by wind. Biomass was only used promptly some days due to its dispatchable behavior. Moreover, results showed that the studied method allows for an off grid HRES easy design tool, which can be approached not only by the scientific community, but also by technical students, early researchers or users with a previous engineering background.

As many of its previous researches, publication 4 considered technical criteria for the design of HRES in remote areas. Hence, the fifth publication addressed this issue and provided a novel methodology for experimented researchers to assess all the influential criteria in the optimal design of HRES for remote areas. The method included context analysis, literature review and the application of the MCDM tool ANP, with the aid of a panel of experts. To verify the suitability of the methodology, it was applied to the rural community of “El Santuario”, which is placed in the Mesoamerican Dry Corridor in Honduras. Results showed that influential criteria in the design of HRES for off grid rural areas could be grouped in five different clusters: economic, environmental, institutional, social and technical. The most influential criteria for “El Santuario” were the institutional support, the possible expansion of the grid to the community and the availability of local energy resources. These factors determined which renewable energy resources for a HRES in “El Santuario” were preferred: solar PV followed by wind, and a biomass gasifier as support.

Finally, the sixth publication tackled the inaccessibility to clean cooking systems in remote areas. The study presented a thermodynamic, economic and environmental comparison of TCS and ICS-G performed with two laboratory test methods: Water Boiling test and Controlled Cooking Test. The research was conducted in Bandudu, an agricultural region 409 km away from Kinshasha, the capital city of the Democratic Republic of Congo. The analysis considered two types of fuels: charcoal, which is the traditional fuel for cooking stoves in the community, and briquettes, which is an alternative fuel derived from agricultural wastes of Bandudu with appropriate thermo-physical properties. Results indicated that ICS-G reduces fuel consumption of both charchoal and briquettes in 61% compared to TCS. However, using briquettes as fuel allowed for a reduction of 41% and 67% of carbon monoxide, and 84% of 93% of fine particles during high and low power phases of the tests, respectively. Outcomes revealed also that utilizing ICS-G with briquettes instead of TCS with charcoal derives in cooking time reduction of 18%, economic savings of 353.5$/year per family and emissions decrease of 3.2 tCO_2/year per family.

Chapter 4.
Conclusions

This chapter presents the main conclusions extracted from this scientific work. Firstly, it analyses the fulfilment of the proposed goals. Secondly, the main contributions of thisdoctoral thesis to the scientific knowledge are shown. Finally, the section introduces the new research lines derived from this thesis.

4.1. Goals fulfilment

The goals proposed for this thesis have been achieved along the doctoral dissertation, as this section demonstrates.

The first objective "Identification of the main energetic issues for both developed and developing countries and literature review about renewable energy solutions to address the identified problems" was solved along chapter 1. Firstly, section 1.1. of this chapter presented an extended scientific revision about the role of energy for the sustainable development together with the identification of the energy problems for developed and developing countries. It also reflected the great differences between both energy issues. By means of an extensive literature review, section 1.2 distinguished the appropriate renewable advanced systems to face the energy challenges: strategic renewable energy planning, EVs, EVCS, HRES and ICS-G.

Referring to the second goal "Renewable energy planning and recharging strategies development for electric transport decarbonization in industrialized countries", publication 1 and publication 2 approached it. Firstly, publication 1 proposed a method to introduce renewable resources into the electricity generation system to achieve a sustainable introduction of the expected massive EVs fleet. Then, publication 2 addressed this EVs large-scale introduction with a load-shifting method to avoid negative impacts on the grid. This method aimed to achieve a flat load demand considering three recharge strategies: at home, at public building and at EVCS.

Publication 3 solved the third objective "EVCS HRES characterization for sustainable EVs introduction in developed communities". This paper provided a multicriteria design tool for EVCS HRES, based on economic, technical and environmental factors. Besides, it included an experimental validation stage. Results demonstrated that the final design for the HRES in EVCS was supported not only by a complete numerical evaluation, but also by an experimental verification of the demand being fully covered.

Regarding the fourth aim "HRES characterization for electricity access in remote developing communities", it was sorted out with publication 4 and publication 5. On the one hand, publication 4 provided an easily applicable off grid HRES design method based on technical requirements to boost rural electrification. On the other hand, publication 5 introduced all the influential criteria on HRES design for isolated areas, having been some of them traditionally neglected despite their importance.

Finally, publication 6 shed light on the fifth objective "ICS-G characterization for clean energy cooking systems access in remote developing areas". Specifically, this paper compared ICS-G with TCS using traditional and alternative fuels: charcoal and briquettes, respectively. All the experimental validations demonstrated the technical, economic, environmental and social suitability of the advanced renewable ICS-G and briquettes.

4.2. Main contributions

The thesis participates in the scientific knowledge with some specific contributions, as this section shows.

Firstly, the thesis includes two new methodologies to enhance a sustainable introduction of EVs. On the one hand, the new methodology included in publication 1 determines the necessary renewable contribution to the electricity mix to ensure a net emissions balance based on WtW tool for the expected EVs fleet. On the other hand, the novel method presented in publication 2 develops a load-shifting strategy to avoid negative impacts on the grid with the massive forecasted penetration of EVs. Both researches provide helpful tools for policy makers on transition towards sustainable transport electrification.

Secondly, the dissertation proposes a novel method to design HRES for EVCS presented in publication 3. It includes a complete weighted multicriteria method, based on technical, economic and environmental factors, together with an experimental validation stage. This method aims the development of HRES for EVCS, which will promote a sustainable introduction of EVs and relieve their negative impacts on the grid.

Thirdly, this thesis provides two novel methodologies to boost rural electrification by means of off-grid HRES. The first one, introduced in publication 4, is a new and easily applicable method to design HRES in remote areas. It bridges the gap between this kind of systems and non-experts technicians willing to fight against electricity inaccessibility. The second one, presented in publication 5, is a novel methodology based on ANP to design HRES in isolated communities. It considers all influential criteria on the system, having been some of them traditionally neglected despite their importance. This method is mainly focused to advanced researchers with vast experience on the field.

Finally, the thesis introduces a breakthrough ICS-G model and alternative fuel (briquettes) to enhance access to clean and sustainable energy cooking systems in developing countries. This novelty was published in publication 6, where all their technical, economic, environmental and social improvements compared to TCS and traditional charcoal fuel were described.

To conclude, this doctoral dissertation contributes to the scientific knowledge with the above mentioned scientific methods to improve renewable advanced systems. Hence, this thesis demonstrates not only the suitability of these systems for sustainable energy development but also their versatility of application depending on the progress level of the communities.

4.3. Future research lines

The research developed during the PhD program have led to some new research lines based on the thesis.

Firstly, the multicriteria methodology for HRES in EVCS have been applied to developed communities. Their adaptation and later application to remote villages with and without HRES for electricity access would define another future research line.

Secondly, the assessment of the barriers to the introduction of EVs in urban mobility by MCDM methods, such as ANP, results necessary for further research.

The third research line includes studies about optimal location of recharging points or EVCS in urban areas considering technical, environmental and social aspects. For instance, grid proximity or solar PV self-consumption possibilities.

Another line of investigation contemplates the adjustment of general demand loads to specific patterns. Specifically, the adjustment of proposed EVs recharging strategies to cope with a massive introduction of renewable technologies in electricity generation systems.

Finally, it would be of utmost importance to investigate about energy management technics for remote villages with HRES for electricity access. These technics would need to deal with different load demands due to distinct energy requirements, facing also social criteria.

The research team would like to address in parallel the above-mentioned research lines in the near future.

Chapter 5.
Bibliography

Abaye, A.E., Haro, R.D., 2018. Assessment of resource potential and feasibility study of standalone PV - Wind-biogas hybrid system for rural electrification, in: 2018 2nd International Conference on Electronics, Materials Engineering and Nano-Technology, IEMENTech 2018. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/IEMENTECH.2018.8465317

Abbas, M.K., Qadeer-Ul-Hasan, 2015. Economic power generation for an off-grid site in Pakistan, in: 2015 Power Generation Systems and Renewable Energy Technologies, PGSRET 2015. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/PGSRET.2015.7312189

ACA, 2021. What is the energy poverty? [WWW Document]. URL https://www.cienciasambientales.org.es/index.php/ique-es-la-pobreza-energetica (accessed 2.24.21).

Academic Press, 2017. Units and conversion factors, in: Renewable Energy. Elsevier, pp. xxvii–xxix. https://doi.org/10.1016/b978-0-12-804567-1.00017-7

Acciona, 2020. Hydroelectric power [WWW Document]. URL https://www.acciona-energia.com/es/areas-de-actividad/otras-tecnologias/hidroelectrica/ (accessed 7.8.20).

Adnan, N., Nordin, S.M., Rahman, I., Amini, M.H., 2017. A market modeling review study on predicting Malaysian consumer behavior towards widespread adoption of PHEV/EV. Environ. Sci. Pollut. Res. 24, 17955–17975. https://doi.org/10.1007/s11356-017-9153-8

AECC, 2018. Recharge electric vehicles [WWW Document]. URL http://www.aedecc.com/enlaces-de-interes/informacion-estadistica/ (accessed 8.5.19).

AENOR, 2020. UNE standards [WWW Document]. URL https://www.aenor.com/normas-y-libros/buscador-de-normas?k=(i:7516040) (accessed 3.21.20).

Ahmadi, L., Croiset, E., Elkamel, A., Douglas, P., Unbangluang, W., Entchev, E., 2012. Impact of PHEVs Penetration on Ontario's Electricity Grid and Environmental Considerations. Energies 5, 5019–5037. https://doi.org/10.3390/en5125019

Ahmed, S., Islam, M.T., Karim, M.A., Karim, N.M., 2014. Exploitation of renewable energy for sustainable development and overcoming power crisis in Bangladesh. Renew. Energy. https://doi.org/10.1016/j.renene.2014.07.003

Akikur, R.K., Saidur, R., Ping, H.W., Ullah, K.R., 2013. Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.06.043

Akitt, J.W., 2018. Some observations on the greenhouse effect at the Earth's surface. Spectrochim. Acta Part A Mol. Biomol. Spectrosc. 188, 127–134. https://doi.org/10.1016/J.SAA.2017.06.051

Aklin, M., Cheng, C.-Y., Urpelainen, J., 2018. Social acceptance of new energy technology in developing countries: A framing experiment in rural India. Energy Policy 113, 466–477. https://doi.org/10.1016/J.ENPOL.2017.10.059

Al-Alawi, B.M., Bradley, T.H., 2013. Review of hybrid, plug-in hybrid, and electric vehicle market modeling Studies. Renew. Sustain. Energy Rev. 21, 190–203. https://doi.org/10.1016/j.rser.2012.12.048

Alam, M.S., Roychowdhury, A., Islam, K.K., Huq, A.M.Z., 1998. A revisited model for the physical quality of life (PQI) as a function of electrical energy consumption. Energy 23, 791–801. https://doi.org/10.1016/S0360-5442(98)00005-X

Alami Merrouni, A., Elwali Elalaoui, F., Mezrhab, Ahmed, Mezrhab, Abdelhamid, Ghennioui, A., 2018. Large scale PV sites selection by combining GIS and Analytical Hierarchy Process. Case study: Eastern Morocco. Renew. Energy 119, 863–873. https://doi.org/10.1016/j.renene.2017.10.044

Aldersey-Williams, J., Rubert, T., 2019. Levelised cost of energy – A theoretical justification and critical assessment. Energy Policy 124, 169–179. https://doi.org/10.1016/j.enpol.2018.10.004

Alhazmi, Y.A., Mostafa, H.A., Salama, M.M.A., 2017. Optimal allocation for electric vehicle charging stations using Trip Success Ratio. Int. J. Electr. Power Energy Syst. 91, 101–116. https://doi.org/10.1016/j.ijepes.2017.03.009

Ali Ahmed, A., Elizondo Azuela, G., Bazilian, M., Bertheau, P., Cader Reiner, C., Kempener, R., Lavagne, O., Saygin, D., Skeer, J., Vinci, S., Gielen, D., 2015. OFF-GRID RENEWABLE ENERGY SYSTEMS: STATUS AND METHODOLOGICAL ISSUES.

Álvarez Fernández, R., 2018. A more realistic approach to electric vehicle contribution to greenhouse gas emissions in the city. J. Clean. Prod. 172, 949–959. https://doi.org/10.1016/j.jclepro.2017.10.158

ANESDOR, 2019. Two wheels vehicles sector in Spain [WWW Document]. URL https://www.anesdor.com/wp-content/uploads/2019/02/190121_PPT_RP_Madrid.pdf (accessed 1.28.20).

ANFAC, 2018. Annual Report [WWW Document]. URL https://anfac.com/categorias_publicaciones/informe-anual/ (accessed 12.5.19).

