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LAS ENERGÍAS MARINAS COMO RECURSOS FUNDAMENTALES EN SISTEMAS HÍBRIDOS DE ENERGÍA RENOVABLE DE LATITUDES MEDIAS-ALTAS

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A la hermosa libélula en el espeso bosque...

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Al cosmos, al amor, mi gente linda y sus enseñanzas... Muchas personas aportaron y transformaron un sueño en Conquista. Gracias a ustedes por creer en mi, mi trabajo y mi crecimiento, son ¡FANTÁSTICOS!

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Nomenclatura

ADCP	Acoustic Doppler Current Profilers
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
COE	Cost Of Energy
CFOE	Carbon Footprint Of Energy
BESS	Battery Energy Storage System
ESS	Energy Storage System
GHG	Greenhouse Gas
HOMER	Hybrid Optimization Model for Multiple Energy Resources
HRES	Hybrid Renewable Energy System
HRES-OFF	Off-grid Hybrid Renewable Energy System
IEA	International Energy Agency
LCOE	Levelized Cost Of Energy
LPS	Loss of Power Supply
LPSP	Loss of Power Supply Probability
NPC	Net Present Cost
OPEX	Operational Expenditure
ORES	Ocean Renewable Energy Storage
OTEC	Ocean Thermal Energy Conversion
O&M	Operations and Maintenance
PHS	Pumped Hydro Storage
PV	Photovoltaic solar panel
PV-BESS	HRES configuration consisting of solar panels and BESS
RF	Renewable Fraction
SAIDI	System Average Interruption Duration Index
SHP	Small Hydro Power
TT	Tidal Turbine
TT-BESS	HRES configuration consisting of tidal turbines and BESS
WEC	Wave Energy Converter
WEC-BESS	HRES configuration consisting of wave energy converters and BESS
WT	Wind Turbine
WT-BESS	HRES configuration consisting of wind turbines and BESS

Resumen

Las energías marinas (undimotriz y mareomotriz) tienen una escasa integración en HRES off-grid a nivel mundial. Esta sentencia se fundamenta en una extensa y profunda revisión bibliográfica donde se destaca que: i) el 86 % de las 168 investigaciones analizadas enfocan su atención en sistemas solares fotovoltaicos y, en segundo lugar, las turbinas eólicas tienen un 68 % de participación, ii) más del 50 % de las investigaciones confían en generadores diesel como fuentes de soporte energético a los recursos renovables, iii) en zonas tropicales no se encontró inserción de tecnologías OTEC en HRES para comunidades costeras, iv) a medida que la latitud se incrementa, el potencial energético de las olas y corriente mareal es extraordinario, sin embargo, el enfoque de las soluciones energéticas off-grid está centrado en el uso del recurso solar y eólico y, v) solo el 9 % de los HRES examinados incorporó un recurso marino renovable.

Alrededor de 700 millones de personas no poseen un servicio eléctrico continuo y confiable. La mayoría pertenece al grupo rural, especialmente, poblaciones en zonas aisladas, olvidadas y muy vulnerables. Aunque el servicio eléctrico en zonas urbanas es el resultado de complejos y extensos sistemas centralizados de generación, la solución para pequeñas poblaciones obliga a dimensionar soluciones descentralizadas. En ese sentido, los HRES son una solución muy acertada y ampliamente estudiada en la literatura. Aunque la implementación de HRES cobija diversas latitudes, no hay coherencia entre los recursos con mayor potencial energético y los recursos utilizados en su implementación. Es decir, comunidades costeras con recursos marinos de alto potencial energético, son abordadas con simulaciones o implementaciones del tipo PV-Wind-Diesel-Battery (se mantiene la dependencia energética). Un argumento para esta preferencia, es la madurez tecnológica de los paneles solares y turbinas eólicas, sin embargo, en latitudes medias-altas los altos índices energéticos de las olas y corrientes mareales y los altos factores de planta de los WEC, incrementa la producción de energía eléctrica anual, que reduce el LCOE en un HRES off-grid. Es así como, una solución WEC-BESS tipo ***attenuator*** y ***overtopping***, puede alimentar la carga (981 MWh/año) de una comunidad en los fiordos chilenos, con un exceso de energía que oscila entre 127 % al 1135 % y un LCOE entre 1.35 $/kWh y 1.94 $/kWh (con LPSP variando del 0 % al 5 %). Estos indicadores son mucho mejores que los obtenidos en soluciones PV-BESS: surplus de energía entre 129 % y 234 % y LCOE entre 1.59 $/kWh y 2.4 $/kWh. En áreas con flujos de corriente mareal promedio de 1.5 m/s, la solución TT-BESS alcanzó un LCOE entre 2.14$/kWh y 2.81 $/kWh, indicadores que le compiten a los "tradicionales" sistemas PV-BESS y WT-BESS. Estas soluciones energéticas, dependiendo de la fuente de información que caracterice el recurso renovable, pueden estar sobredimensionando (o subdimensionando) la configuración optimizada, realidad que se publicó en el segundo artículo de esta investigación, donde simular y optimizar un PV-Wind-Diesel-BESS, produce un 40 % de variabilidad en el tamaño de la planta solar, utilizando tres fuentes de información diferentes.

Keywords – algoritmo de optimización, pobreza energética, LCOE y LPSP, comunidades remotas

Abstract

Marine energies (wave and tidal) are poorly integrated in off-grid HRES worldwide. This judgment is based on an extensive and exhaustive bibliographic review where it is highlighted that: i) 86 % of the 168 studies analyzed focus their attention on solar photovoltaic systems and, in second place, wind turbines have a 68 % share, ii) more than 50 % of the investigations rely on diesel generators as sources of energy support for renewable resources, iii) in tropical zones, no OTEC technology insertion was found in HRES for coastal communities, iv) As latitude increases, the energy potential of waves and tidal currents is extraordinary, however, the focus of off-grid energy solutions is centered on the use of solar and wind resources, and, v) Only 9 % of the HRES examined incorporated a renewable marine resource.

Around 700 million people do not have continuous and reliable electricity service. Most of them belong to the rural group, especially populations in isolated, forgotten and very vulnerable areas. Although electricity service in urban areas is the result of complex and extensive centralized generation systems, the solution for small populations requires decentralized solutions. In this sense, HRESs are a very successful solution and have been widely studied in the literature. Although the implementation of HRESs covers various latitudes, there is no consistency between the resources with the greatest energy potential and the resources used in its implementation. That is, coastal communities with marine resources with high energy potential are addressed with simulations or implementations of the type: PV-Wind-Diesel-Battery (energy dependence remains). One argument for this preference is the technological maturity of solar panels and wind turbines, however, in mid-high latitudes the high energy rates of waves and tidal currents and the high capacity factors of WECs, increase the annual electrical energy production, which reduces the LCOE in an off-grid HRES. A WEC-BESS solution with ***attenuator*** and ***overtopping*** devices can supply the load (981 MWh/year) of a community in the Chilean fjords, with excess energy ranging from 127 % to 1135 % and an LCOE between 1.35 $/kWh and 1.94 $/kWh (LPSP varying from 0 % to 5 %). These indicators are much better than those obtained in PV-BESS solutions: energy surplus between 129 % and 234 % and LCOE between 1.59 $/kWh and 2.4 $/kWh. In areas with an average tidal current of 1.5 m/s, the TT-BESS solution achieved an LCOE between 2.14 $/kWh and 2.81 $/kWh, indicators that compete with the "traditional" PV-BESS and WT-BESS systems. These energy solutions, depending on the source of information that characterizes the renewable resource, may be oversizing (or undersizing) the optimized configuration, a reality that was published in the second article of this research, where simulating and optimizing a PV-Wind-Diesel-BESS, produces a 40 % variability in the size of the solar plant, using three different sources of information.

Keywords – optimization algorithm, energy poverty, LCOE and LPSP, remote communities

Capítulo 1

Introducción

La energía eléctrica es la base fundamental del desarrollo social, la educación, salud y, por consiguiente, calidad de vida. De acuerdo a cifras del Banco Mundial el 90.5 % de la población mundial (2020) tiene acceso a energía eléctrica, es decir, ∼7.000 millones de personas [8]. Esta estadística puede desagregarse en dos componentes principales: población urbana y población rural. La primera, y considerando su alta concentración en un área específica del territorio, accede fácilmente a energía eléctrica proporcionada por complejos y extensos sistemas de generación y distribución. En ese sentido, el 97.3 % de la población urbana tiene garantizado el acceso a la energía eléctrica y disfruta sus beneficios. Sin embargo, la población rural convive con una situación diferente: el 82.7 % de este grupo de personas accede a electricidad, y el porcentaje restante (∼601 millones) carecen de esta energía. Las cifras son preocupantes y señalan que más de 700 millones de personas no acceden a electricidad en pleno siglo XXI.