Arabzadeh Saheli, M., Fazelpour, F., Soltani, N., Rosen, M.A., 2019. Performance analysis of a photovoltaic/wind/diesel hybrid power generation system for domestic utilization in winnipeg, manitoba, canada. Environ. Prog. Sustain. Energy 38, 548–562. https://doi.org/10.1002/ep.12939

Aragonés-Beltrán, P., Chaparro-González, F., Pastor-Ferrando, J.P., Pla-Rubio, A., 2014. An AHP (Analytic Hierarchy Process)/ANP (Analytic Network Process)-based multi-criteria decision approach for the selection of solar-thermal power plant investment projects. Energy 66, 222–238. https://doi.org/10.1016/j.energy.2013.12.016

Aragonés-Beltrán, P., Chaparro-González, F., Pastor-Ferrando, J.P., Rodríguez-Pozo, F., 2010. An ANP-based approach for the selection of photovoltaic solar power plant investment projects. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2009.07.012

Arto, I., Capellán-Pérez, I., Lago, R., Bueno, G., Bermejo, R., 2016. The energy requirements of a developed world. Energy Sustain. Dev. 33, 1–13. https://doi.org/10.1016/j.esd.2016.04.001

Athanasopoulou, L., Bikas, H., Stavropoulos, P., 2018. Comparative Well-to-Wheel Emissions Assessment of Internal Combustion Engine and Battery Electric Vehicles, in: Procedia CIRP. Elsevier B.V., pp. 25–30. https://doi.org/10.1016/j.procir.2018.08.169

Ayodele, E., Misra, S., Damasevicius, R., Maskeliunas, R., 2019. Hybrid microgrid for microfinance institutions in rural areas – A field demonstration in West Africa. Sustain. Energy Technol. Assessments 35, 89–97. https://doi.org/10.1016/j.seta.2019.06.009

Azoumah, Y., Yamegueu, D., Ginies, P., Coulibaly, Y., Girard, P., 2011. Sustainable electricity generation for rural and peri-urban populations of sub-Saharan Africa: The "flexy-energy" concept. Energy Policy 39, 131–141. https://doi.org/10.1016/j.enpol.2010.09.021

Bagher Sadati, S.M., Moshtagh, J., Shafie-khah, M., Rastgou, A., Catalão, J.P.S., 2019. Operational scheduling of a smart distribution system considering electric vehicles parking lot: A bi-level approach. Int. J. Electr. Power Energy Syst. 105, 159–178. https://doi.org/10.1016/J.IJEPES.2018.08.021

Bailis, R., 2004. Controlled Cooking Test (CCT).

Bailis, R., Berrueta, V., Chengappa, C., Dutta, K., Edwards, R., Masera, O., Still, D., Smith, K.R., 2007. Performance testing for monitoring improved biomass stove interventions: experiences of the Household Energy and Health Project This paper is one of six describing work done as part of the Household Energy and Health (HEH) Project. Energy Sustain. Dev. 11, 57–70. https://doi.org/10.1016/S0973-0826(08)60400-7

Baldwin, S.F., 1987. Biomass stoves: engineering design, development, and dissemmination.

Banerjee, S.G., Moreno, F.A., Sinton, J.E., Primiani, T., Seong, J., 2017. Regulatory indicators for sustainable energy : a global scorecard for policy makers.

Baran, R., Legey, L.F.L., 2013. The introduction of electric vehicles in Brazil: Impacts on oil and electricity consumption. Technol. Forecast. Soc. Change 80, 907–917. https://doi.org/10.1016/J.TECHFORE.2012.10.024

Barbieri, J., Parigi, F., Riva, F., Colombo, E., 2018. Laboratory Testing of the Innovative Low-Cost Mewar Angithi Insert for Improving Energy Efficiency of Cooking Tasks on Three-Stone Fires in Critical Contexts. Energies 11, 3463. https://doi.org/10.3390/en11123463

Barbieri, J., Riva, F., Colombo, E., 2017. Cooking in refugee camps and informal settlements: A review of available technologies and impacts on the socio-economic and environmental perspective. Sustain. Energy Technol. Assessments 22, 194–207. https://doi.org/10.1016/j.seta.2017.02.007

Bastida-Molina, P., Alfonso-Solar, D., Vargas-Salgado, C., Montuori, L., 2019. Assessing the increase of solar fields in the Iberian Peninsula. https://doi.org/10.4995/CARPE2019.2019.10205

Bastida-Molina, P., Hurtado-Perez, E., Gomez, M.C.M., Vargas-Salgado, C., 2021. Multicriteria design and experimental verification of hybrid renewable energy systems. Application to electric vehicle charging stations. ArxiV.org.

Bastida-Molina, P., Hurtado-Pérez, E., Peñalvo-López, E., Moros-Gómez, M.C., 2020a. Assessing transport emissions reduction while increasing electric vehicles and renewable generation levels. Transp. Res. Part D Transp. Environ. 88, 102560. https://doi.org/10.1016/j.trd.2020.102560

Bastida-Molina, P., Hurtado-Pérez, E., Pérez-Navarro, Á., Alfonso-Solar, D., 2020b. Light electric vehicle charging strategy for low impact on the grid. Environ. Sci. Pollut. Res. 1–17.

https://doi.org/10.1007/s11356-020-08901-2

Bastida-Molina, P., Hurtado-Pérez, E., Vargas-Salgado, C., Ribó-Pérez, D., 2020c. Microrredes híbridas, una solución para países en vías de desarrollo. Técnica Ind. 325, 28–34. https://doi.org/10.23800/10218

Bastida Molina, P., 2018. Diseño de un sistema híbrido de energía para el suministro eléctrico a una comunidad aislada de 50 kW de potencia máxima a través de recursos solares, eólicos y de biomasa. RiuNET.

Bastida Molina, P., Saiz Jiménez, J.Á., Molina Palomares, M.P., Álvarez Valenzuela, B., 2017. Instalaciones solares fotovoltaicas de autoconsumo para pequeñas instalaciones. Aplicación a una nave industrial. 3C Tecnol. 1–14. https://doi.org/http://dx.doi.org/10.17993/3ctecno.2017.v6n1e21.1-14

Baurzhan, S., Jenkins, G.P., 2016. Off-grid solar PV: Is it an affordable or appropriate solution for rural electrification in Sub-Saharan African countries? Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2016.03.016

Bekele, G., Tadesse, G., 2012. Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia. Appl. Energy 97, 5–15. https://doi.org/10.1016/j.apenergy.2011.11.059

Belonio, A.T., 2005. Rice Husk Gas Stove Handbook.

Bensch, G., Peters, J., Sievert, M., 2017. The lighting transition in rural Africa — From kerosene to battery-powered LED and the emerging disposal problem. Energy Sustain. Dev. 39, 13–20. https://doi.org/10.1016/j.esd.2017.03.004

Berrueta, V.M., Edwards, R.D., Masera, O.R., 2008. Energy performance of wood-burning cookstoves in Michoacan, Mexico. Renew. Energy 33, 859–870. https://doi.org/10.1016/j.renene.2007.04.016

Bhandari, B., Lee, K.T., Lee, C.S., Song, C.K., Maskey, R.K., Ahn, S.H., 2014. A novel off-grid hybrid power system comprised of solar photovoltaic, wind, and hydro energy sources. Appl. Energy 133, 236–242. https://doi.org/10.1016/j.apenergy.2014.07.033

Bhattacharyya, S.C., 2012. Review of alternative methodologies for analysing off-grid electricity supply. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2011.08.033

Bhojvaid, V., Jeuland, M., Kar, A., Lewis, J., Pattanayak, S., Ramanathan, N., Ramanathan, V., Rehman, I., 2014. How do People in Rural India Perceive Improved Stoves and Clean Fuel? Evidence from Uttar Pradesh and Uttarakhand. Int. J. Environ. Res. Public Health 11, 1341–1358. https://doi.org/10.3390/ijerph110201341

Bhowmik, C., Bhowmik, S., Ray, A., 2018. Social acceptance of green energy determinants using principal component analysis. Energy 160, 1030–1046. https://doi.org/10.1016/j.energy.2018.07.093

Bhuiyan, M.M.H., Ali Asgar, M., 2003. Sizing of a stand-alone photovoltaic power system at Dhaka. Renew. Energy 28, 929–938. https://doi.org/10.1016/S0960-1481(02)00154-4

Bhutto, A.W., Bazmi, A.A., Karim, S., Abro, R., Mazari, S.A., Nizamuddin, S., 2019. Promoting sustainability of use of biomass as energy resource: Pakistan's perspective. Environ. Sci.

Pollut. Res. https://doi.org/10.1007/s11356-019-06179-7

Bjerkan, K.Y., Nørbech, T.E., Nordtømme, M.E., 2016. Incentives for promoting Battery Electric Vehicle (BEV) adoption in Norway. Transp. Res. Part D Transp. Environ. 43, 169–180. https://doi.org/10.1016/J.TRD.2015.12.002

Blum, N.U., Sryantoro Wakeling, R., Schmidt, T.S., 2013. Rural electrification through village grids—Assessing the cost competitiveness of isolated renewable energy technologies in Indonesia. Renew. Sustain. Energy Rev. 22, 482–496. https://doi.org/10.1016/J.RSER.2013.01.049

BOE, 2019. TEC/1141/2019 [WWW Document]. URL https://www.boe.es/diario_boe/txt.php?id=BOE-A-2019-16856 (accessed 12.12.19).

Burchart-Korol, D., Jursova, S., Folęga, P., Pustejovska, P., 2020. Life cycle impact assessment of electric vehicle battery charging in European Union countries. J. Clean. Prod. 257, 120476. https://doi.org/10.1016/j.jclepro.2020.120476

Canals Casals, L., Martinez-Laserna, E., Amante García, B., Nieto, N., 2016. Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction. J. Clean. Prod. 127, 425–437. https://doi.org/10.1016/j.jclepro.2016.03.120

CARD, 2013. National Rice Development Strategy.

Castillo-Ramírez, A., Mejía-Giraldo, D., Molina-Castro, J.D., 2017. Fiscal incentives impact for RETs investments in Colombia. Energy Sources, Part B Econ. Planning, Policy 12, 759–764. https://doi.org/10.1080/15567249.2016.1276648

CCA, 2014. Burning of agricultural waste [WWW Document]. URL http://www3.cec.org/islandora/es/item/11405-la-quema-de-residuos-agr-colas-es-una-fuente-de-dioxinas-es.pdf (accessed 3.21.20).

Ceballos Delgado, J.E., Caicedo Bravo, E., Ospina Arango, S., 2016. A Methodological Proposal to Measure the Impact of Electric Vehicles on the Electric Grid. Ingeniería 21, 154–175. https://doi.org/10.14483/udistrital.jour.reving.2016.2.a03

Chamania, S., Chouhan, R., Awasthi, A., Bendell, R., Marsden, N., Gibson, J., Whitaker, I.S., Potokar, T.S., 2015. Pilot project in rural western Madhya Pradesh, India, to assess the feasibility of using LED and solar-powered lanterns to remove kerosene lamps and related hazards from homes. Burns 41, 595–603. https://doi.org/10.1016/j.burns.2014.09.001

Chatterjee, A., Rayudu, R., 2018. Techno-economic analysis of hybrid renewable energy system for rural electrification in India, in: 2017 IEEE Innovative Smart Grid Technologies - Asia: Smart Grid for Smart Community, ISGT-Asia 2017. Institute of Electrical and Electronics Engineers Inc., pp. 1–5. https://doi.org/10.1109/ISGT-Asia.2017.8378470

Chatzimouratidis, A.I., Pilavachi, P.A., 2008. Sensitivity analysis of the evaluation of power plants impact on the living standard using the analytic hierarchy process. Energy Convers. Manag. 49, 3599–3611. https://doi.org/10.1016/j.enconman.2008.07.009

Cherni, J.A., Dyner, I., Henao, F., Jaramillo, P., Smith, R., Font, R.O., 2007. Energy supply for sustainable rural livelihoods. A multi-criteria decision-support system. Energy Policy 35, 1493–1504. https://doi.org/10.1016/j.enpol.2006.03.026

Cherni, J.A., Preston, F., 2007. Rural electrification under liberal reforms: the case of Peru. J. Clean. Prod. 15, 143–152. https://doi.org/10.1016/j.jclepro.2006.01.029

Chica, E., Pérez, J.F., 2019. Development and performance evaluation of an improved biomass cookstove for isolated communities from developing countries. Case Stud. Therm. Eng. 14, 100435. https://doi.org/10.1016/j.csite.2019.100435

Chiteculo, V., Lojka, B., Surový, P., Verner, V., Panagiotidis, D., Woitsch, J., 2018. Value Chain of Charcoal Production and Implications for Forest Degradation: Case Study of Bié Province, Angola. Environments 5, 113. https://doi.org/10.3390/environments5110113