Una de las características de las comunidades rurales es su baja densidad poblacional y alta diseminación en el territorio [9]. Estas particularidades son un factor determinante en el incremento de la pobreza multidimensional de comunidades remotas e insulares. Sin embargo, extender sistemas energéticos tradicionales para suministrar energía eléctrica en zonas remotas, es una solución prácticamente imposible, desde un punto de vista económico y de factibilidad [10]. En su lugar, los sistemas de generación descentralizados, son una solución real y funcional para pequeños perfiles de consumo [11]. Este tipo de sistemas eléctricos, optimizan el proceso de generación a partir del fuentes renovables locales, lo que puede reducir la disparidad energética, garantizar calidad de servicio y promover mejores ingresos a las comunidades [12].

1.1. Sistemas de generación eléctrica off-grid

Sistemas de generación distribuida son soluciones ampliamente utilizadas e investigadas para atender la demanda energética en comunidades aisladas [13, 14, 15, 16, 17, 18, 19]. Estos sistemas son instalados muy cerca al centro de consumo y están integrados por fuentes de energía renovable, pequeños generadores diesel y sistemas de almacenamiento de energía. La implementación de generadores diesel obedece a su madurez tecnológica y bajo costo de instalación [1]. Sin embargo, su uso trae consigo numerosas desventajas: i) alta dependencia energética de combustibles fósiles importados, ii) emisión de gases de efecto invernadero (GHG, por sus siglas en inglés) causantes del acelerado cambio climático [20], iii) degradación de la salud humana [21], iv) altos costos de operación sustentados en el transporte, logística [22] y almacenamiento del diesel. Sumado a lo anterior, la alta y desfavorable incertidumbre en el precio del petróleo, el bajo ingreso per capita de las comunidades remotas [23] y la creciente preocupación de los gobiernos por disminuir los GHG, abren el camino a la incorporación de nuevas sistemas energéticos, que priorizan los recursos primarios con mayor potencial, y mejoran su respuesta, calidad y estabilidad con la asociación de diversos sistemas de almacenamiento. Centros de generación sustentables y descentralizados, deben descartar el uso de combustibles fósiles contaminantes, acelerando la transición e independencia energética.

Los sistemas híbridos de energía renovable (HRES, por sus siglas en inglés), como sistemas de generación distribuida, son soluciones principalmente off-grid que superan la variabilidad de los recursos renovables, al involucrar varias fuentes de energía en su configuración [24]. La mayoría de los recursos renovables tienen una distribución más "homogénea" en los territorios, en comparación con los combustibles fósiles, y pueden ser usados a cualquier latitud. Esta disponibilidad agregada a la creciente diversificación de las matrices energéticas, ha demostrado un aumento en la participación de la energía renovable en la producción de electricidad. Es así como la generación de electricidad a partir de recursos renovables (excluyendo hidroelectricidad) creció de 79 TWh en 1985 a 3657 TWh en 2021, es decir, un incremento del 4630 %. Sin embargo, la mayor atención está concentrada en la instalación de plantas fotovoltaicas y granjas eólicas (onshore y offshore), que en el año 2021 alcanzó el 10.3 % de la electricidad producida a nivel mundial, 0.3 % más electricidad que la obtenida por energía nuclear [25]. Aunque las cifras demuestran un crecimiento sostenido en la participación de las energías renovables, es importante resaltar que estas estadísticas describen las grandes centrales de generación. Los pequeños HRES off-grid que alimentan a pequeñas comunidades insulares, escapan del radar de estas estadísticas, lo que dificulta entender su dinámica, evolución y tendencia.

Definir correctamente un HRES off-grid exige la evaluación integral del recurso renovable local y la caracterización del perfil de consumo. La ubicación geográfica de la comunidad, es una variable relevante para entender la dinámica de los recursos renovables y su potencial. A medida que se incrementa la latitud, el potencial energético de los recursos varía en magnitud. Por lo tanto, el diseño de un HRES debe estar alineado a la riqueza energética del territorio, su caracterización física y la sustentabilidad en el tiempo. Por ejemplo:

- Asentamientos costeros (todos aquellos ubicados en islas y regiones cercanas a costa) tienen acceso a recursos renovables "tradicionales": sol y viento. Sin embargo, en sus costas la presencia de las olas es permanente, y como recurso renovable marino, posee mayor densidad energética que el sol y el viento. Además, los convertidores de energía undimotriz (WEC, por sus siglas en inglés) pueden generar electricidad por mayor tiempo (hasta el 90 % del tiempo) comparado con el 20 %-30 % de los sistemas solares y eólicos [26]. A mayor latitud (en ambos hemisferios), las olas contienen más energía (por cada metro de frente de ola) que en zonas tropicales [27]. Asimismo, las corrientes mareales, relacionadas con el flujo y reflujo de las mareas, son un recurso renovable con alta predictibilidad y, como sucede con las olas, sus altos índices energéticos están presentes en zonas de media-alta latitud. Sin embargo, la incorporación de estos recursos del océano en HRES off-grid es una tarea incipiente que requiere mayor investigación y desarrollo [28].

- Comunidades aisladas que viven al interior del continente, tienen una mayor disponibilidad de recursos biomásicos, acceso a mayor cantidad de fuentes hídricas (con el propósito de utilizar hidroelectricidad a pequeña escala - SHP), aplicaciones geotérmicas de baja y alta entalpía, y por supuesto, el amplio y difundido uso de la radiación solar y viento.

Como se mencionó anteriormente, las estadísticas relacionadas a energía renovable tienen un enfoque macro, y los HRES off-grid dada su condición de baja potencia, no ingresan a los balances energéticos mundiales. Esta situación, exhorta a la búsqueda y análisis de HRES off-grid, su actualidad, los mecanismos de simulación y optimización, su estado de implementación: teórico o instalado, y su integración en comunidades remotas y aisladas. Sus características y preferencias de diseño pueden dar una idea de su evolución y coherencia con el entorno. Dicho esto, en la Sección 3.1 se presenta el primer producto de esta investigación doctoral, que cobija una extensa y profunda revisión literaria de más de 250 investigaciones en HRES, con el objetivo de visualizar los HRES off-grid a nivel mundial, sus principales arquitecturas, la forma en que incorporan los recursos renovables a diferentes latitudes y cuáles son los principales desafíos y tendencias.

1.2. Caracterización de los recursos renovables

Todo sistema eléctrico se divide en dos elementos fundamentales: generación y consumo. El primero se encarga de transformar un recurso primario (renovable o no renovable) en energía eléctrica. El segundo hace referencia a la demanda de electricidad del sector residencial, público, comercial, industrial o de transporte. Un sistema energético debe conservar un equilibrio entre ambos elementos. Por lo tanto, caracterizar el recurso primario es fundamental para establecer su potencial, comportamiento y tecnología de transformación. Sin embargo, la falta de datos confiables y precisos sobre la disponibilidad y potencial de un recurso renovable, obstaculiza el desarrollo de proyectos HRES, especialmente en los países en vía de desarrollo [29], donde se presentan los mayores índices de pobreza energética rural.

Diferentes metodologías se usan para caracterizar recursos renovables [30]:

- ✓ **Mediciones en sitio.** Corresponde a los métodos clásicos que utilizan resultados de campañas de medición en terreno. Torres meteorológicas, boyas, ADCPS (Acoustic Doppler Current Profilers), vuelos con tecnología Lidar o radares son algunos de los instrumentos utilizados para caracterizar los recursos renovables. Este tipo de caracterización del recurso tiene mayor relevancia cuando hay un fuerte interés por la explotación comercial de un lugar, ya que la disponibilidad de mediciones en entidades públicas es escasa.

  Los datos obtenidos con mediciones en terreno son muy fiables y precisos en la caracterización de las variables físicas, lo que proporciona un menor riesgo de inversión en los proyectos con energías renovables.

  Sin embargo, y sumado a la carencia de mediciones que cubran amplias zonas o territorios, son comunes los problemas de lagunas, duplicaciones de datos, pasos de tiempo repetidos y errores en la medición por falta de calibración de los equipos. Estas discrepancias deben ser filtradas para obtener un conjunto de datos continuo [31].

- ✓ **Mediciones con sensores remotos satelitales.** Las velocidades del viento en la capa límite inferior pueden medirse con el uso de satélites. De igual forma, datos de coberturas de nubes obtenidos por satélites, en conjunto con modelos de transferencia radiativa basados en estadística, son útiles para estimar la irradiación solar en superficie. Sin embargo, las resoluciones espacio-temporales del conjunto de datos de satélite están limitados por la capacidades tecnológicas de los sensores utilizados.

- ✓ **Modelos de predicción numérica del tiempo.** Este tipo de metodología utiliza representaciones matemáticas de procesos atmosféricos para hacer predicciones de los principales indicadores metereológicos. Entre las ventajas de usar esta metodología se encuentran: una alta correlación de los campos de viento e irradiación solar al interior de la grilla modelada, simulaciones que cobijan el comportamiento de las variables metereológicas durante largos periodos de tiempo. Por otro lado, entre las desventajas de este enfoque está la resolución gruesa, los altos costos computacionales y la escasa representación de los procesos nubosos, que repercuten en la calidad de la modelización del recurso solar.

Evaluar el recurso marino, solar o eólico en una población aislada representa un desafío mayor en la optimización de un HRES off-grid. La escasa disponibilidad de datos públicos y redes de medición en terreno, la alta resolución de modelos computacionales que no cubren el comportamiento de variables físicas a microescala o simplemente, la carencia de resultados de modelos del océano o climatológicos en países en vía de desarrollo, suponen un esfuerzo mayor en la investigación de soluciones energéticas. Por lo tanto, ¿qué consecuencias se evidencian en el dimensionamiento de un HRES off-grid si se usan mediciones en sitio – cuando existen –, sobre datos obtenidos por sensores remotos? En la mayoría de los casos, seleccionar una fuente de información, es cuestión de disponibilidad. Sin embargo, se presentan casos donde el investigador tiene acceso a datos del recurso renovable resultado de diversas técnicas de caracterización, por lo tanto, ¿cuál es el resultado si se simula y optimiza un HRES con tres fuentes de información?.

Explicado lo anterior, es lógico pensar que utilizar diversas fuentes de información origina un conjunto de soluciones en los HRES simulados y optimizados. A los ojos de investigadores experimentados ese axioma se confirma, sin embargo, en nuestro mejor esfuerzo, no encontramos información que cuantifique la diferencia en la optimización de HRES con diferentes fuentes de información. En ese sentido, el segundo producto de esta investigación doctoral reduce esa brecha del conocimiento, al cuantificar el sobre- o sub-dimensionamiento en la optimización de una arquitectura HRES off-grid. Para lograrlo, se usó HOMER (Hybrid Optimization of Multiple Energy Resources) Pro v3.14, uno de los software comerciales más empleados en la literatura para simular y optimizar HRES [32]. La propuesta es dimensionar un sistema híbrido de energía renovable compuesto por: paneles solares, miniturbinas eólicas, generadores diesel de soporte y baterías Li-Ion. Por el lado de la carga, se caracterizó el perfil de consumo de la isla Las Huichas (caso de estudio), comunidad insular ubicada en los fiordos de Chile, con 840 habitantes y dependiente de la importación de combustibles fósiles para alimentar 2 generadores diesel. Aunque esta investigación propone HRES off-grid sustentables e independientes energéticamente de recursos foráneos, se estableció como criterio de diseño un backup energético asociado a uno de los 2 generadores instalados en la isla.

La solución energética propuesta, se alimenta con tres fuentes de información, donde se ha caracterizado, con series de datos de un año, el recurso eólico y solar de la isla. Las fuentes de información usadas son: *Caso a)* NASA Power Database que corresponde a un producto climatológico, *Caso b)* resultados de un año de datos de modelos atmosféricos y de radiación solar, y *Caso c)* campaña en terreno para caracterizar los recursos en la isla Las Huichas (45.15°S 73.52°O). En la Sección 3.2 se describen con detalle los elementos del sistema energético estudiado: generación y consumo, además de exponer sólidas conclusiones en los resultados obtenidos.

1.3. Energías marinas en HRES off-grid

Más del 70 % de la superficie terrestre está cubierta de agua. Los océanos, además de proveer alimento, transporte, recreación, también concentran un recurso energético aprovechable que oscila entre 45000 a 130000 TWh/año [33]. Este potencial puede cubrir la demanda mundial de electricidad que se ubica en 28466 TWh/yr (año 2021). Sin embargo, y como se explica en [1], la participación de las energías marinas en soluciones HRES off-grid es escasa. La Tabla 1.3.1 detalla la participación de los principales recursos renovables en HRES off-grid. Allí se evidencia que la mayor atención e investigación está asociada a soluciones solares y eólicas. No obstante, a mayor latitud el recurso solar reduce su potencial debido a: i) una mayor nubosidad que impacta directamente la irradiación que incide en la superficie terrestre y, ii) la variación en la cantidad de horas de sol efectivas por los cambios estacionales a lo largo del año. Respecto al viento, en latitudes medias-altas, se identifican altos potenciales eólicos en zonas costa afuera. Este viento offshore tiene una mayor consistencia y fuerza que se ve reflejado en la generación de olas, lo que impacta positivamente el potencial undimotriz disponible para comunidades costeras. Una situación similar ocurre con las velocidades de la corriente mareal, que alcanzan niveles extraordinarios en zonas de media-alta latitud como los fiordos [34].

De las 168 investigaciones analizadas en [1], únicamente el 9 % contempla algún tipo de energía marina (un HRES en fase operacional, el resto en fase conceptual), todas ubicadas en el hemisferio Norte. A su vez, más del 50 % de los WEC tienen procedencia Europea, con una fuerte tendencia hacia los ***point absorber***. EE.UU en segunda posición, demuestra un creciente interés en dispositivos WEC, mientras países como Chile (con un ***point absorber*** instalado) y Nueva Zelanda están rezagados en esta industria, a pesar de contar con excelentes condiciones de oleaje [35]. En ese sentido, Chile es un país bendecido con toda clase de recursos renovables. Desde el desierto de Atacama hasta el estrecho de Magallanes, los recursos renovables registran los mejores índices energéticos. Particularmente, las olas en la zona austral poseen uno de los mayores potenciales energéticos del mundo (hasta 90 kW/m) [36] y existen flujos de corriente mareal excepcionales que pueden exceder los 4 m/s [37].

Tabla 1.3.1: Investigaciones en HRES off-grid a nivel mundial, discriminadas por el tipo de recurso primario utilizado y clasificadas en tres zonas climáticas: tropical, subtropical ($+23°$ $<$latitud $\leqslant +36°$ y -23° $>$latitud $\geqslant -36°$) y temperada ($+36°$ $<$latitud $\leqslant +63°$ and -36° $>$latitud $\geqslant -63°$). Los HRES que incluyen al menos un recurso marino pertenecen al hemisferio norte. Adaptado de [1].

Latitud	Olas	Corriente Mareal	OTEC	Sol	Viento	Biomasa	Pequeña Hidro	Biogas	Diesel	Observaciones
Tropical	2	2	0	67	45	3	9	4	51	El sol y el viento prevalecen; OTEC no se utiliza en HRES incluso cuando el gradiente de temperatura del océano es óptimo. Las olas y las mareas son poco involucradas en HRES.
Subtropical	3	0	1	46	35	6	6	3	29	El sol y el viento son los recursos más estudiados e integrados en los HRES. Las olas sólo se evalúan en 3 investigaciones.
Temperada	5	2	0	32	34	1	1	1	23	Zona climática con alto potencial energético marino, sin embargo, el sol y el viento se consolidan como los recursos preferidos con mayor atención.

Alrededor de 2400 millones de personas están asentadas en una franja de 100km desde la costa [38]. Aunque el potencial energético del océano supera la demanda actual de electricidad, la participación de energías marinas en matrices energéticas a nivel mundial es de apenas el 0.015 % [39]. La alta predictibilidad de la energía marina, el alto potencial energético y su operación con cero GHG, la convierten en aliada de la transición energética, la mitigación del cambio climático y un recurso complementario en los sistemas solares y eólicos offshore.

Ahora bien, no solo hay poca integración de recursos marinos en HRES off-grid, además, los software comerciales más usados para simulación y optimización de HRES: HOMER, RETScreen, iHOGA, Energy Plan, TRNSYS, Hybrid2 [32], no poseen módulos específicos y detallados para cada energía marina. Bajo estas circunstancias, algunas investigaciones [40, 41, 42, 43] intentan emular el comportamiento de un dispositivo WEC o turbina marina con los módulos existentes en HOMER, lo que indudablemente puede llevar a imprecisiones en los resultados. Todo lo anterior, exhibe bases sólidas para:

- Investigar e incorporar las energías marinas en soluciones HRES off-grid que sustenten el perfil de carga de poblaciones remotas y cercanas a la costa. Hay un enorme potencial energético en el océano, que utilizado de manera sustentable y responsable, puede reducir la pobreza energética de las comunidades. En este sentido, Chile, y el hemisferio sur en general, no escapa a la carencia de investigaciones que simulen y optimicen HRES con energías marinas [1]. Por lo tanto, hay una oportunidad para que las matrices energéticas primarias (grandes centros de generación) como secundarias (sistemas pequeños y medianos de generación), integren los recursos renovables marinos, luego de iniciar y sostener la evaluación de los impactos en el uso de dispositivos WEC y de corriente mareal en los territorios.

- La poca integración de energías marinas en HRES va acompañada de una baja disponibilidad de software comercial que modele su comportamiento en sistemas de generación. Por lo tanto, esta investigación propone un algoritmo novedoso que, a través de optimización lineal, dimensiona HRES off-grid con una función multiobjetivo. La minimización del indicador LPSP (Loss of Power Supply Probability) y el indicador LCOE (Levelized Cost Of Energy) conlleva a un conjunto de configuraciones con factibilidad técnica y económica para satisfacer cargas off-grid en cualquier latitud.