Choi, H., Shin, J., Woo, J.R., 2018. Effect of electricity generation mix on battery electric vehicle adoption and its environmental impact. Energy Policy 121, 13–24. https://doi.org/10.1016/j.enpol.2018.06.013

Choi, W., Song, H.H., 2018. Well-to-wheel greenhouse gas emissions of battery electric vehicles in countries dependent on the import of fuels through maritime transportation: A South Korean case study. Appl. Energy 230, 135–147. https://doi.org/10.1016/j.apenergy.2018.08.092

Chowdhury, N., Hossain, C., Longo, M., Yaïci, W., 2018. Optimization of Solar Energy System for the Electric Vehicle at University Campus in Dhaka, Bangladesh. Energies 11, 2433. https://doi.org/10.3390/en11092433

Chowdhury, T., Chowdhury, H., Miskat, M.I., Chowdhury, P., Sait, S.M., Thirugnanasambandam, M., Saidur, R., 2020. Developing and evaluating a stand-alone hybrid energy system for Rohingya refugee community in Bangladesh. Energy 191, 116568. https://doi.org/10.1016/j.energy.2019.116568

Clairand, J.-M., Rodríguez-García, J., Álvarez-Bel, C., 2018. Electric Vehicle Charging Strategy for Isolated Systems with High Penetration of Renewable Generation. Energies 11, 3188. https://doi.org/10.3390/en11113188

Clement-Nyns, K., Haesen, E., Driesen, J., 2010. The impact of Charging plug-in hybrid electric vehicles on a residential distribution grid. IEEE Trans. Power Syst. 25, 371–380. https://doi.org/10.1109/TPWRS.2009.2036481

Colmenar-Santos, A., Muñoz-Gómez, A.M., Rosales-Asensio, E., López-Rey, Á., 2019. Electric vehicle charging strategy to support renewable energy sources in Europe 2050 low-carbon scenario. Energy 183, 61–74. https://doi.org/10.1016/j.energy.2019.06.118

Corporate Finance Institute, 2020. Levelized Cost of Electricity [WWW Document]. URL https://corporatefinanceinstitute.com/resources/knowledge/finance/levelized-cost-of-energy-lcoe/ (accessed 5.14.20).

Cuenca-García, E., Sánchez, A., Navarro-Pabsdorf, M., 2019. Assessing the performance of the least developed countries in terms of the Millennium Development Goals. Eval. Program Plann. 72, 54–66. https://doi.org/10.1016/j.evalprogplan.2018.09.009

Dai, Q., Cai, T., Duan, S., Zhao, F., 2014. Stochastic modeling and forecasting of load demand for electric bus battery-swap station. IEEE Trans. Power Deliv. 29, 1909–1917. https://doi.org/10.1109/TPWRD.2014.2308990

Dang, Q., 2018. Electric Vehicle (EV) Charging Management and Relieve Impacts in Grids. 9th

IEEE Int. Symp. Power Electron. Distrib. Gener. Syst. https://doi.org/10.1109/PEDG.2018.8447802

Dang, Q., Huo, Y., 2018. Modeling EV fleet Load in Distribution Grids: A Data-Driven Approach, in: 2018 IEEE Transportation Electrification Conference and Expo (ITEC). IEEE, pp. 720–724. https://doi.org/10.1109/ITEC.2018.8450195

Danté, A.W., Agbossou, K., Kelouwani, S., Cardenas, A., Bouchard, J., 2019. Online modeling and identification of plug-in electric vehicles sharing a residential station. Int. J. Electr. Power Energy Syst. 108, 162–176. https://doi.org/10.1016/J.IJEPES.2018.12.024

Das, B.K., Zaman, F., 2019. Performance analysis of a PV/Diesel hybrid system for a remote area in Bangladesh: Effects of dispatch strategies, batteries, and generator selection. Energy 169, 263–276. https://doi.org/10.1016/j.energy.2018.12.014

de Jong, E., Vijge, M.J., 2021. From Millennium to Sustainable Development Goals: Evolving discourses and their reflection in policy coherence for development. Earth Syst. Gov. 7, 100087. https://doi.org/10.1016/j.esg.2020.100087

Deb, P., Mahapatra, S., Rajbongshi, R., Dasappa, S., 2016. BIOMASS GASIFIER BASED HYBRID ENERGY SYSTEM OPTIMIZATION FOR ENERGY ACCESS BY USING HOMER.

Deb, S., Tammi, K., Kalita, K., Mahanta, P., 2018. Impact of Electric Vehicle Charging Station Load on Distribution Network. Energies 11, 178. https://doi.org/10.3390/en11010178

Desai, R.R., Chen, R.B., Armington, W., 2018. A Pattern Analysis of Daily Electric Vehicle Charging Profiles: Operational Efficiency and Environmental Impacts. J. Adv. Transp. 2018, 1–15. https://doi.org/10.1155/2018/6930932

DGT, 2019. Traffic information [WWW Document]. URL http://infocar.dgt.es/etraffic/ (accessed 9.19.19).

DGT, 2017. Vehicle fleet historical data base [WWW Document]. URL http://www.dgt.es/es/seguridad-vial/estadisticas-e-indicadores/parque-vehiculos/series-historicas/ (accessed 1.2.19).

Dhass, A.D., Harikrishnan, S., 2013. Cost effective hybrid energy system employing solar-wind-biomass resources for rural electrification. Int. J. Renew. Energy Res. 3, 222–229. https://doi.org/10.20508/ijrer.50150

Dias, R.A., Mattos, C.R., Balestieri, J.A.P., 2006. The limits of human development and the use of energy and natural resources. Energy Policy 34, 1026–1031. https://doi.org/10.1016/j.enpol.2004.09.008

Díaz, P., Peña, R., Muñoz, J., Arias, C.A., Sandoval, D., 2011. Field analysis of solar PV-based collective systems for rural electrification. Energy 36, 2509–2516. https://doi.org/10.1016/j.energy.2011.01.043

Dickinson, K.L., Piedrahita, R., Coffey, E.R., Kanyomse, E., Alirigia, R., Molnar, T., Hagar, Y., Hannigan, M.P., Oduro, A.R., Wiedinmyer, C., 2019. Adoption of improved biomass stoves and stove/fuel stacking in the REACCTING intervention study in Northern Ghana. Energy Policy 130, 361–374. https://doi.org/10.1016/j.enpol.2018.12.007

Diego Jiménez, J., Maria Vives, S., Guillermo Jiménez, E., Patricio Mendoza, A., 2017.

Development of a methodology for planning and design of microgrids for rural electrification, in: 2017 CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies, CHILECON 2017 - Proceedings. Institute of Electrical and Electronics Engineers Inc., pp. 1–6. https://doi.org/10.1109/CHILECON.2017.8229558

Dieterich, M., 2018. Sustainable development as a driver for innovation and employment. Int. J. Innov. Sustain. Dev. 12, 2. https://doi.org/10.1504/IJISD.2018.10009931

Dijk, M., Orsato, R.J., Kemp, R., 2013. The emergence of an electric mobility trajectory. Energy Policy 52, 135–145. https://doi.org/10.1016/J.ENPOL.2012.04.024

Dino, I.G., Meral Akgül, C., 2019. Impact of climate change on the existing residential building stock in Turkey: An analysis on energy use, greenhouse gas emissions and occupant comfort. Renew. Energy 141, 828–846. https://doi.org/10.1016/j.renene.2019.03.150

Dixon, J., Bukhsh, W., Edmunds, C., Bell, K., 2020. Scheduling electric vehicle charging to minimise carbon emissions and wind curtailment. Renew. Energy 161, 1072–1091. https://doi.org/10.1016/j.renene.2020.07.017

Domenech, B., Ferrer-Martí, L., Pastor, R., 2015. Including management and security of supply constraints for designing stand-alone electrification systems in developing countries. Renew. Energy 80, 359–369. https://doi.org/10.1016/j.renene.2015.02.033

Domínguez-Navarro, J.A., Dufo-López, R., Yusta-Loyo, J.M., Artal-Sevil, J.S., Bernal-Agustín, J.L., 2019. Design of an electric vehicle fast-charging station with integration of renewable energy and storage systems. Int. J. Electr. Power Energy Syst. 105, 46–58. https://doi.org/10.1016/j.ijepes.2018.08.001

Dong, X., Wang, B., Yip, H.L., Chan, Q.N., 2019. CO2 Emission of Electric and Gasoline Vehicles under Various Road Conditions for China, Japan, Europe and World Average—Prediction through Year 2040. Appl. Sci. 9, 2295. https://doi.org/10.3390/app9112295

Dresen, E., DeVries, B., Herold, M., Verchot, L., Müller, R., 2014. Fuelwood Savings and Carbon Emission Reductions by the Use of Improved Cooking Stoves in an Afromontane Forest, Ethiopia. Land 3, 1137–1157. https://doi.org/10.3390/land3031137

Driscoll, Á., Lyons, S., Mariuzzo, F., Tol, R.S.J., 2013. Simulating demand for electric vehicles using revealed preference data. Energy Policy 62, 686–696. https://doi.org/10.1016/j.enpol.2013.07.061

Dufo-López, R., Cristóbal-Monreal, I.R., Yusta, J.M., 2016. Optimisation of PV-wind-diesel-battery stand-alone systems to minimise cost and maximise human development index and job creation. Renew. Energy 94, 280–293. https://doi.org/10.1016/j.renene.2016.03.065

Duran, A.S., Sahinyazan, F.G., 2020. An analysis of renewable mini-grid projects for rural electrification. Socioecon. Plann. Sci. https://doi.org/10.1016/j.seps.2020.100999

Dutta, R., 2019. Use of Clean, Renewable and Alternative Energies in Mitigation of Greenhouse Gases, in: Reference Module in Materials Science and Materials Engineering. Elsevier. https://doi.org/10.1016/b978-0-12-803581-8.11048-3

Edwards, R. (Jrc/Ies), Larive, J.-F. (Concawe), Mahieu, V. (Jrc/Ies), Rounveirolles, P. (Renault),

2007. Well-to-Wheels analysis of future automotive fuels and well-to-wheels Report. Europe Version 2c, 88. https://doi.org/10.2788/79018

Ehrenberger, S.I., Dunn, J.B., Jungmeier, G., Wang, H., 2019. An international dialogue about electric vehicle deployment to bring energy and greenhouse gas benefits through 2030 on a well-to-wheels basis. Transp. Res. Part D Transp. Environ. 74, 245–254. https://doi.org/10.1016/j.trd.2019.07.027

Elisa, P., Alessandro, P., Andrea, A., Silvia, B., Mathis, P., Dominik, P., Manuela, R., Francesca, T., Voglar, G.E., Tine, G., Nike, K., Thomas, S., 2020. Environmental and climate change impacts of eighteen biomass-based plants in the alpine region: A comparative analysis. J. Clean. Prod. 242. https://doi.org/10.1016/j.jclepro.2019.118449

Erdinc, O., Uzunoglu, M., 2012. Optimum design of hybrid renewable energy systems: Overview of different approaches. Renew. Sustain. Energy Rev. 16, 1412–1425. https://doi.org/10.1016/J.RSER.2011.11.011

ETECNIC, 2020. MOVES Plan 2020: financial support for electric cars and charging points [WWW Document]. URL https://etecnic.es/noticias/sector/ayudas-subvenciones/plan-moves-2020/ (accessed 7.7.20).

Eurostat, 2018. Database - Eurostat [WWW Document]. URL https://ec.europa.eu/eurostat/web/lfs/data/database (accessed 8.2.19).

Ezbakhe, F., Pérez-Foguet, A., 2021. Decision analysis for sustainable development: The case of renewable energy planning under uncertainty. Eur. J. Oper. Res. 291, 601–613. https://doi.org/10.1016/j.ejor.2020.02.037

Fandiño-Del-Rio, M., Kephart, J.L., Williams, K.N., Moulton, L.H., Steenland, K., Checkley, W., Koehler, K., 2020. Household air pollution exposure and associations with household characteristics among biomass cookstove users in Puno, Peru. Environ. Res. 191, 110028. https://doi.org/10.1016/j.envres.2020.110028

FAO, 2017. Dry Corridor Central America. Situation Report.

FAO, 2016. Dry Corridor Central America. Situation Report.

FAO, 2015. World food production [WWW Document]. URL https://perspective.usherbrooke.ca/bilan/servlet/BMTendanceStatPays?codeTheme=5&codeStat=RS.NUT.PROD.PP.MT&codePays=COD&optionsPeriodes=Aucune&codeTheme2=5&codeStat2=RSA.FAO.RicePaddy&codePays2=COD&optionsDetPeriodes=avecNomP&langue=fr (accessed 8.7.20).