- Hay una excesiva concentración de investigaciones de HRES off-grid en el hemisferio Norte. De ellas, muy pocas han estudiado los beneficios y oportunidades vinculados a los recursos renovables marinos. Lamentablemente, países con un potencial marino superior como Chile, Nueva Zelanda, República de Mauricio [35], incluso Sudáfrica, hasta donde sabemos, no han dedicado suficientes esfuerzos en el estudio y transformación de sus recursos marinos, con un enfoque en soluciones descentralizadas HRES. Esta investigación propone trabajar en ese sentido, evaluando la energía undimotriz y mareomotriz en soluciones HRES off-grid que incrementen la independencia energética de comunidades insulares/costeras.

La Sección 3.3 describe con detalle la metodología utilizada para diseñar el algoritmo que simula y optimiza sistemas híbridos de energía renovable, poniendo mayor atención a la incorporación de recursos marinos, que en ciertas configuraciones de diseño, se convierten en recursos complementarios a los HRES "tradicionales". Además, el algoritmo es capaz de decidir, en el escenario de no cumplir los criterios iniciales, el momento adecuado para acoplar un sistema de almacenamiento de energía (baterías Li-Ion) en el HRES simulado. Los resultados son prometedores y revelan que los dispositivos WEC pueden competir con sistemas solares, donde dispositivos clasificados como ***overtopping*** y ***attenuator***, poseen índices de LCOE muy interesantes bajo diferentes condiciones de diseño (LPSP).

Capítulo 2

Hipótesis y objetivos de investigación

2.1. Hipótesis

La integración de la energía marina en los sistemas híbridos off-grid tradicionales: PV/Wind/Diesel/Battery, aumenta la confiabilidad del suministro eléctrico a comunidades remotas costeras en latitudes medias-altas.

2.2. Objetivos

2.2.1. Objetivo General

Integrar el potencial de las energías marinas: undimotriz y mareomotriz, en el diseño de sistemas híbridos de generación eléctrica off-grid tradicional, para incrementar la confiabilidad del suministro eléctrico en poblaciones costeras aisladas de la red en latitudes medias-altas.

2.2.2. Objetivos específicos

1. Detallar las características técnicas y operativas de los HRES off-grid a nivel mundial.
2. Evaluar el impacto en el dimensionamiento de los HRES off-grid, debido al uso de diferentes métodos para caracterizar los recursos renovables.
3. Caracterizar la demanda de energía eléctrica y potencial de las olas y corriente mareal en una comunidad insular – caso de estudio.
4. Simular y optimizar un HRES con energías marinas y evaluar la factibilidad técnica y económica en el caso de estudio.

A continuación se describen las principales tareas que tributan al cumplimiento de los objetivos específicos y evaluación de la hipótesis planteada:

Detallar las características técnicas y operativas de los HRES off-grid a nivel mundial

Una amplia y exhaustiva revisión literaria es indispensable para establecer el estado del arte de los HRES off-grid y su dinámica en diferentes latitudes. Los HRES son sistemas que transforman energía primaria en electricidad, acoplados a sistemas de almacenamiento de energía. La generación descentralizada y el aprovechamiento de los recursos locales son factores diferenciadores de estos sistemas energéticos. Sin embargo, ¿Cuál ha sido la evolución y penetración de los HRES off-grid en las zonas remotas?, ¿Cuáles son las arquitecturas más empleadas en los HRES off-grid?, ¿Qué rol juegan las energías marinas en estos sistemas? Aunque de manera preliminar se reseña una baja integración de energías marinas en HRES, responder a las preguntas planteadas despejará el estado actual de las energías marinas en HRES.

La información concerniente a los HRES off-grid se va a categorizar en tres (3) grandes grupos:

- ✓ Latitud: Se hace una diferenciación entre tres zonas geográficas principales. La zona tropical que comprende latitudes entre -23° y +23°, zona subtropical para estudios que se realizaron entre 23° y 36° del hemisferio norte y sur y, por último, la zona templada que obedece a latitudes mayores a 36° en ambos hemisferios. La diferenciación entre latitudes da una idea clara de los recursos renovables con mayor potencial, y cómo se integran esos recursos en los HRES estudiados.

- ✓ Población y sector económico: Las comunidades rurales se caracterizan por su baja densidad poblacional y poseer economías primarias: agricultura, pesca y minería artesanal, explotación forestal, etc., actividades con baja demanda de energía eléctrica. Por lo tanto, identificar el perfil de consumo de las comunidades es importante al momento de configurar un HRES. Dicha caracterización proporciona datos relevantes en la elección del recurso renovable más apropiado, además de validar los periodos de mayor consumo y su sincronización con la producción de electricidad.

- ✓ Almacenamiento de energía: Los HRES son sistemas energéticos que incluyen sistemas de almacenamiento de energía. Los recursos renovables son altamente variables y su comportamiento es difícil de predecir con anticipación (a excepción de la energía mareomotriz), lo que puede ser contrarrestado con sistemas que acumulen energía para ser usada en periodos de baja generación o alto consumo energético.

Evaluar el impacto en el dimensionamiento de los HRES off-grid, debido al uso de diferentes métodos para caracterizar los recursos renovables

Para caracterizar los recursos renovables los investigadores emplean alguna de las fuentes de información disponible: registros a corto plazo y registros a largo plazo. Por lo general, los registros a corto plazo están asociados a equipos instalados por períodos de tiempo de un año (por ejemplo, torres meteorológicas). Estos registros implican una pequeña cobertura espacio-temporal, que puede ser compensada con mayor precisión en las mediciones. Por otro lado, los registros a largo plazo están vinculados a resultados de modelos numéricos de predicción o sensores de satélites. Las climatologías basadas en registros a largo plazo, al ser una media, filtran los detalles de las variaciones climáticas interanuales e interdecadales. Por lo tanto, es esencial seleccionar una fuente de información adecuada para caracterizar los recursos renovables.

En ese sentido, si se simula y optimiza un HRES con diferentes fuentes de información, inequívocamente se obtendrá un conjunto distinto de resultados. Sin embargo, ¿se han cuantificado esos resultados que la experiencia y el sentido común nos advierten? ¿cuál es el rango de variabilidad de los indicadores técnicos y económicos de cada "HRES optimizado"?, o dicho de otro modo, ¿cuál es el porcentaje de sobredimensionamiento o subdimensionamiento en los "HRES simulados y optimizados"? Para responder estas preguntas, se utilizará uno de los principales software comerciales de optimización de HRES: el Hybrid Optimization of Multiple Energy Resources (HOMER) del National Renewable Energy Laboratory (NREL) version 3.14. Con HOMER Pro se va a simular un HRES PV-Wind-Diesel-Battery: sistema compuesto por paneles solares, turbinas eólicas, generador diesel y banco de baterías, y se estudiará el impacto originado por el uso de tres fuentes diferentes de radiación solar y velocidad del viento: NASA

Power DataBase (caso a), resultados de modelos atmosféricos y de radiación solar (caso b) y, campañas de prospección de recursos eólicos y solares en el caso de estudio (caso c).

Caracterizar la demanda de energía eléctrica y potencial de las olas y corriente mareal en una comunidad insular – Caso de estudio

En consonancia con el objetivo general de esta investigación, se va a emplear un caso de estudio en los fiordos chilenos, zona de media-alta latitud con alto potencial energético asociado a olas y corriente mareal, para integrar las energías marinas en HRES off-grid y determinar su factibilidad técnica y económica. Como caso de estudio se eligió La Isla Las Huichas (45.15°S 73.52°O), ubicada en el noreste del Archipiélago de los Chonos, Región de Aysén, donde vive una pequeña comunidad que es dependiente de combustibles foráneos para atender su demanda de electricidad.

Todo sistema eléctrico tiene dos elementos fundamentales para lograr el equilibrio: generación y consumo (carga). Obtener registros precisos de la carga y una acertada caracterización de los recursos renovables, es tarea fundamental para una correcta optimización del HRES. Por lo tanto, es necesario contar con un perfil de carga con patrones horarios y anuales de la comunidad insular. En esta investigación se han programado viajes a la región de Aysén, con el firme objetivo de obtener registros históricos de la carga, donde se pueda observar la variación de consumo por temporada climática.

Utilizando técnicas similares a las ya definidas, se recopilarán los datos asociados al consumo de diesel, eficiencia del grupo electrógeno, indicador SAIDI para establecer calidad del servicio eléctrico en la comunidad. Adicionalmente, se tiene que caracterizar cada recurso renovable disponible: olas, corriente mareal, sol y viento, los cuales serán modelados y simulados en un algoritmo novedoso, diseñado específicamente para esta investigación.

Toda la descripción física detrás de los recursos renovables, se realizará con la evaluación de textos científicos, bases de datos de centros de investigación, bases de datos con información climatológica y oceanográfica, además de entrevistas con expertos.

Simular y optimizar un HRES con energías marinas y evaluar la factibilidad técnica y económica en el caso de estudio

En esta investigación se desarrollará un algoritmo de optimización lineal para simular y optimizar HRES off-grid. Los principales módulos que componen el algoritmo son: i) **módulo olas** encargado de estudiar la producción de electricidad a partir de 3 WEC de diferente tecnología, **módulo corriente mareal** donde se evalúa una turbina marina y se crea una serie anual con la producción de electricidad, **módulo solar** responsable de informar la radiación global horizontal en superficie inclinada (para 7 grados de inclinación, β) y su posterior aporte en energía eléctrica y, iv) **módulo viento** donde se estudia el comportamiento de una miniturbina eólica y su producción de energía. Estos cuatros módulos alimentarán un módulo central de optimización, que se encarga de encontrar la solución mínima a dos funciones objetivo: LPSP y LCOE.

Basándonos en múltiples combinaciones de HRES: WEC-BESS, TT-BESS, PV-BESS, WT-BESS, el algoritmo optimizará la mejor configuración que responda a los criterios de diseño de LPSP y menor LCOE. De otro lado, el algoritmo tendrá la capacidad de simular el HRES sin sistema de almacenamiento. En caso de no encontrar soluciones viables, incorporará un sistema de almacenamiento basado en baterías Li-Ion, que mejore el flujo de energía desde el HRES hacia la carga. Otros indicadores que se informarán son: surplus de energía anual, Costo Actual Neto (NPC, por sus siglas en inglés), horas de autonomía, energía generada a partir de cada fuente, entre otros.

El concepto de confiabilidad de un sistema eléctrico se puede definir como la continuidad del servicio eléctrico cumpliendo con indicadores de calidad y seguridad. Es decir, contar con la generación suficiente para poder atender la demanda de energía eléctrica de los clientes finales. En ese entender, los sistemas híbridos simulados deben ofrecer un servicio eléctrico continuo, que atienda la totalidad de la demanda (LPSP = 0) y que sea continuo en el tiempo. Para ello, el indicador técnico LPSP es fundamental en la evaluación de la confiabilidad, ya que explica la capacidad del HRES para atender el 100 % de la carga cuando se requiera, especialmente en periodos de máxima demanda de energía.

Capítulo 3

Resultados

3.1. Tendencias y características de los HRES off-grid

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Off-Grid Hybrid Electrical Generation Systems in Remote Communities: Trends and Characteristics in Sustainability Solutions

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Abstract

The objective of this review is to present the characteristics and trends in hybrid renewable energy systems for remote off-grid communities. Traditionally, remote off-grid communities have used diesel oil-based system to generate electricity. Increased technological options and lower costs have resulted in the adoption of hybrid renewable energy-based systems. The evaluated 168 studies from the period 2002–2019 considered energy developments in Asia, northern Europe, Africa and South America, with the great majority in the northern hemisphere (n = 152, 90.5 %). Many of the studied systems were located in tropical (44.1 %) and subtropical areas (31.0 %).

Our review shows that most of the studied approaches combined photovoltaic (PV) and wind energy, and that diesel generators are the preferred backup system (61.3 %), while batteries are the preferred method of energy storage (80.4 %). Communities far from coasts have more options for renewable energy sources, such as biogas. Although half the studies were related to communities with access to marine-based renewable energy resources, their use was only referred to in fifteen studies. In terms of trends, the studies show mature development of PV and wind-power technology for off-grid hybrid systems independent of the latitude, which is preferred for being proven and accessible methods. The preferred storage method is batteries, and diesel is the preferred backup system given the low efficiency of PV and the intermittent character of wind power.

Introduction

The development of communities is closely related to uninterrupted access to electrical energy. The isolation of communities in remote rural areas hinders the provision of electrical energy by traditional electrical power generation and transmission methods. The World Bank reported in 2018 that around 724 million people did not have regular and reliable supply of electrical energy, with 84.2 % of these people living in rural areas isolated from power grids, and the remaining 15.8 % living in urban areas [8]. Electrical energy is a fundamental pillar of economic and social development, because of which it is common that the highest indices of poverty and the lowest levels of technological development are found in rural communities [44]. The problem is more acute with remote communities and communities on islands. One of the characteristics of rural communities is low population density. The families that make up these populations are widely scattered, making it difficult to meet energy demands and making electrical transmission networks expensive. Complex geographic conditions and low energy demand make providing electrical energy by conventional methods impractical (that is, extension of electrical transmission networks and substations), especially in developing countries, where electricity is vital for economic participation and the social welfare of rural communities. Areas that do not have electricity generally also lack essential infrastructure like schools, medical centers, means of communication, access to potable water and others, which is reflected the fact that the human development indices of electrified communities are higher than those of communities without electricity [45].

A widely used method for generating electricity for remote communities is distributed generation systems, characterized by the use of electric generators that produce electricity by burning fossil fuels, in particular diesel [15, 46, 47, 48, 49]. Diesel generators are relatively inexpensive, the technology is wide-spread and the construction time for an electrical station is comparatively short. Remote communities are often not easily accessible, so that system maintenance can be deficient. Because fuel and replacement parts must be obtained from urban centers, together with continuous fluctuations in fuel prices, this approach is not advisable for poor rural communities

[50]. The use of diesel plants in remote areas depends on the presence of roadways to deliver the fuel, with high transport costs for remote communities. The remoteness of communities also negatively affect the required and frequent maintenance. Despite all the disadvantages, diesel is still the main resource for generating energy for isolated communities [51]. Diesel is associated with other negative effects like: (i) contributing to concentrations of greenhouse gases [20], (ii) reducing air quality [52], (iii) deteriorating human health [21], (iv) high transport [22] and storage costs, (v) volatility in international prices [53], (vi) the need for periodic maintenance [51] by qualified staff, (vii) fire hazard during transportation and storage [54], and (viii) it is a limited primary resource [55] that is not renewable on a human time scale.

Off-grid hybrid renewable energy systems (HRES-OFF) have been proposed to mitigate the negative aspects of using diesel to generate electricity ([56, 57, 58]). These systems involve different renewable resources to generate electricity, like solar, wind, hydro, geothermal, biomass, biofuel, wave, tidal, and fuel cell energy, among others, as well as energy storage systems like batteries, pumped hydro storage (PHS), hydrogen, flywheel and others. They can also involve small electrical generators. Solar and wind power are the most often used renewable energy sources worldwide in HRES-OFF. The main studied and implemented HRES-OFF configurations are photovoltaic (PV)-Wind-Diesel-Battery, PV-Wind-Battery and PV-Diesel-Battery.

Batteries are the main storage method used in HRES-OFF systems, followed by hydrogen and pumped hydro storage systems, which have limited application owing to the topography in many isolated areas. However, the level of solar radiation decreases at latitudes nearer to the poles, while offshore wind power is greater in middle and high latitudes [59]. Related to stronger and more consistent winds is the generation of waves along coasts, which can be used as an energy source by remote coastal communities. Likewise, tidal changes are a common phenomenon to all the marine coasts of the world, and that reach extraordinary levels in certain places in the middle and high latitudes [60], making the tides an alternative source of renewable energy.

Investing in a single technology generally results in oversizing systems, which increases initial costs. A hybrid system can overcome the intermittent nature of renewable energy sources and the problem of oversizing and improve the reliability of energy supply. However, hybrid systems have received limited attention because of their greater complexity and the scarcity of works that have considered the question of reliable supply of electricity to rural areas [61]. We expect this study will contribute to decision-making regarding the use and configuration of HRES-OFF systems in remote communities as the use of renewable energy becomes more economically viable due to the increased cost of fossil fuels and lower costs of equipment to make use of renewable energy [62].

This article is structured as follows: Section 2 presents the criteria used in this review of the state-of-the-art in implementing or simulating off-grid hybrid systems in remote communities. Section 3 summarizes the results found in the reviewed studies in terms of the methodologies used (Section 3.1), geographic location (Section 3.2), the latitudes of the studied areas (Section 3.3), the population where HRES-OFF are established (Section 3.4), the type of energy used (Section 3.5), and trends in these factors (Section 3.6). Section 4 discusses the main findings, and finally the conclusions are presented in Section 5.

Methods

We reviewed around 250 articles that had a combination of keywords "remote areas", "hybrid-power systems", "hybrid renewable energy systems", and "off-grid power systems". We excluded articles that described on-grid systems and off-grid systems in urban areas given that our interest is off-grid power systems in remote communities. We also excluded studies that only quantified the availability or variability of renewable energy [37, 63, 64, 65] This selection led us to study in detail a total of 168 articles investigating HRES-OFF in remote communities isolated from electricity grids. The articles were classified according to the variables: geographic location, HRES-OFF configuration, electricity demand, number of inhabitants, and main economic activity. The geographic location includes several components, namely: i) hemisphere, ii) latitude according to the classification of three main climatic zones: tropical (latitudes between $+23°$ and $-23°$), subtropical (($+23° <$ Latitude $\leq +36°$ and $-23° >$ Latitude $\geq -36°$) and temperate ($+36° <$ Latitude $\leq +63°$ and $-36° >$ Latitude $\geq -63°$), iii) continent and country. Categorizing the geographic locations of target communities establishes an evaluation criteria in terms of the potential of local energy resources, that is to say, coastal communities (which can be island communities and communities near coasts) have greater access to marine-based solar and offshore wind resources, while communities in continental interiors have more access to biomass, small-scale hydro, geothermal and other energy resources.