FAO and UNEP, 2020. The State of the World’s Forests 2020. https://doi.org/10.4060/ca8642en

Fernández-Baldor, Á., Boni, A., Lillo, P., Hueso, A., 2014. Are technological projects reducing social inequalities and improving people’s well-being? A capability approach analysis of renewable energy-based electrification projects in Cajamarca, Peru. J. Hum. Dev. Capab. 15, 13–27. https://doi.org/10.1080/19452829.2013.837035

GACC, 2014. The Water Boiling Test.

Galiveeti, H.R., Goswami, A.K., Dev Choudhury, N.B., 2018. Impact of plug-in electric vehicles and distributed generation on reliability of distribution systems. Eng. Sci. Technol. an Int. J. 21, 50–59. https://doi.org/10.1016/J.JESTCH.2018.01.005

Gallet, M., Massier, T., Hamacher, T., 2018. Estimation of the energy demand of electric buses based on real-world data for large-scale public transport networks. Appl. Energy 230, 344–356. https://doi.org/10.1016/j.apenergy.2018.08.086

Garba, I., Bellingham, R., 2021. Energy poverty: Estimating the impact of solid cooking fuels on GDP per capita in developing countries - Case of sub-Saharan Africa. Energy 221, 119770. https://doi.org/10.1016/j.energy.2021.119770

Georgopoulou, E., Lalas, D., Papagiannakis, L., 1997. A Multicriteria Decision Aid approach for energy planning problems: The case of renewable energy option. Eur. J. Oper. Res. 103, 38–54. https://doi.org/10.1016/S0377-2217(96)00263-9

Gitau, J.K., Sundberg, C., Mendum, R., Mutune, J., Njenga, M., 2019. Use of Biochar-Producing Gasifier Cookstove Improves Energy Use Efficiency and Indoor Air Quality in Rural Households. Energies 12, 4285. https://doi.org/10.3390/en12224285

GIZ, 2016. What size shall it be? A guide to mini-grid sizing and demand forecasting.

Goel, S., Sharma, R., 2017. Performance evaluation of stand alone, grid connected and hybrid renewable energy systems for rural application: A comparative review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2017.05.200

Gómez-Navarro, T., Ribó-Pérez, D., 2018. Assessing the obstacles to the participation of renewable energy sources in the electricity market of Colombia. Renew. Sustain. Energy Rev. 90, 131–141. https://doi.org/10.1016/j.rser.2018.03.015

Gong, L., Cao, W., Liu, K., Zhao, J., Li, X., 2018. Spatial and Temporal Optimization Strategy for Plug-In Electric Vehicle Charging to Mitigate Impacts on Distribution Network. Energies 11, 1373. https://doi.org/10.3390/en11061373

González-Eguino, M., 2015. Energy poverty: An overview. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2015.03.013

GVA, 2017a. Electric Mobility Plan [WWW Document]. URL https://www.gva.es/es/inicio/area_de_prensa/not_detalle_area_prensa?id=860077 (accessed 7.2.20).

GVA, 2017b. Valencian Climate Change and Energy Strategy 2030 [WWW Document]. URL http://www.agroambient.gva.es/es/web/cambio-climatico/2020-2030 (accessed 7.2.20).

Hailu Kebede, M., Bekele Beyene, G., 2018. Feasibility Study of PV-Wind-Fuel Cell Hybrid Power System for Electrification of a Rural Village in Ethiopia. J. Electr. Comput. Eng. 2018. https://doi.org/10.1155/2018/4015354

Hanbar, R.D., Karve, P., 2002. National Programme on Improved Chulha (NPIC) of the Government of India: An overview. Energy Sustain. Dev. 6, 49–55. https://doi.org/10.1016/S0973-0826(08)60313-0

Hansen, J.M., Xydis, G.A., 2020. Rural electrification in Kenya: a useful case for remote areas in sub-Saharan Africa. Energy Effic. 13, 257–272. https://doi.org/10.1007/s12053-018-9756-z

Hansen, K., 2019. Decision-making based on energy costs: Comparing levelized cost of energy and energy system costs. Energy Strateg. Rev. https://doi.org/10.1016/j.esr.2019.02.003

Haralambopoulos, D.A., Polatidis, H., 2003. Renewable energy projects: Structuring a multi-criteria group decision-making framework. Renew. Energy 28, 961–973. https://doi.org/10.1016/S0960-1481(02)00072-1

Harijan, K., Uqaili, M.A., 2013. Potential of Biomass Conservation Through Dissemination of Efficient Cook Stoves in Pakistan. APCBEE Procedia 5, 358–362. https://doi.org/10.1016/j.apcbee.2013.05.061

Hasan, M.A., Frame, D.J., Chapman, R., Archie, K.M., 2019. Emissions from the road transport sector of New Zealand: key drivers and challenges. Environ. Sci. Pollut. Res. 26, 23937–23957. https://doi.org/10.1007/s11356-019-05734-6

Hass, H., Huss, A., Maas, H., 2014. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context: Tank-to-Wheels Appendix 1 - Version 4.a, Joint Research Centre of the European Commission, EUCAR, and CONCAWE. https://doi.org/10.2790/95839

He, X.., Reiner, D., 2014. Electricity Demand and Basic Needs: Empirical Evidence from China's Households. Cambridge Work. Pap. Econ. https://doi.org/10.17863/CAM.5834

He, Y., Song, Z., Liu, Z., 2019. Fast-charging station deployment for battery electric bus systems considering electricity demand charges. Sustain. Cities Soc. 48, 101530. https://doi.org/10.1016/j.scs.2019.101530

Hidalgo Batista, E.R., Villavicencio Proenza, D.D., 2011. The reliability of stationary internal combustion diesel engines. Rev. Científica Trimest. 1–10.

Hoekstra, A., 2019. The Underestimated Potential of Battery Electric Vehicles to Reduce Emissions. Joule. https://doi.org/10.1016/j.joule.2019.06.002

HOMER, 2020. Hybrid Renewable and Distributed Generation System Design Software [WWW Document]. URL https://www.homerenergy.com/ (accessed 5.14.20).

Hu, X., Murgovski, N., Johannesson, L., Egardt, B., 2013. Energy efficiency analysis of a series plug-in hybrid electric bus with different energy management strategies and battery sizes. Appl. Energy 111, 1001–1009. https://doi.org/10.1016/j.apenergy.2013.06.056

Huang, P., Ma, Z., Xiao, L., Sun, Y., 2019. Geographic Information System-assisted optimal design of renewable powered electric vehicle charging stations in high-density cities. Appl. Energy 255, 113855. https://doi.org/10.1016/j.apenergy.2019.113855

Huo, H., Cai, H., Zhang, Q., Liu, F., He, K., 2015. Life-cycle assessment of greenhouse gas and air emissions of electric vehicles: A comparison between China and the U.S. Atmos. Environ. 108, 107–116. https://doi.org/10.1016/j.atmosenv.2015.02.073

Huo, H., Zhang, Q., Wang, M.Q., Streets, D.G., He, K., 2010. Environmental implication of electric vehicles in china. Environ. Sci. Technol. 44, 4856–4861. https://doi.org/10.1021/es100520c

Hurtado, E., Peñalvo-López, E., Pérez-Navarro, Á., Vargas, C., Alfonso, D., 2015. Optimization of a hybrid renewable system for high feasibility application in non-connected zones. Appl.

Energy 155, 308–314. https://doi.org/10.1016/J.APENERGY.2015.05.097

Hurtado Pérez, E., Mulumba Ilunga, O., Alfonso Solar, D., Moros Gómez, M.C., Bastida-Molina, P., 2020. Sustainable Cooking Based on a 3 kW Air-Forced Multifuel Gasification Stove Using Alternative Fuels Obtained from Agricultural Wastes. Sustainability 12, 7723. https://doi.org/10.3390/su12187723

Hurtado Pérez, E.J., Mulumba Ilunga, O., Moros Gómez, M.C., Vargas Salgado, C., 2017. Analyse des impacts économico-environnementaux du changement d'usage d'un foyer de cuisson traditionnel par un foyer de cuisson amélioré optimisé à charbon de bois dans les ménages de la ville de Kinshasa. Déchets, Sci. Tech. https://doi.org/10.4267/dechets-sciences-techniques.3714

Hussain, C.M.I., Norton, B., Duffy, A., 2017. Technological assessment of different solar-biomass systems for hybrid power generation in Europe. Renew. Sustain. Energy Rev. 68, 1115–1129. https://doi.org/10.1016/J.RSER.2016.08.016

IDAE, 2020a. National Integrated Plan about Energy and Climate 2021-2030 [WWW Document]. URL https://www.idae.es/informacion-y-publicaciones/plan-nacional-integrado-de-energia-y-clima-pniec-2021-2030 (accessed 12.13.19).

IDAE, 2020b. Wind resource analyses. Wind atlas of Spain [WWW Document]. URL https://www.idae.es/uploads/documentos/documentos_11227_e4_atlas_eolico_A_9b90ff10.pdf (accessed 7.8.20).

IDAE, 2019. Biomass potential evaluation [WWW Document]. URL https://www.idae.es/uploads/documentos/documentos_11227_e14_biomasa_A_8d51bf1c.pdf (accessed 7.8.20).

IDAE, 2012. Technological electric mobility map [WWW Document]. URL http://www.idae.es/uploads/documentos/documentos_Movilidad_Electrica_ACC_c603f868.pdf (accessed 1.7.19).

IDAE, 2006. Fuel management guide for road transport fleets [WWW Document]. URL https://www.idae.es/uploads/documentos/documentos_10232_Guia_gestion_combustible_flotas_carretera_06_32bad0b7.pdf (accessed 11.14.19).

IDAE - UE, 2019. Hybrid electric buses introduction in the Transport Fleet Company S.A.M [WWW Document]. URL https://www.idae.es/uploads/documentos/documentos_detalle_proyecto_Autobuses_Malaga_c260fac8.pdf (accessed 12.5.19).

IEA, 2018. World Energy Outlook.

IEA, 2017a. World Energy Outlook.

IEA, 2017b. Data & Statistics [WWW Document]. URL https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy consumption&indicator=Oil products final consumption by sector (accessed 2.13.20).

IEA, 2016. Data and statistics [WWW Document]. URL https://www.iea.org/data-and-statistics/data-tables?country=WORLD&energy=Balances&year=2016 (accessed 12.12.19).

IISD, 2021. Sustainable Development [WWW Document]. URL https://www.iisd.org/about-iisd/sustainable-development (accessed 2.16.21).

Ilskog, E., 2008. Indicators for assessment of rural electrification-An approach for the comparison of apples and pears. Energy Policy 36, 2665–2673. https://doi.org/10.1016/j.enpol.2008.03.023

Ilskog, E., Kjellström, B., 2008. And then they lived sustainably ever after?-Assessment of rural electrification cases by means of indicators. Energy Policy 36, 2674–2684. https://doi.org/10.1016/j.enpol.2008.03.022

INE, 2018. Average distance covered by vehicles fleet [WWW Document]. URL http://www.ine.es/jaxi/Tabla.htm?path=/t25/p500/2008/p10/l0/&file=10020.px&L=0 (accessed 12.30.18).

Ingeborgrud, L., Ryghaug, M., 2019. The role of practical, cognitive and symbolic factors in the successful implementation of battery electric vehicles in Norway. Transp. Res. Part A Policy Pract. 130, 507–516. https://doi.org/10.1016/j.tra.2019.09.045

Jagger, P., Das, I., 2018. Implementation and scale-up of a biomass pellet and improved cookstove enterprise in Rwanda. Energy Sustain. Dev. 46, 32–41. https://doi.org/10.1016/j.esd.2018.06.005

Jetter, J.J., Kariher, P., 2009. Solid-fuel household cook stoves: Characterization of performance and emissions. Biomass and Bioenergy 33, 294–305. https://doi.org/10.1016/j.biombioe.2008.05.014

Jeuland, M.A., Pattanayak, S.K., Samaddar, S., Shah, R., Vora, M., 2020. Adoption and impacts of improved biomass cookstoves in rural Rajasthan. Energy Sustain. Dev. 57, 149–159. https://doi.org/10.1016/j.esd.2020.06.005

Jochem, P., Babrowski, S., Fichtner, W., 2015. Assessing CO 2 emissions of electric vehicles in Germany in 2030. Transp. Res. Part A Policy Pract. 78, 68–83. https://doi.org/10.1016/j.tra.2015.05.007

Jones, D., Ryan, C.M., Fisher, J., 2016. Charcoal as a diversification strategy: The flexible role of charcoal production in the livelihoods of smallholders in central Mozambique. Energy Sustain. Dev. 32, 14–21. https://doi.org/10.1016/j.esd.2016.02.009

Joshi, L., Choudhary, D., Kumar, P., Venkateswaran, J., Solanki, C.S., 2019. Does involvement of local community ensure sustained energy access? A critical review of a solar PV technology intervention in rural India. World Dev. 122, 272–281. https://doi.org/10.1016/j.worlddev.2019.05.028

Jyothy, K.R., Raju, C.P., Srinivasarao, R., 2017. Simulation studies on WTG-FC-battery hybrid energy system, in: IEEE International Conference on Innovative Mechanisms for Industry Applications, ICIMIA 2017 - Proceedings. Institute of Electrical and Electronics Engineers Inc., pp. 710–716. https://doi.org/10.1109/ICIMIA.2017.7975557

Kabak, M., Dağdeviren, M., 2014. Prioritization of renewable energy sources for Turkey by using a hybrid MCDM methodology. Energy Convers. Manag. 79, 25–33. https://doi.org/http://dx.doi.org/10.1016/j.enconman.2013.11.036

Kamble, P., Khan, Z., Gillespie, M., Farooq, M., McCalmont, J., Donnison, I., Watson, I., 2019.

Biomass gasification of hybrid seed Miscanthus in Glasgow's downdraft gasifier testbed system, in: Energy Procedia. Elsevier Ltd, pp. 1174–1181. https://doi.org/10.1016/j.egypro.2019.01.303

Kanagawa, M., Nakata, T., 2008. Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries. Energy Policy 36, 2016–2029. https://doi.org/10.1016/j.enpol.2008.01.041

Karmaker, A.K., Ahmed, M.R., Hossain, M.A., Sikder, M.M., 2018. Feasibility assessment & design of hybrid renewable energy based electric vehicle charging station in Bangladesh. Sustain. Cities Soc. 39, 189–202. https://doi.org/10.1016/j.scs.2018.02.035

Kartite, J., Cherkaoui, M., 2019. Study of the different structures of hybrid systems in renewable energies: A review. Energy Procedia 157, 323–330. https://doi.org/10.1016/J.EGYPRO.2018.11.197

Katre, A., Tozzi, A., 2018. Assessing the Sustainability of Decentralized Renewable Energy Systems: A Comprehensive Framework with Analytical Methods. Sustainability 10, 1058. https://doi.org/10.3390/su10041058

Kaygusuz, K., 2012. Energy for sustainable development: A case of developing countries. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2011.11.013

Ke, W., Zhang, S., He, X., Wu, Y., Hao, J., 2017. Well-to-wheels energy consumption and emissions of electric vehicles: Mid-term implications from real-world features and air pollution control progress. Appl. Energy 188, 367–377. https://doi.org/10.1016/j.apenergy.2016.12.011

Khamis, A., Khatib, T., Amira Haziqah Mohd Yosliza, N., Nazmin Azmi, A., 2020. Optimal selection of renewable energy installation site in remote areas using segmentation and regional technique: A case study of Sarawak, Malaysia. Sustain. Energy Technol. Assessments 42, 100858. https://doi.org/10.1016/j.seta.2020.100858

Khare, V., Nema, S., Baredar, P., 2016. Solar–wind hybrid renewable energy system: A review. Renew. Sustain. Energy Rev. 58, 23–33. https://doi.org/10.1016/J.RSER.2015.12.223

Kim, B., Azzaro-Pantel, C., Pietrzak-David, M., Maussion, P., 2019. Life cycle assessment for a solar energy system based on reuse components for developing countries. J. Clean. Prod. 208, 1459–1468. https://doi.org/10.1016/J.JCLEPRO.2018.10.169

Kirch, T., Medwell, P.R., Birzer, C.H., van Eyk, P.J., 2020. Feedstock Dependence of Emissions from a Reverse-Downdraft Gasifier Cookstove. Energy Sustain. Dev. 56, 42–50. https://doi.org/10.1016/j.esd.2020.02.008

Kobashi, T., Yoshida, T., Yamagata, Y., Naito, K., Pfenninger, S., Say, K., Takeda, Y., Ahl, A., Yarime, M., Hara, K., 2020. On the potential of "Photovoltaics + Electric vehicles" for deep decarbonization of Kyoto's power systems: Techno-economic-social considerations. Appl. Energy 275, 115419. https://doi.org/10.1016/j.apenergy.2020.115419

Kolhe, M.L., Ranaweera, K.M.I.U., Gunawardana, A.G.B.S., 2015. Techno-economic sizing of off-grid hybrid renewable energy system for rural electrification in Sri Lanka. Sustain. Energy Technol. Assessments 11, 53–64. https://doi.org/10.1016/j.seta.2015.03.008

Kosai, S., Nakanishi, M., Yamasue, E., 2018. Vehicle energy efficiency evaluation from well-to-wheel lifecycle perspective. Transp. Res. Part D Transp. Environ. 65, 355–367. https://doi.org/10.1016/j.trd.2018.09.011

Kruyt, B., van Vuuren, D.P., de Vries, H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Policy 37, 2166–2181. https://doi.org/10.1016/j.enpol.2009.02.006

Kshirsagar, M.P., Kalamkar, V.R., 2014. A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.10.039

Kumar, S.S., Pitchandi, K., Natarajan, E., 2008. Modeling and simulation of down draft wood gasifier. J. Appl. Sci. 8, 271–279. https://doi.org/10.3923/jas.2008.271.279

Ladenburg, J., 2009. Visual impact assessment of offshore wind farms and prior experience. Appl. Energy. https://doi.org/10.1016/j.apenergy.2008.05.005

Lai, C.S., Jia, Y., Xu, Z., Lai, L.L., Li, X., Cao, J., McCulloch, M.D., 2017. Levelized cost of electricity for photovoltaic/biogas power plant hybrid system with electrical energy storage degradation costs. Energy Convers. Manag. 153, 34–47. https://doi.org/10.1016/j.enconman.2017.09.076

Lai, C.S., McCulloch, M.D., 2017. Levelized cost of electricity for solar photovoltaic and electrical energy storage. Appl. Energy 190, 191–203. https://doi.org/10.1016/j.apenergy.2016.12.153

Lambert, J.G., Hall, C.A.S., Balogh, S., Gupta, A., Arnold, M., 2014. Energy, EROI and quality of life. Energy Policy 64, 153–167. https://doi.org/10.1016/j.enpol.2013.07.001

Leary, J., Schaube, P., Clementi, L., 2019. Rural electrification with household wind systems in remote high wind regions. Energy Sustain. Dev. 52, 154–175. https://doi.org/10.1016/j.esd.2019.07.008

Lhendup, T., 2008. Rural electrification in Bhutan and a methodology for evaluation of distributed generation system as an alternative option for rural electrification. Energy Sustain. Dev. 12, 13–24. https://doi.org/10.1016/S0973-0826(08)60434-2

Li, J., Gao, S., Xu, B., Chen, H., 2019. Modeling and Controllability Evaluation of EV Charging Facilities Changed from Gas Stations with Renewable Energy Sources, in: 2019 Asia Power and Energy Engineering Conference, APEEC 2019. Institute of Electrical and Electronics Engineers Inc., pp. 269–273. https://doi.org/10.1109/APEEC.2019.8720700

Lillo, P., Ferrer-Martí, L., Boni, A., Fernández-Baldor, Á., 2015. Assessing management models for off-grid renewable energy electrification projects using the Human Development approach: Case study in Peru. Energy Sustain. Dev. 25, 17–26. https://doi.org/10.1016/j.esd.2014.11.003

Limmer, S., Rodemann, T., 2019. Peak load reduction through dynamic pricing for electric vehicle charging. Int. J. Electr. Power Energy Syst. 113, 117–128. https://doi.org/10.1016/J.IJEPES.2019.05.031

Lindgren, S.A., 2020. Clean cooking for all? A critical review of behavior, stakeholder engagement, and adoption for the global diffusion of improved cookstoves. Energy Res. Soc. Sci. https://doi.org/10.1016/j.erss.2020.101539

Liu, F., Zhao, F., Liu, Z., Hao, H., 2018. China's Electric Vehicle Deployment: Energy and Greenhouse Gas Emission Impacts. Energies 11, 3353. https://doi.org/10.3390/en11123353

Liu, Z., Wu, D., He, B.J., Wang, Q., Yu, H., Ma, W., Jin, G., 2019. Evaluating potentials of passive solar heating renovation for the energy poverty alleviation of plateau areas in developing countries: A case study in rural Qinghai-Tibet Plateau, China. Sol. Energy 187, 95–107. https://doi.org/10.1016/j.solener.2019.05.049

Liu, Z., Wu, Q., Nielsen, A., Wang, Y., 2014. Day-Ahead Energy Planning with 100% Electric Vehicle Penetration in the Nordic Region by 2050. Energies 7, 1733–1749. https://doi.org/10.3390/en7031733

Lombardi, F., Riva, F., Bonamini, G., Barbieri, J., Colombo, E., 2017. Laboratory protocols for testing of Improved Cooking Stoves (ICSs): A review of state-of-the-art and further developments. Biomass and Bioenergy. https://doi.org/10.1016/j.biombioe.2017.02.005

Lombardi, F., Riva, F., Colombo, E., 2018. Dealing with small sets of laboratory test replicates for Improved Cooking Stoves (ICSs): Insights for a robust statistical analysis of results. Biomass and Bioenergy 115, 27–34. https://doi.org/10.1016/j.biombioe.2018.04.004

Loo, J., Hyseni, L., Ouda, R., Koske, S., Nyagol, R., Sadumah, I., Bashin, M., Sage, M., Bruce, N., Pilishvili, T., Stanistreet, D., 2016. User Perspectives of Characteristics of Improved Cookstoves from a Field Evaluation in Western Kenya. Int. J. Environ. Res. Public Health 13, 167. https://doi.org/10.3390/ijerph13020167

López-González, A., Ranaboldo, M., Domenech, B., Ferrer-Martí, L., 2020. Evaluation of small wind turbines for rural electrification: Case studies from extreme climatic conditions in Venezuela. Energy 209, 118450. https://doi.org/10.1016/j.energy.2020.118450

López, M.A., de la Torre, S., Martín, S., Aguado, J.A., 2015. Demand-side management in smart grid operation considering electric vehicles load shifting and vehicle-to-grid support. Int. J. Electr. Power Energy Syst. 64, 689–698. https://doi.org/10.1016/J.IJEPES.2014.07.065

Losev, O.G., Grigor'ev, A.S., Mel'nik, D.A., Grigor'ev, S.A., 2020. Charging Station for Electric Transport Based on Renewable Power Sources. Russ. J. Electrochem. 56, 163–169. https://doi.org/10.1134/S1023193520020093

Luca de Tena, D., Pregger, T., 2018. Impact of electric vehicles on a future renewable energy-based power system in Europe with a focus on Germany. Int. J. Energy Res. 42, 2670–2685. https://doi.org/10.1002/er.4056

Lynch, M., 2002. Reducing Environmental Damage Caused by the Collection of Cooking Fuel by Refugees. Refug. Canada's J. Refug. 18–27. https://doi.org/10.25071/1920-7336.21280

Ma, T., Yang, H., Lu, L., Peng, J., 2014. Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong. Renew. Energy 69, 7–15. https://doi.org/10.1016/j.renene.2014.03.028

MacCarty, N., Ogle, D., Still, D., Bond, T., Roden, C., 2008. A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. Energy Sustain. Dev. 12, 56–65. https://doi.org/10.1016/S0973-0826(08)60429-9

Madlener, R., Stagl, S., 2005. Sustainability-guided promotion of renewable electricity generation. Ecol. Econ. 53, 147–167. https://doi.org/10.1016/j.ecolecon.2004.12.016

Maes, W.H., Verbist, B., 2012. Increasing the sustainability of household cooking in developing countries: Policy implications. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2012.03.031

Mainali, B., Dhital, R., 2015. Isolated and Mini-Grid Solar PV Systems: An Alternative Solution for Providing Electricity Access in Remote Areas (Case Study from Nepal), in: Solar Energy Storage. Elsevier Inc., pp. 359–374. https://doi.org/10.1016/B978-0-12-409540-3.00015-3

Mandal, S., Das, B.K., Hoque, N., 2018. Optimum sizing of a stand-alone hybrid energy system for rural electrification in Bangladesh. J. Clean. Prod. 200, 12–27. https://doi.org/10.1016/j.jclepro.2018.07.257

Mandelli, S., Barbieri, J., Mereu, R., Colombo, E., 2016. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renew. Sustain. Energy Rev. 58, 1621–1646. https://doi.org/10.1016/J.RSER.2015.12.338

Manjunath, A., Gross, G., 2017. Towards a meaningful metric for the quantification of GHG emissions of electric vehicles (EVs). Energy Policy 102, 423–429. https://doi.org/10.1016/j.enpol.2016.12.003

Manoj Kumar, Sachin Kumar, Tyagi, S.K., 2013. Design, development and technological advancement in the biomass cookstoves: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.05.010

Mao, D., Gao, Z., Wang, J., 2019. An integrated algorithm for evaluating plug-in electric vehicle’s impact on the state of power grid assets. Int. J. Electr. Power Energy Syst. 105, 793–802. https://doi.org/10.1016/J.IJEPES.2018.09.028

Martínez-Lao, J., Montoya, F.G., Montoya, M.G., Manzano-Agugliaro, F., 2017. Electric vehicles in Spain: An overview of charging systems [WWW Document]. Renew. Sustain. Energy Rev. https://doi.org/10.1016/J.RSER.2016.11.239

Mawhood, R., Gross, R., 2014. Institutional barriers to a ‘perfect’ policy: A case study of the Senegalese Rural Electrification Plan. Energy Policy 73, 480–490. https://doi.org/10.1016/J.ENPOL.2014.05.047

Mazur, A., Rosa, E., 1974. Energy and life-style. Science (80-.). 186, 607–610. https://doi.org/10.1126/science.186.4164.607

Mehetre, S.A., Panwar, N.L., Sharma, D., Kumar, H., 2017. Improved biomass cookstoves for sustainable development: A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2017.01.150

Ministry of Agriculture, 2012. Production, sustainable consumption and agricultural waste [WWW Document]. URL https://www.miteco.gob.es/images/es/Residuos agrarios_tcm30-193059.pdf (accessed 3.21.20).