The renewable energy sources, storage strategy and combination with backup electric generating systems of all the HRES-OFF were identified, as well as the number of inhabitants and economic activities, these being variables that indicate the behavior and energy profile of isolated communities. Therefore, daily energy requirements vary according to economic characteristics and the potential of the surrounding territory.

Results

HRES-OFF have been implemented and evaluated around the world to meet the need to generate electricity in areas isolated from conventional electrical networks, (Figure 3.3.10). The evaluated HRES-OFF studies were concentrated in the northern hemisphere (90 %), with only 10 % of the studies dealing with HRES-OFF applications in the southern hemisphere.

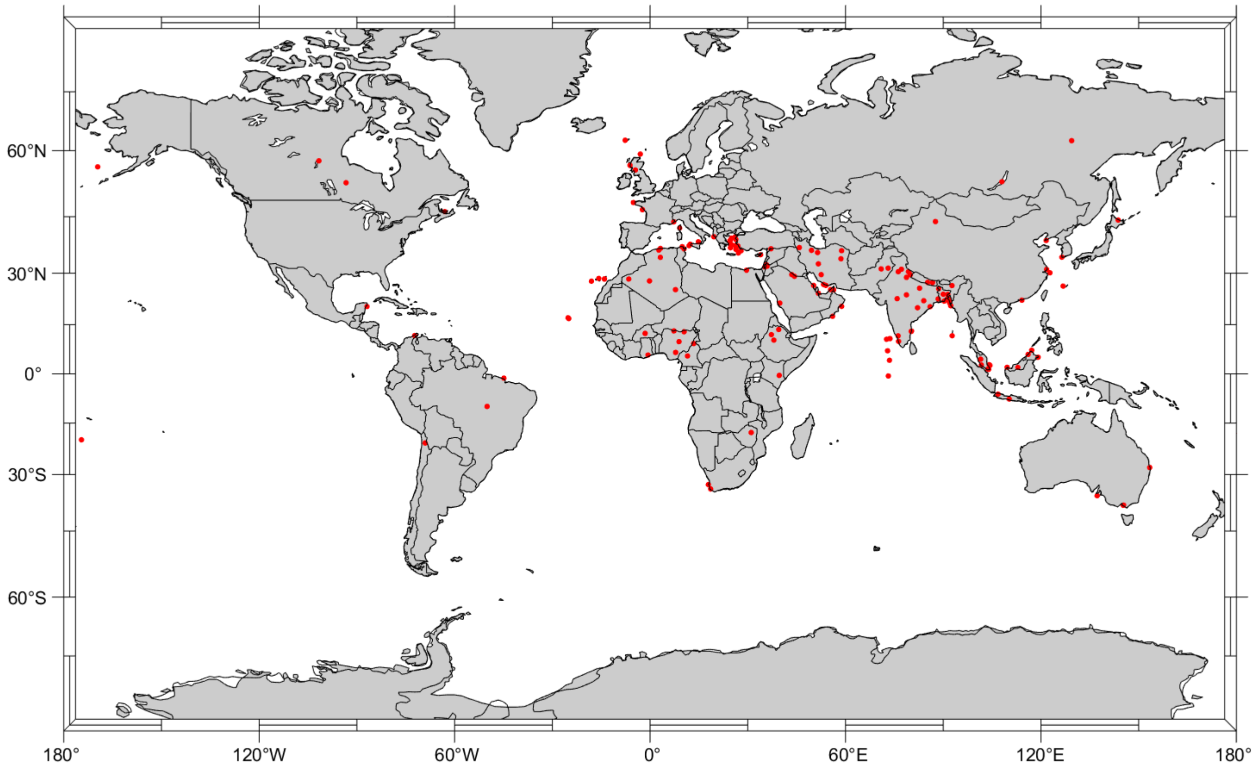

Figura 3.1.1: Geographic locations of the investigations that evaluated HRES-OFF in remote communities.

Methodologies Used

The investigations into HRES-OFF did not have a common systematic methodology to characterize the power generation system and the relevant communities. Consequently, it was not possible in all cases to determine the technical and socioeconomic variables established for this review.

Regardless of the state of development of a renewable energy project, off-grid or on-grid, it is essential that researchers employ software tools or analytical methodologies to determine the technical and economic feasibility of the proposed system. According to the classification in [66], RETSCreen and HOMER are widely used tools in renewable energy systems, including hybrid systems. RETScreen includes all aspects related to heating and electricity. The tool H_2RES models all aspects of the heating sector, as well as transport technology related to the use of biofuels as vehicle fuel. Consequently, each tool responds to a particular objective. In HRES-OFF studies, a different frequency of use was observed.

Table 3.1.1 presents the main computer programs used in the HRES-OFF studies or in the absence of computer programs, the methodologies used. A marked preference can be noted for the HOMER program [67], which was developed by the National Renewable Energy Laboratory in the USA. HOMER includes wind turbines, PV arrays, biomass, microturbines, run-of-river hydropower, fuel cells, and internal combustion engine generators as energy sources, and batteries, flywheels and hydrogen as storage strategies. It does not include wave, tidal, OTEC, salinity gradient and geothermal as primary sources of energy. Twelve studies did not indicate the software/methodology used to analyze the hybrid system. In some investigations, the authors used two analytical methods. For example, in [68], the authors investigated an optimal HRES-OFF system based on PV arrays and wind turbines, which precisely and adequately resolved the technical and economic feasibility of employing a hybrid distributed power generation system in a community in northeastern Nigeria. To do that, the researchers used RETScreen to analyze the feasibility and HOMER to optimize the HRES-OFF system. Finally, 35 studies used algorithms and mathematical models designed by the authors, using different informatic tools like C++, THESIS, Excel Spreadsheet, Engineering Equation Solver (EES) and others.

Tabla 3.1.1: Methodology or software used in HRES-OFF analyses.

Software/Methodology	**# Articles**
HOMER	90
Not indicate	12
MATLAB	6
GSA/NGSA	5
Genetic Algorithm	4
HOMER & Matlab	3
TRNSYS	3
HOMER & RETScreens	2
HOMER & HYBRIDS	1
HOMER & Digsilent	1
HOMER & Grasshopper-Cuckoo-TLBO	1
HOMER & PSO-CPSO	1
H_2RES	1
HOGA	1
RETScreen	1
WindPro	1
Others	35
	168

Results by Geographic Location

A total of 152 studies focused on communities in the northern hemisphere. Table 3.1.2 shows the main variables of the representative investigations. There were only 16 studies for the southern hemisphere, the details of which are shown in Table 3.1.3. The highest number of HRES-OFF studies were in Asia, followed by Europe in second place, Africa close behind, the Americas in fourth place with nine studies, and finally Oceania (Figure 3.1.2). The Asian country with the largest number of HRES-OFF-related studies was India, with 21 studies, which may reflect the introduction of an electrification policy in 2003, as well as the need to reduce the use of fossil fuels. India intends to increase the share of non-fossil fuels in generating electricity from 15 % (2016) to 57 % (2027) [69]. Bangladesh, Greece, Malaysia, Iran and China, with 13, 12, 12, 10 and 9 studies, respectively, complete the list of countries with the highest number of HRES-OFF-related studies. Of these, the only developed country is Greece, according to the classification of the United Nations [70]. The others are in transition toward development, that is, they have made a transition from an agricultural to a more industrial economy. Oceania had the lowest number of publications on HRES-OFF, with four for Australia and one each for Fiji and Tonga.