Mohamed, M., Farag, H., El-Taweel, N., Ferguson, M., 2017. Simulation of electric buses on a full transit network: Operational feasibility and grid impact analysis. Electr. Power Syst. Res. 142, 163–175. https://doi.org/10.1016/j.epsr.2016.09.032

Moner-Girona, M., Ghanadan, R., Jacobson, A., Kammen, D.M., 2006. Decreasing PV costs in Africa: Opportunities for Rural Electrification using Solar PV in Sub-Saharan Africa. Refocus 7, 40–42. https://doi.org/10.1016/S1471-0846(06)70517-0

Moner-Girona, M., Solano-Peralta, M., Lazopoulou, M., Ackom, E.K., Vallve, X., Szabó, S., 2018. Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: Reducing the gap between current business models and on-site experience. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2018.04.018

Moro, A., Helmers, E., 2017. A new hybrid method for reducing the gap between WTW and LCA in the carbon footprint assessment of electric vehicles. Int. J. Life Cycle Assess. 22, 4–14. https://doi.org/10.1007/s11367-015-0954-z

Moro, A., Lonza, L., 2018. Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. Transp. Res. Part D Transp. Environ. 64, 5–14. https://doi.org/10.1016/j.trd.2017.07.012

Morrissey, P., Weldon, P., O'Mahony, M., 2016. Future standard and fast charging infrastructure planning: An analysis of electric vehicle charging behaviour. Energy Policy 89, 257–270. https://doi.org/10.1016/J.ENPOL.2015.12.001

Mostofi, F., Shayeghi, H., 2012. Feasibility and Optimal Reliable Design of Renewable Hybrid Energy System for Rural Electrification in Iran, INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH Hossein Shayegh et al.

Muh, E., Tabet, F., 2019. Comparative analysis of hybrid renewable energy systems for off-grid applications in Southern Cameroons. Renew. Energy 135, 41–54. https://doi.org/10.1016/J.RENENE.2018.11.105

Mukunda, H., 2009. Understanding Combustion, 2nd ed. Universities Press.

Munasinghe, M., 2002. The sustainomics trans-disciplinary meta-framework for making development more sustainable: Applications to energy issues. Int. J. Sustain. Dev. 5, 125–182. https://doi.org/10.1504/ijsd.2002.002563

Muneer, T., Milligan, R., Smith, I., Doyle, A., Pozuelo, M., Knez, M., 2015. Energetic, environmental and economic performance of electric vehicles: Experimental evaluation. Transp. Res. Part D Transp. Environ. 35, 40–61. https://doi.org/10.1016/j.trd.2014.11.015

Muralikrishna, M., Lakshminarayana, V., 2008. Hybrid (solar and wind) energy systems for rural electrification 3.

Mutter, A., 2019. Obduracy and change in urban transport-understanding competition between sustainable fuels in swedish municipalities. Sustain. 11. https://doi.org/10.3390/su11216092

Mwampamba, T.H., Ghilardi, A., Sander, K., Chaix, K.J., 2013. Dispelling common misconceptions to improve attitudes and policy outlook on charcoal in developing countries. Energy Sustain. Dev. https://doi.org/10.1016/j.esd.2013.01.001

Ndindeng, S.A., Wopereis, M., Sanyang, S., Futakuchi, K., 2019. Evaluation of fan-assisted rice husk fuelled gasifier cookstoves for application in sub-Sahara Africa. Renew. Energy 139, 924–935. https://doi.org/10.1016/j.renene.2019.02.132

Nizam, M., Wicaksono, F.X.R., 2019. Design and Optimization of Solar, Wind, and Distributed Energy Resource (DER) Hybrid Power Plant for Electric Vehicle (EV) Charging Station in Rural Area, in: Proceeding - 2018 5th International Conference on Electric Vehicular Technology, ICEVT 2018. Institute of Electrical and Electronics Engineers Inc., pp. 41–45. https://doi.org/10.1109/ICEVT.2018.8628341

Njoh, A.J., Etta, S., Essia, U., Ngyah-Etchutambe, I., Enomah, L.E.D., Tabrey, H.T., Tarke, M.O., 2019. Implications of institutional frameworks for renewable energy policy administration: Case study of the Esaghem, Cameroon community PV solar electrification project. Energy Policy 128, 17–24. https://doi.org/10.1016/j.enpol.2018.12.042

Nna, C.D., Gbadegesin, A.O., Lawal, K.O., 2016. A decentralized, renewable-energy-powered business hub for rural areas: A case study of Ilakan community, Nigeria, in: Clemson University Power Systems Conference, PSC 2016. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/PSC.2016.7462814

Noble, B.F., 2004. A multi-criteria analysis of Canadian electricity supply futures. Can. Geogr. 48, 11–28. https://doi.org/10.1111/j.1085-9489.2004.002b16.x

O, N.C., Kim, H., 2019. Towards the 2 °C goal: Achieving Sustainable Development Goal (SDG) 7 in DPR Korea. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2019.104412

Odou, O.D.T., Bhandari, R., Adamou, R., 2020. Hybrid off-grid renewable power system for sustainable rural electrification in Benin. Renew. Energy 145, 1266–1279. https://doi.org/10.1016/j.renene.2019.06.032

Ojolo, S.J., Abolarin, S.M., Adegbenro, O., 2012. Development of a Laboratory Scale Updraft Gasifier. Int. J. Manuf. Syst. 2, 21–42. https://doi.org/10.3923/ijmsaj.2012.21.42

Onn, C.C., Mohd, N.S., Yuen, C.W., Loo, S.C., Koting, S., Abd Rashid, A.F., Karim, M.R., Yusoff, S., 2018. Greenhouse gas emissions associated with electric vehicle charging: The impact of electricity generation mix in a developing country. Transp. Res. Part D Transp. Environ. 64, 15–22. https://doi.org/10.1016/j.trd.2017.06.018

OPPCharge, 2019. Common Interface for Automated Charging of Hybrid Electric and Electric Commercial Vehicles.

Ortega-Vazquez, M.A., Bouffard, F., Silva, V., 2013. Electric Vehicle Aggregator/System Operator Coordination for Charging Scheduling and Services Procurement. IEEE Trans. Power Syst. 28, 1806–1815. https://doi.org/10.1109/TPWRS.2012.2221750

Østergaard, P.A., Duic, N., Noorollahi, Y., Mikulcic, H., Kalogirou, S., 2020. Sustainable development using renewable energy technology. Renew. Energy. https://doi.org/10.1016/j.renene.2019.08.094

Palit, D., 2013. Solar energy programs for rural electrification: Experiences and lessons from South Asia. Energy Sustain. Dev. 17, 270–279. https://doi.org/10.1016/j.esd.2013.01.002

Panwar, N.L., 2009. Design and performance evaluation of energy efficient biomass gasifier based cookstove on multi fuels. Mitig. Adapt. Strateg. Glob. Chang. 14, 627–633. https://doi.org/10.1007/s11027-009-9187-4

Panwar, N.L., Kurchania, A.K., Rathore, N.S., 2009. Mitigation of greenhouse gases by adoption of improved biomass cookstoves. Mitig. Adapt. Strateg. Glob. Chang. 14, 569–578.

https://doi.org/10.1007/s11027-009-9184-7

Panwar, N.L., Rathore, N.S., 2008. Design and performance evaluation of a 5 kW producer gas stove. Biomass and Bioenergy 32, 1349–1352. https://doi.org/10.1016/j.biombioe.2008.04.007

Parajuli, R., 2011. Access to energy in Mid/Far west region-Nepal from the perspective of energy poverty. Renew. Energy. https://doi.org/10.1016/j.renene.2011.01.014

Pérez-Navarro, A., Alfonso, D., Ariza, H.E., Cárcel, J., Correcher, A., Escrivá-Escrivá, G., Hurtado, E., Ibáñez, F., Peñalvo, E., Roig, R., Roldán, C., Sánchez, C., Segura, I., Vargas, C., 2016. Experimental verification of hybrid renewable systems as feasible energy sources. Renew. Energy 86, 384–391. https://doi.org/10.1016/J.RENENE.2015.08.030

Pérez Martínez, P. J., & Monzón de Cáceres, A., 2008. Consumo de energía por el transporte en España y tendencias de emisión. Obs. Medioambient. 11, 127–147. https://doi.org/10.5209/obmd

Petruschke, P., Gasparovic, G., Voll, P., Krajačić, G., Duić, N., Bardow, A., 2014. A hybrid approach for the efficient synthesis of renewable energy systems. Appl. Energy 135, 625–633. https://doi.org/10.1016/j.apenergy.2014.03.051

Philipsen, R., Brell, T., Brost, W., Eickels, T., Ziefle, M., 2018. Running on empty – Users' charging behavior of electric vehicles versus traditional refueling. Transp. Res. Part F Traffic Psychol. Behav. 59, 475–492. https://doi.org/10.1016/j.trf.2018.09.024

Photovoltaics Bulletin, 2003. An assessment of solar PV for rural electrification in Northern Ghana 11. https://doi.org/10.1016/s1473-8325(03)00237-2

Phuangpornpitak, N., Kumar, S., 2011. User acceptance of diesel/PV hybrid system in an island community. Renew. Energy 36, 125–131. https://doi.org/10.1016/j.renene.2010.06.007

Pinheiro, G., Rendeiro, G., Pinho, J., Macedo, E., 2011. Rural electrification for isolated consumers: Sustainable management model based on residue biomass. Energy Policy 39, 6211–6219. https://doi.org/10.1016/j.enpol.2011.07.020

PNIEC, 2019. Spanish climate change draft law [WWW Document]. URL https://www.miteco.gob.es/es/prensa/ultimas-noticias/el-consejo-de-ministros-da-luz-verde-al-anteproyecto-de-ley-de-cambio-climático-/tcm:30-487294 (accessed 4.12.19).

PNUD, 2019. Human Development Report.

Polatidis, H., Haralambopoulos, D.A., Munda, G., Vreeker, R., 2006. Selecting an Appropriate Multi-Criteria Decision Analysis Technique for Renewable Energy Planning. Energy Sources, Part B Econ. Planning, Policy 1, 181–193. https://doi.org/10.1080/009083190881607

Pratiti, R., Vadala, D., Kalynych, Z., Sud, P., 2020. Health effects of household air pollution related to biomass cook stoves in resource limited countries and its mitigation by improved cookstoves. Environ. Res. https://doi.org/10.1016/j.envres.2020.109574

Purwanto, W.W., Afifah, N., 2016. Assessing the impact of techno socioeconomic factors on sustainability indicators of microhydro power projects in Indonesia: A comparative study. Renew. Energy 93, 312–322. https://doi.org/10.1016/j.renene.2016.02.071

PVGIS, 2020. Solar irradiation [WWW Document]. URL http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=es&map=europe (accessed 12.26.18).

Qiao, Q., Zhao, F., Liu, Z., He, X., Hao, H., 2019. Life cycle greenhouse gas emissions of Electric Vehicles in China: Combining the vehicle cycle and fuel cycle. Energy 222–233. https://doi.org/10.1016/j.energy.2019.04.080

Quddus, M.A., Kabli, M., Marufuzzaman, M., 2019. Modeling electric vehicle charging station expansion with an integration of renewable energy and Vehicle-to-Grid sources. Transp. Res. Part E Logist. Transp. Rev. 128, 251–279. https://doi.org/10.1016/j.tre.2019.06.006

Rahman, E.M.L., 2010. Improved Cooking Stoves in South Asia.