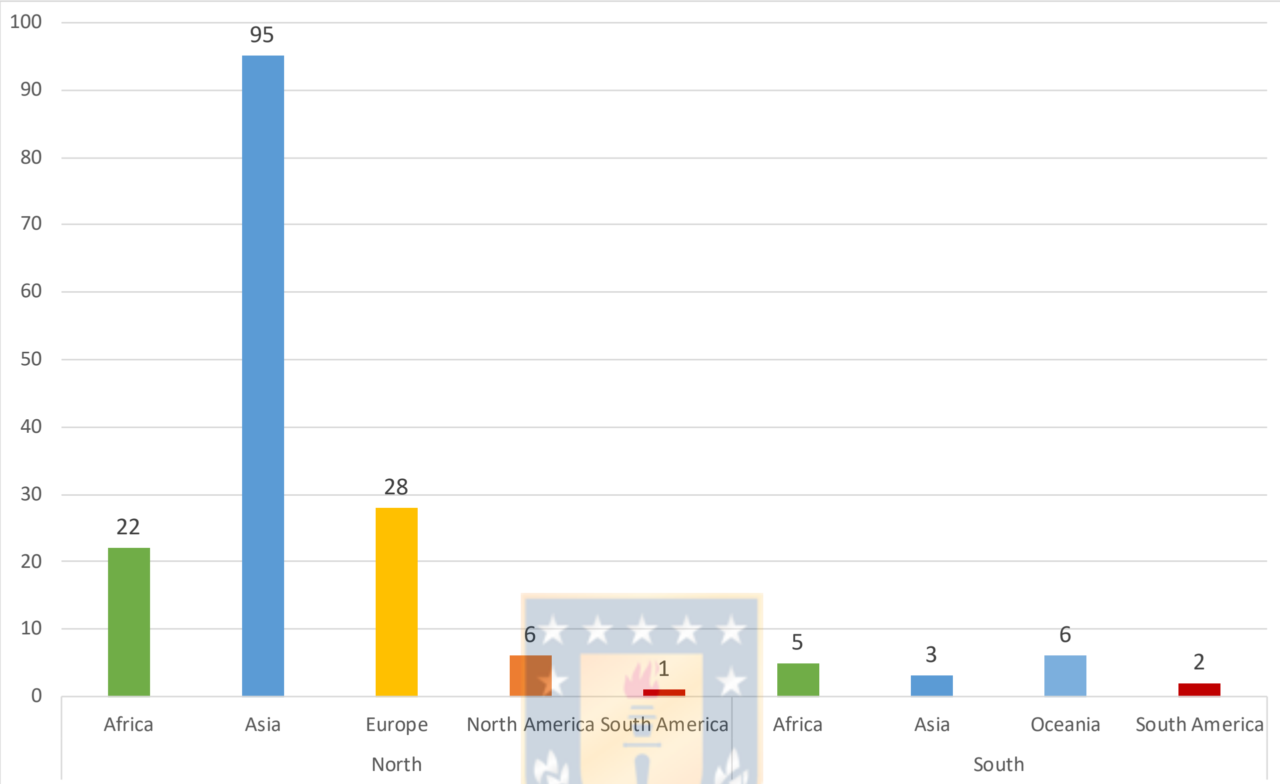

Figura 3.1.2: Classification of the investigations by hemisphere and continent.

Given their geographic situation, island countries, islands, and coastal areas (communities located less than a kilometer from a coast) have more access to marine-based energy resources (wave, tidal, OTEC, salinity gradient), offshore wind energy (with more plant factors than with onshore/inland wind power systems), which can be used as a renewable resource in the definition of HRES-OFF. Communities located in continental interiors have a wider range of available renewable energy sources, such as biomass (associated with residues from forests, harvests, wastewater and solid waste), biogas, small-scale hydro generators, solar, wind and others. Figure 3.1.3 shows that 54 % of the studies, excluding marine-related studies that compared the performance of PV–diesel–battery systems in ports or on ships [21], deal with communities surrounded by or near the sea, that is, more than half deal with communities that have access to marine-based energy resources.

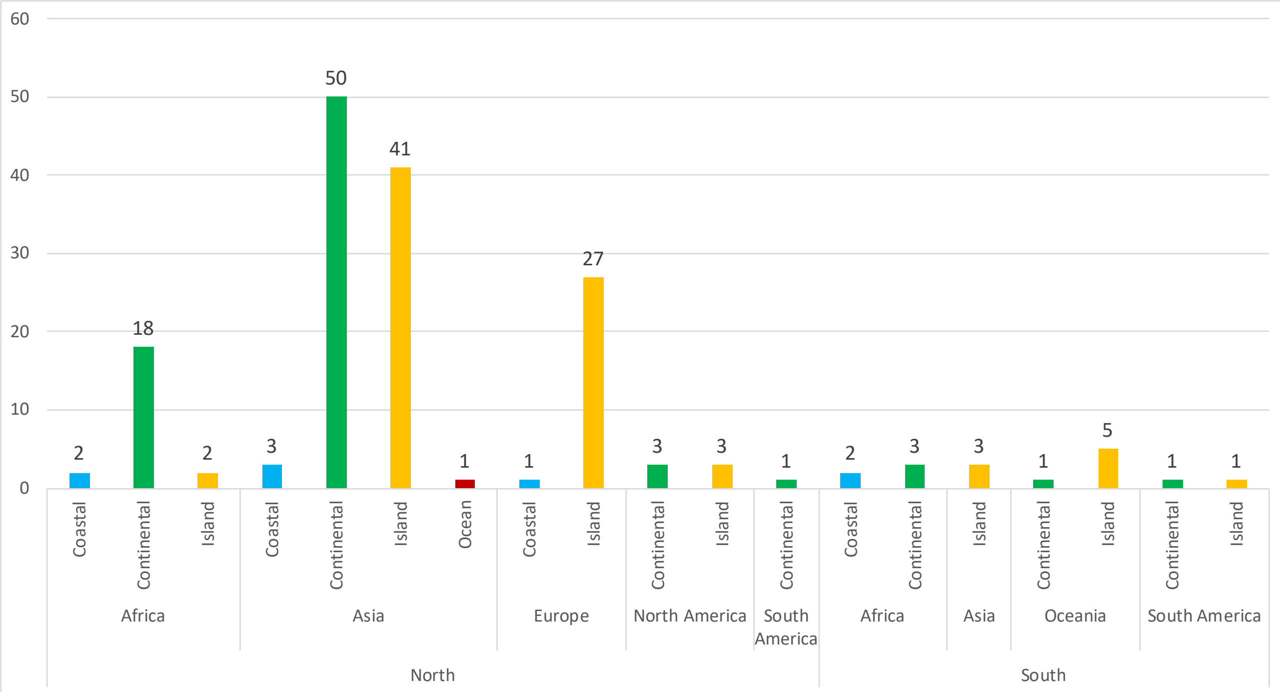

Figura 3.1.3: Geographic classification of the evaluated investigations.

Results by Latitude

One of the advantages of renewable or unconventional energy resources over fossil fuels (coal, petroleum, gas) is their availability and wide distribution globally. However, the energy potential of a renewable resource varies according to atmospheric and geographic conditions, the time of day, and even astronomical forces, such as the tide. There is less solar radiation closer to the poles, and offshore wind power increases in middle and high latitudes. Wave generation all along the coast is associated with stronger and more consistent winds. Likewise, the tides are a physical phenomenon common to all the coasts of the world and reach extraordinary levels in certain places in the middle and high latitudes.

Some 44.1 % of the studies were focused on tropical areas, where solar rays are almost perpendicular. The second highest number of HRES-OFF studies by latitude, with 30.95 % of the studies, was the subtropics. There were fewer studies that dealt with HRES-OFF in the middle and high latitudes (Figure 3.1.4). Therefore, a staggered evaluation was made in each of the climatic zones defined above, making a brief description of some of the studies carried out and a classification of the types of specific configurations (relative to HRES-OFF), type of primary energy source, and storage strategy.

Tabla 3.1.2: Characteristics of some of the evaluated off-grid hybrid systems in the northern hemisphere.

Item	Country/Site	Position	Population	Economical sector	Energy demand	Software	Application	Ref.
1	Greece/Agathonisi	Island	105	Livestock, fish farming and tourism	450 MWh/a	Homer	Simulation	[48]
2	China/Remote Island in Hong Kong	Island	100	N/A	250 kWh/d	Customized[1]	EO	[71]
3	India/Bastar district	Continental	1624	Agriculture	434 kWh/d	Homer	EO	[61]
4	Greece/Ikaria	Island	9000	Fishing and Tourism	4020 kW_p	Customized[2]	Installed	[72]
5	Ethiopia/Dejen District	Continental	63000	N/A	563 kWh/d	Homer	EO	[73]
6	Nepal/Remote villages	Continental	1700	Agriculture	4.67 kWh/d	N/A	Installed	[74]
7	Cape Verde/Sao Vicente	Island	74301	N/A	57 GWh/a	H_2RES	EO	[75]
8	Algeria/Remote village	Continental	425	N/A	4.6 MWh/d	Homer	EO	[76]
9	Canada/Brochet	Continental	537	N/A	8 MWh/d	Homer	EO	[77]
10	Blangladesh/Dhankhali village	Continental	884	Agriculture and Fishing	255 kWh/d	Homer	EO	[78]
11	Saudi Arabia/Rafha	Continental	10000	N/A	44 MWh/d	Homer	EO	[79]
12	Oman/Masirah	Island	12825	N/A	171.5 MWh/d	Homer and Digsilent	EO	[80]
13	Mexico/Cozumel island	Island	79535	Tourism	312 up to 1305 GWh/a	Homer and RETScreens	EO	[81]
14	Spain/El Hierro island	Island	10995	N/A	44.6 GWh/a	Software Red Eléctrica	Installed	[82]
15	Turkey/Bozcaada island	Island	375	N/A	1875 kWh/d	Homer	EO	[83]
16	India/Madhya Pradesh	Continental	120	Agriculture	70 kWh/d	Homer	EO	[84]
17	Malaysia/Kapit	Island Country	350	N/A	140 kWh/d	Homer	EO	[85]
18	Italy/Island of Salina	Island	44362[3]	Tourism	11.36 kWh/d/pers	TRNSYS	EO	[86]

E0 = Evaluation Only; [1] Mathematical models designed by the author; [2] A Monte Carlo simulation; [3] 2504 residents and 41858 tourist in 2009.