Rahman, M.M., Paatero, J. V., Poudyal, A., Lahdelma, R., 2013. Driving and hindering factors for rural electrification in developing countries: Lessons from Bangladesh. Energy Policy 61, 840–851. https://doi.org/10.1016/j.enpol.2013.06.100

Ramanathan, V., Carmichael, G., 2008. Global and regional climate changes due to black carbon. Nat. Geosci. https://doi.org/10.1038/ngeo156

Ramírez Delgado, A.I., Rivero González, J., García Rojas, L.M., Leal Fernández, J.R., Días Navarro, P.L., 2013. Propuesta de alternativas energéticas para la electrificación de la comunidad rural La Majagua, Los Palacios, Pinar del Río. Avances 15, 357–373.

Ranaboldo, M., Domenech, B., Reyes, G.A., Ferrer-Martí, L., Pastor Moreno, R., García-Villoria, A., 2015. Off-grid community electrification projects based on wind and solar energies: A case study in Nicaragua. Sol. Energy 117, 268–281. https://doi.org/10.1016/j.solener.2015.05.005

Rasheed, R., Khan, N., Yasar, A., Su, Y., Tabinda, A.B., 2016. Design and cost-benefit analysis of a novel anaerobic industrial bioenergy plant in Pakistan. Renew. Energy 90, 242–247. https://doi.org/10.1016/j.renene.2016.01.008

Rashid, M.M., Islam Maruf, M.N., Akhtar, T., 2019. An RES-based grid connected electric vehicle charging station for Bangladesh, in: 1st International Conference on Robotics, Electrical and Signal Processing Techniques, ICREST 2019. Institute of Electrical and Electronics Engineers Inc., pp. 205–210. https://doi.org/10.1109/ICREST.2019.8644130

Rasoulkhani, M., Ebrahimi-Nik, M., Abbaspour-Fard, M.H., Rohani, A., 2018. Comparative evaluation of the performance of an improved biomass cook stove and the traditional stoves of Iran. Sustain. Environ. Res. 28, 438–443. https://doi.org/10.1016/j.serj.2018.08.001

REE, 2018. Electric mobility guide for local entities [WWW Document]. URL https://www.ree.es/sites/default/files/downloadable/Guia_movilidad_electrica_para_entidades_locales.pdf (accessed 7.31.19).

REE, 2017a. Historical Data Base [WWW Document]. URL https://www.ree.es/es/estadisticas-del-sistema-electrico-espanol/series-estadisticas/series-estadisticas-nacionales (accessed 12.26.18).

REE, 2017b. Electrical demand, energy generation structure and CO2 emissions [WWW Document]. URL https://demanda.ree.es/visiona/peninsula/demanda/total/2018-10-16 (accessed 12.27.18).

Renewable Energy Agency, I., 2014. Evaluating Renewable Energy Policy: A Review of Criteria and Indicators for Assessment Acknowledgements About IRENA.

Ribó-Pérez, D., Bastida-Molina, P., Gómez-Navarro, T., Hurtado-Pérez, E., 2020. Hybrid assessment for a hybrid microgrid: A novel methodology to critically analyse generation technologies for hybrid microgrids. Renew. Energy 157, 874–887. https://doi.org/10.1016/j.renene.2020.05.095

Ristic, B., Mahlooji, M., Gaudard, L., Madani, K., 2019. The relative aggregate footprint of electricity generation technologies in the European Union (EU): A system of systems approach. Resour. Conserv. Recycl. 143, 282–290. https://doi.org/10.1016/J.RESCONREC.2018.12.010

Rohani, G., Nour, M., 2014. Techno-economical analysis of stand-alone hybrid renewable power system for Ras Musherib in United Arab Emirates. Energy 64, 828–841. https://doi.org/10.1016/j.energy.2013.10.065

Saaty, T.L., 2005. Theory and Applications of the Analytic Network Process. RWS Publications, Pittsburgh, PA.

Saaty, T.L., 2001. The Analytic Network Process: Decision Making with Dependence and Feedback. RWS Publications.

Salisu, S., Mustafa, W., Mohammed, O.O., Mustapha, M., Jumani, A., 2019. Techno-Economic Feasibility Analysis of an Off-grid Hybrid Energy System for Rural Electrification in Nigeria.

Sarker, M.R., Pandžić, H., Ortega-Vazquez, M.A., 2015. Optimal operation and services scheduling for an electric vehicle battery swapping station. IEEE Trans. Power Syst. 30, 901–910. https://doi.org/10.1109/TPWRS.2014.2331560

Savio, D.A., Juliet, V.A., Chokkalingam, B., Padmanaban, S., Holm-Nielsen, J.B., Blaabjerg, F., 2019. Photovoltaic Integrated Hybrid Microgrid Structured Electric Vehicle Charging Station and Its Energy Management Approach. Energies 12, 168. https://doi.org/10.3390/en12010168

Scarinci, R., Zanarini, A., Bierlaire, M., 2019. Electrification of urban mobility: The case of catenary-free buses. Transp. Policy 80, 39–48. https://doi.org/10.1016/j.tranpol.2019.05.006

Scheubel, C., Zipperle, T., Tzscheutschler, P., 2017. Modeling of industrial-scale hybrid renewable energy systems (HRES) – The profitability of decentralized supply for industry. Renew. Energy 108, 52–63. https://doi.org/10.1016/j.renene.2017.02.038

Sehar, F., Pipattanasomporn, M., Rahman, S., 2017. Demand management to mitigate impacts of plug-in electric vehicle fast charge in buildings with renewables. Energy 120, 642–651. https://doi.org/10.1016/J.ENERGY.2016.11.118

Shafiee, S., Fotuhi-Firuzabad, M., Rastegar, M., 2013. Investigating the impacts of plug-in hybrid electric vehicles on power distribution systems. IEEE Trans. Smart Grid 4, 1351–1360. https://doi.org/10.1109/TSG.2013.2251483

Shamshirband, M., Salehi, J., Gazijahani, F.S., 2018. Decentralized trading of plug-in electric vehicle aggregation agents for optimal energy management of smart renewable penetrated microgrids with the aim of CO2 emission reduction. J. Clean. Prod. 200, 622–640. https://doi.org/10.1016/j.jclepro.2018.07.315

Sharma, R., Goel, S., 2016. Stand-alone hybrid energy system for sustainable development in rural India. Environ. Dev. Sustain. 18, 1601–1614. https://doi.org/10.1007/s10668-015-9705-3

Shen, W., Han, W., Wallington, T.J., 2014. Current and future greenhouse gas emissions associated with electricity generation in China: Implications for electric vehicles. Environ. Sci. Technol. 48, 7069–7075. https://doi.org/10.1021/es500524e

Shen, W., Han, W., Wallington, T.J., Winkler, S.L., 2019. China Electricity Generation Greenhouse Gas Emission Intensity in 2030: Implications for Electric Vehicles. Environ. Sci. Technol. 53, 6063–6072. https://doi.org/10.1021/acs.est.8b05264

Shezan, S.K.A., Das, N., Mahmudul, H., 2017. Techno-economic Analysis of a Smart-grid Hybrid Renewable Energy System for Brisbane of Australia, in: Energy Procedia. Elsevier Ltd, pp. 340–345. https://doi.org/10.1016/j.egypro.2017.03.150

Shmelev, S.E., van den Bergh, J.C.J.M., 2016. Optimal diversity of renewable energy alternatives under multiple criteria: An application to the UK. Renew. Sustain. Energy Rev. 60, 679–691. https://doi.org/10.1016/J.RSER.2016.01.100

Simsek, Y., Santika, W.G., Anisuzzaman, M., Urmee, T., Bahri, P.A., Escobar, R., 2020. An analysis of additional energy requirement to meet the sustainable development goals. J. Clean. Prod. 272. https://doi.org/10.1016/j.jclepro.2020.122646

Singh, M., Balachandra, P., 2019. Microhybrid Electricity System for Energy Access, Livelihoods, and Empowerment. Proc. IEEE 107, 1995–2007. https://doi.org/10.1109/JPROC.2019.2910834

Siskos, J., Hubert, P., 1983. Multi-criteria analysis of the impacts of energy alternatives: A survey and a new comparative approach. Eur. J. Oper. Res. 13, 278–299. https://doi.org/10.1016/0377-2217(83)90057-7

Smit, S., Musango, J.K., Brent, A.C., 2019. Understanding electricity legitimacy dynamics in an urban informal settlement in South Africa: A Community Based System Dynamics approach. Energy Sustain. Dev. 49, 39–52. https://doi.org/10.1016/j.esd.2019.01.004

Smith, K.R., Dutta, K., Chengappa, C., Gusain, P.P.S., Berrueta, O.M. and V., Edwards, R., Bailis, R., Shields, K.N., 2007. Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: conclusions from the Household Energy and Health Project. Energy Sustain. Dev. 11, 5–18. https://doi.org/10.1016/S0973-0826(08)60396-8

Smith, K.R., Shuhua, G., Kun, H., Daxiong, Q., 1993. One hundred million improved cookstoves in China: How was it done? World Dev. 21, 941–961. https://doi.org/10.1016/0305-750X(93)90053-C

Smith, K.R., Uma, R., Kishore, V.V.N., Zhang, J., Joshi, V., Khalil, M.A.K., 2000. Greenhouse Implications of Household Stoves: An Analysis for India. Annu. Rev. Energy Environ. 25, 741–763. https://doi.org/10.1146/annurev.energy.25.1.741

Sovacool, B.K., Mukherjee, I., 2011. Conceptualizing and measuring energy security: A synthesized approach. Energy 36, 5343–5355. https://doi.org/10.1016/j.energy.2011.06.043

Spangher, L., Gorman, W., Bauer, G., Xu, Y., Atkinson, C., 2019. Quantifying the impact of U.S. electric vehicle sales on light-duty vehicle fleet CO2 emissions using a novel agent-based simulation. Transp. Res. Part D Transp. Environ. 72, 358–377. https://doi.org/10.1016/j.trd.2019.05.004

Spanish Ministry of Development, 2016. Urban and metropolitan transport in Spain [WWW Document]. URL https://www.fomento.gob.es/recursos_mfom/00transporteurbano.pdf (accessed 12.16.19).

Spanish Nuclear Industry Forum, 2019. Nuclear Power Plants [WWW Document]. URL https://www.foronuclear.org/es/ (accessed 3.7.20).

Steinberger, J.K., Roberts, J.T., 2010. From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975-2005. Ecol. Econ. 70, 425–433. https://doi.org/10.1016/j.ecolecon.2010.09.014

Su, J., Lie, T.T., Zamora, R., 2019. Modelling of large-scale electric vehicles charging demand: A New Zealand case study. Electr. Power Syst. Res. 167, 171–182. https://doi.org/10.1016/J.EPSR.2018.10.030

Sundstrom, O., Binding, C., 2012. Flexible Charging Optimization for Electric Vehicles Considering Distribution Grid Constraints. IEEE Trans. Smart Grid 3, 26–37. https://doi.org/10.1109/TSG.2011.2168431

Taele, B.M., Gopinathan, K.K., Mokhuts'oane, L., 2007. The potential of renewable energy technologies for rural development in Lesotho. Renew. Energy 32, 609–622. https://doi.org/10.1016/j.renene.2006.02.014

Technical Management Board, 2012. Guidelines for evaluating cookstove performance [WWW Document]. URL https://www.iso.org/standard/61975.html (accessed 3.21.20).

Teixeira, A.C.R., Sodré, J.R., 2018. Impacts of replacement of engine powered vehicles by electric vehicles on energy consumption and CO2 emissions. Transp. Res. Part D Transp. Environ. 59, 375–384. https://doi.org/10.1016/J.TRD.2018.01.004

The German Federal Goverment, 2009. Federal Government's National Electromobility Development Plan.

Tietge, U., Díaz, S., Mock, P., German, J., Bandivadekar, A., Ligterink, N., 2016a. From laboratory to road: A 2016 update of official and "real-world" fuel consumption and CO2 values for passenger cars in Europe. Int. Counc. Clean Transp.

Tietge, U., Mock, P., Zacharof, N., Franco, V., 2016b. Real-world fuel consumption of popular European passenger car models | International Council on Clean Transportation. Int. Counc. Clean Transp.

Tong, C.W., Zainon, M.Z., Chew, P.S., Kui, S.C., Keong, W.S., Chen, P.K., 2010. Innovative power-augmentation-guide-vane design of wind-solar hybrid renewable energy harvester for urban high rise application, in: AIP Conference Proceedings. pp. 507–521. https://doi.org/10.1063/1.3464898

Tucho, G., Nonhebel, S., 2015. Bio-Wastes as an Alternative Household Cooking Energy Source in Ethiopia. Energies 8, 9565–9583. https://doi.org/10.3390/en8099565

Tulpule, P.J., Marano, V., Yurkovich, S., Rizzoni, G., 2013. Economic and environmental impacts of a PV powered workplace parking garage charging station. Appl. Energy 108, 323–332. https://doi.org/10.1016/j.apenergy.2013.02.068

Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.08.013

UE, 2020. EU Emissions Trading Framework [WWW Document]. URL https://ec.europa.eu/clima/policies/ets_es (accessed 7.7.20).

UE, 2019. Regulation 2019/631 of the European Parliament [WWW Document]. URL https://eur-lex.europa.eu/legal-content/ES/TXT/?uri=CELEX:32019R0631 (accessed 7.9.20).

UE, 2015. Paris agreement [WWW Document]. URL https://ec.europa.eu/clima/policies/international/negotiations/paris_es (accessed 7.7.20).

UE, 2010. 2010/75/UE [WWW Document]. URL https://eur-lex.europa.eu/legal-content/ES/TXT/PDF/?uri=CELEX:32010L0075&from=ES (accessed 7.7.20).

UN, 2021. Small-Scale Methodology: Energy Efficiency Measures in Thermal Applications ofNon-Renewable Biomass [WWW Document]. URL https://cdm.unfccc.int/methodologies/DB/ZI2M2X5P7ZLRGFO37YBVDYOW62UHQP (accessed 12.9.19).

UN, 2019. Sustainable Development Goals [WWW Document]. URL https://sdgs.un.org/es/goals (accessed 4.15.19).

UNDP, 2021a. Human Development Index [WWW Document]. URL http://hdr.undp.org/en/content/human-development-index-hdi (accessed 2.24.21).

UNDP, 2021b. Human Development Index Ranking [WWW Document]. URL http://hdr.undp.org/en/content/latest-human-development-index-ranking (accessed 2.24.21).

Vahlne, N., Ahlgren, E.O., 2014. Policy implications for improved cook stove programs—A case study of the importance of village fuel use variations. Energy Policy 66, 484–495. https://doi.org/10.1016/j.enpol.2013.11.042

Valsera-Naranjo, E., Sumper, A., Villafafila-Robles, R., Martínez-Vicente, D., Valsera-Naranjo, E., Sumper, A., Villafafila-Robles, R., Martínez-Vicente, D., 2012. Probabilistic Method to Assess the Impact of Charging of Electric Vehicles on Distribution Grids. Energies 5, 1503–1531. https://doi.org/10.3390/en5051503

van den Broek, M., Faaij, A., Turkenburg, W., 2008. Planning for an electricity sector with carbon capture and storage. Case of the Netherlands. Int. J. Greenh. Gas Control 2, 105–129. https://doi.org/10.1016/S1750-5836(07)00113-2

Vera, I., Langlois, L., 2007. Energy indicators for sustainable development. Energy 32, 875–882.

https://doi.org/10.1016/j.energy.2006.08.006

Vermaak, H.J., Kusakana, K., 2014. Design of a photovoltaic-wind charging station for small electric Tuk-tuk in D.R.Congo. Renew. Energy 67, 40–45. https://doi.org/10.1016/j.renene.2013.11.019

Vishnupriyan, J., Manoharan, P.S., 2017. Demand side management approach to rural electrification of different climate zones in Indian state of Tamil Nadu. Energy 138, 799–815. https://doi.org/10.1016/j.energy.2017.07.140

Wang, L., Chen, B., 2019. Distributed control for large-scale plug-in electric vehicle charging with a consensus algorithm. Int. J. Electr. Power Energy Syst. 109, 369–383. https://doi.org/10.1016/J.IJEPES.2019.02.020

Wang, R., Xiong, J., He, M., Gao, L., Wang, L., 2019. Multi-objective optimal design of hybrid renewable energy system under multiple scenarios. Renew. Energy. https://doi.org/10.1016/j.renene.2019.11.015

Wang, W., Zhao, D., Mi, Z., Fan, L., 2019. Prediction and Analysis of the Relationship between Energy Mix Structure and Electric Vehicles Holdings Based on Carbon Emission Reduction Constraint: A Case in the Beijing-Tianjin-Hebei Region, China. Sustainability 11, 1–20.

Wang, X., Wei, X., Dai, H., 2019. Estimation of state of health of lithium-ion batteries based on charge transfer resistance considering different temperature and state of charge. J. Energy Storage 21, 618–631. https://doi.org/10.1016/j.est.2018.11.020

Wang, Y., Infield, D., 2018. Markov Chain Monte Carlo simulation of electric vehicle use for network integration studies. Int. J. Electr. Power Energy Syst. 99, 85–94. https://doi.org/10.1016/J.IJEPES.2018.01.008

Wassie, Y.T., Adaramola, M.S., 2021a. Socio-economic and environmental impacts of rural electrification with Solar Photovoltaic systems: Evidence from southern Ethiopia. Energy Sustain. Dev. 60, 52–66. https://doi.org/10.1016/j.esd.2020.12.002

Wassie, Y.T., Adaramola, M.S., 2021b. Analysis of potential fuel savings, economic and environmental effects of improved biomass cookstoves in rural Ethiopia. J. Clean. Prod. 280, 124700. https://doi.org/10.1016/j.jclepro.2020.124700

WB, 2021. Transport: general overview [WWW Document]. URL https://www.bancomundial.org/es/topic/transport/overview (accessed 2.26.21).

Weiss, M., Dekker, P., Moro, A., Scholz, H., Patel, M.K., 2015. On the electrification of road transportation - A review of the environmental, economic, and social performance of electric two-wheelers. Transp. Res. Part D Transp. Environ. 41, 348–366. https://doi.org/10.1016/j.trd.2015.09.007

Woo, J.R., Choi, H., Ahn, J., 2017. Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: A global perspective. Transp. Res. Part D Transp. Environ. 51, 340–350. https://doi.org/10.1016/j.trd.2017.01.005

Wu, C., Gao, S., Liu, Y., Song, T.E., Han, H., 2021. A model predictive control approach in microgrid considering multi-uncertainty of electric vehicles. Renew. Energy 163, 1385–1396. https://doi.org/10.1016/j.renene.2020.08.137

Wu, Y., Yang, Z., Lin, B., Liu, H., Wang, R., Zhou, B., Hao, J., 2012. Energy consumption and CO 2 emission impacts of vehicle electrification in three developed regions of China. Energy Policy 48, 537–550. https://doi.org/10.1016/j.enpol.2012.05.060

Wu, Y., Zhang, L., 2017. Can the development of electric vehicles reduce the emission of air pollutants and greenhouse gases in developing countries? Transp. Res. Part D Transp. Environ. 51, 129–145. https://doi.org/10.1016/j.trd.2016.12.007

Wu, Z., Guo, F., Polak, J., Strbac, G., 2019. Evaluating grid-interactive electric bus operation and demand response with load management tariff. Appl. Energy 255, 113798. https://doi.org/10.1016/j.apenergy.2019.113798

Xie, R., Wei, W., Khodayar, M.E., Wang, J., Mei, S., 2018. Planning Fully Renewable Powered Charging Stations on Highways: A Data-Driven Robust Optimization Approach. IEEE Trans. Transp. Electrif. 4, 817–830. https://doi.org/10.1109/TTE.2018.2849222

Xu, X., Hu, W., Cao, D., Huang, Q., Chen, C., Chen, Z., 2020. Optimized sizing of a standalone PV-wind-hydropower station with pumped-storage installation hybrid energy system. Renew. Energy 147, 1418–1431. https://doi.org/10.1016/j.renene.2019.09.099

Yang, Y., El Baghdadi, M., Lan, Y., Benomar, Y., Van Mierlo, J., Hegazy, O., 2018. Design Methodology, Modeling, and Comparative Study of Wireless Power Transfer Systems for Electric Vehicles. Energies 11, 1716. https://doi.org/10.3390/en11071716

Yaqoot, M., Diwan, P., Kandpal, T.C., 2016. Review of barriers to the dissemination of decentralized renewable energy systems. Renew. Sustain. Energy Rev. 58, 477–490. https://doi.org/10.1016/J.RSER.2015.12.224

Yeh, T.-M., Huang, Y.-L., 2014. Factors in determining wind farm location: Integrating GQM, fuzzy DEMATEL, and ANP. Renew. Energy 66, 159–169. https://doi.org/http://dx.doi.org/10.1016/j.renene.2013.12.003

Yetano Roche, M., Verolme, H., Agbaegbu, C., Binnington, T., Fischedick, M., Oladipo, E.O., 2019. Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways. Clim. Policy. https://doi.org/10.1080/14693062.2019.1661818

Zhang, K., Ma, J., Zhao, X., Liu, X., Zhang, Y., 2019. Parameter Identification and State of Charge Estimation of NMC Cells Based on Improved Ant Lion Optimizer. Math. Probl. Eng. 1–18. https://doi.org/10.1155/2019/4961045

Zhang, X., 2018. Short-Term Load Forecasting for Electric Bus Charging Stations Based on Fuzzy Clustering and Least Squares Support Vector Machine Optimized by Wolf Pack Algorithm. Energies 11, 1449. https://doi.org/10.3390/en11061449

Zhang, Y., Yuan, J., Zhao, C., Lyu, L., 2020. Can dispersed wind power take off in China: A technical & institutional economics analysis. J. Clean. Prod. 256, 120475. https://doi.org/10.1016/j.jclepro.2020.120475

Zhang, Y., Zhang, Z., Zhou, Y., Dong, R., 2018. The Influences of Various Testing Conditions on the Evaluation of Household Biomass Pellet Fuel Combustion. Energies 11, 1131. https://doi.org/10.3390/en11051131

Zhao, X., Ma, J., Wang, S., Ye, Y., Wu, Y., Yu, M., 2018a. Developing an electric vehicle urban driving cycle to study differences in energy consumption. Environ. Sci. Pollut. Res. 26, 13839–13853. https://doi.org/10.1007/s11356-018-3541-6

Zhao, X., Yu, Q., Ma, J., Wu, Y., Yu, M.S., Ye, Y., 2018b. Development of a Representative EV Urban Driving Cycle Based on a k- Means and SVM Hybrid Clustering Algorithm. J. Adv. Transp. 1–18. https://doi.org/10.1155/2018/1890753

Zheng, J., Sun, X., Jia, L., Zhou, Y., 2020. Electric passenger vehicles sales and carbon dioxide emission reduction potential in China’s leading markets. J. Clean. Prod. 243, 118607. https://doi.org/10.1016/j.jclepro.2019.118607

Zheng, Y., He, X., Wang, H., Wang, M., Zhang, S., Ma, D., Wang, B., Wu, Y., 2019. Well-to-wheels greenhouse gas and air pollutant emissions from battery electric vehicles in China. Mitig. Adapt. Strateg. Glob. Chang. https://doi.org/10.1007/s11027-019-09890-5

Zongxi, Z., Zhenfeng, S., Yinghua, Z., Hongyan, D., Yuguang, Z., Yixiang, Z., Ahmad, R., Pemberton-Pigott, C., Renjie, D., 2017. Effects of biomass pellet composition on the thermal and emissions performances of a TLUD cooking stove. Int. J. Agric. Biol. Eng. 10, 189–197. https://doi.org/10.25165/j.ijabe.20171004.2963

Annex

List of acronyms

Acronym	Definition
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BEVs	Battery Electric Vehicles
BSW	Briquettes
CCT	Control Kitchen Test
CI	Carbon Intensity
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DRC	Democratic Republic of the Congo
EBs	Electric Buses
EVCs	Electric Vehicle Charging Station
EVs	Electric Vehicles
FAO	Food and Agriculture Organization
FCR	Fuel Consumption Rate
GHG	Greenhouse Gases
HDI	Human Development Index
HEVs	Hybrid Electric Vehicles
HPCS	High Power Cold Start
HRES	Hybrid Renewable Energy System
ICEVs	Internal Combustion Engine Vehicles
ICS	Improved Cooking Stoves
ICS-G	Improved Cooking Stoves using Biomass Gasification
IEA	International Energy Agency
LabDER	Laboratory of Distributed Energy Resources

Acronym	**Definition**
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
LEVs	Light Electric Vehicles
LICEVs	Light Internal Combustion Engine Vehicles
LP	Low Power
LRSI	Level of renewable sources introduction
MCDM	Multi Criteria Decision Making
NPC	Net Present Cost
PEMS	Portable Emission Monitoring System
PHEVs	Plug-in Hybrid Electric Vehicle
PM	Fine Particles
SGR	Specific Gasification Rate
SOC	State of Charge
TCS	Traditional Cooking Stoves
TtW	Tank-to-Wheel
WB	World Bank
WBT	Water Boil Test
WtW	Well-to-Wheel