Tabla 3.1.3: Characteristics of the evaluated off-grid hybrid systems in the southern hemisphere.

Item	Country/Site	Position	Population	Economical sector	Energy demand	Software	Application	Ref.
1	Indonesia/ Indonesian Village	Island Country	1475	Agriculture	Two cases: 162.5 and 558.5 kWh/d	N/A	EO	[15]
2	South Africa/ Six Cities	Continental and Coastal	N/A	N/A	5.6 kW_p	Homer	EO	[17]
3	Kenia/ Garissa district	Continental	500	N/A	190-200 kWh/d	Homer	EO	[87]
4	Australia/ Gold Coast	Continental	1000	Tourism	15,000 kWh/d	Homer and Hybrids	EO	[88]
5	Brazil/ State of Tocantins	Continental	50	Research	23.8 kWh/d	Homer	Installed	[89]
6	Republic of Fiji/ Gau Island	Island	200	N/A	222 kWh/d	Homer	EO	[90]
7	Kingdom of Tonga/ The Ha'pai group	Island	N/A	N/A	4.2 MWh/d	Homer	EO	[91]
8	Brazil/ Lençóis's Island	Island	393	N/A	4134 kWh/m	Scada	Installed	[92]
9	Australia/Christmas and Kangaroo Islands	Island	2072 and 4417	N/A	4.8 and 15 kWh/d	Homer	EO	[93]
10	Australia/ French Island	Island	180[1]	Sheep and cattle farming	2777 kWh/d	Spreadsheed model and Homer	EO	[94]
11	Republic of Maldives/ Five Islands	Island	N/A	Tourism	26442, 3202, 1051, 373 and 483 MWh	Homer	EO	[95]
12	South Africa/Kwazulu Natal province and Western Cape	Continental	One Household and BTS[2]	N/A	35 and 59 kWh/d	Homer	EO	[96]
13	Zimbabwe/Rural community clinics	Continental	N/A	Health	N/A	Matlab	EO	[97]
14	Australia/Frenchs Island Hinchinbrook Island and South Australia	Island and Continental	30, 50 and 180	Tourism	20.2, 409 and 2600 kWh/d	Homer	Installed	[98]
15	South Africa/Kwazulu -Natal and Cape Columbine	Continental and Coastal	N/A	N/A	9.5 and 58.8 kWh/d	Homer	EO	[99]
16	Indonesia/Minggir subdistrict	Island Country	Fish pond	Aquaculture	2 kWh/d	Homer	EO	[100]

E0 = Evaluation Only; [1] 90 full-time residents and 90 part-time; [2] BTS = Base Transceiver Station.

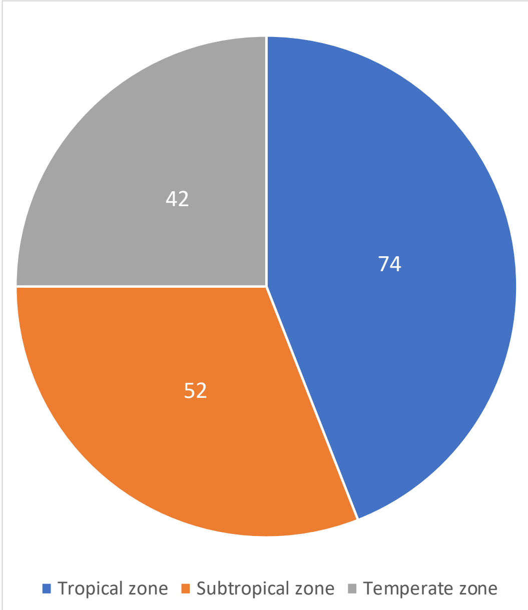

Figura 3.1.4: Number of HRES-OFF investigations categorized by latitude.

Tropical Areas

Ranaboldo et al. (2015) [13] proposed an off-grid electrification project in Nicaragua that would combine solar and wind energy in two power generation strategies, small micro-grids that use the two renewable energy resources, and independent power generation points according to the analysis of demand and the energy potential of the resources at the micro-scale. Ismail et al. (2013a) [14] conducted a technical-economic analysis of an optimal PV–diesel–battery system on a Malaysian island. The main objective of this study was to select the components that make up the hybrid system to minimize the total cost of the system, ensuring the power supply at the required load. To do this, the authors made an energy balance in an 8750-hour time series, and with the application of a genetic algorithm, they established an adequate fit between the energy generated and the load profile at the site of interest. Blum et al. (2013) [15] analyzed a conventional autonomous system (diesel-based electrical generation), and renewable energy options, PV-battery, micro-hydro and hybrid PV–diesel–battery systems to meet the energy demand of an Indonesian community. The parameters for evaluation defined by the authors were the levelized cost of energy generation (LCOE) and the costs and potentials of CO_2 emission abatement. The results showed that micro-hydro electrical generation has the lowest cost of any of the energy technologies, reaching values between 0.14 and 0.16 €/kWh. Hybrid systems that combine diesel and PV are more economical than PV–battery system if diesel price subsidies are integrated into the analysis and/or the community's location is not remote.

Tabla 3.1.4: Configurations used in off-grid hybrid systems in tropical areas.

PV	Wind	Biomass	Biogas	Small Hydro[1]	Wave	Tidal	Fuel Cell	Micro-Turbine	Diesel	Battery	Pumped Hydro Storage	H_2	Flywheel	Ref.
✓	✓									✓				[13, 101, 102, 103, 104] [105, 106]
✓									✓	✓				[14, 49, 107, 108, 109] [57, 95, 97, 110]
✓				✓					✓	✓				[15] [2] [50, 111]
✓	✓									✓	✓			[71]
✓	✓								✓	✓				[20, 56, 112, 113, 114] [45, 91, 92, 115, 116] [68, 84, 117, 118, 119] [120]
✓	✓			✓					✓	✓				[61] [3] [73, 121, 122] [123]
✓										✓				[124, 125]
✓	✓										✓			[126, 127]
	✓								✓		✓			[75]
✓		✓					✓	✓				✓		[128] [4]
✓	✓		✓						✓	✓				[87, 129]
✓									✓					[130]
✓	✓						✓			✓		✓		[52]
✓							✓			✓		✓		[89]
✓	✓						✓		✓	✓		✓		[131]
✓						✓			✓	✓				[78, 132]
✓														[133]
✓	✓								✓					[80, 81]
✓										✓				[100, 134, 135]
	✓								✓	✓				[90, 136, 137]
✓	✓					✓			✓	✓				[41]
✓			✓						✓	✓				[138]
	✓								✓					[139]
✓	✓								✓	✓	✓			[140]
					✓					✓				[141]
✓									✓	✓			✓	[142]
✓							✓		✓	✓		✓		[85]
✓		✓	✓							✓				[143]
✓		✓		✓						✓				[144]
	✓				✓									[53]

[1] Includes Mini- and Micro-Hydro systems; [2] Micro-Hydro was evaluated independently of the hybrid PV-Diesel-Battery system; [3] The author installed a bio-diesel generator;
[4] A co-generation biomass plant a stirling solar dish were included in this system.

A study of a system for a remote island in Hong Kong examined the economic performance of two possible energy storage systems, batteries and pumped hydro storage in a reservoir, using two renewable energy sources, solar and wind (Ma et al. 2014) [71]. The results indicate that the life cycle cost is higher with conventional batteries in an off-grid PV–battery system than with advanced deep cycle batteries, noting that the latter system is more appropriate for renewable resource-based power generation systems. In addition, a PV-pumped hydro storage system combined with a bank of batteries would be only 55 % of the cost of the PV–battery system (deep cycle), making the combination PV-pumped hydro storage-battery much more competitive than the option that only considers batteries. Ani (2016) [49] described a PV–battery system to meet the energy demand of a residential area in Nigeria. The author simulated the system to determine the loss in power generation and compared this to a diesel–battery system in economic and environmental terms.

Kumar et al. (2014) [107] studied the technical and economic feasibility of establishing hybrid PV–diesel–battery systems in different climatic zones of Tamil Nadu State in India. They found that the arid zone in Kanyakumari was the optimal climatic zone to establish hybrid PV–diesel–battery systems, taking into consideration factors like the renewable energy fraction (RF), contaminating gas emissions (tons/year), diesel consumption (liters/year) and net present cost (NPC). Adaramola et al. (2014) [56] conducted an economic analysis of an off-grid hybrid PV–wind–diesel–battery system in rural areas of southern Ghana. Using the software Hybrid Optimization of Multiple Energy Resources (HOMER), the authors determined that the hybrid PV–wind–diesel system (with or without batteries) is the best option economically. The contribution of RF ranged from 47 % (PV–wind–diesel system, the most viable) to 17 % (PV–diesel system, the least viable). The COE of the PV–wind–diesel system was \$0.276/kWh, and of PV–wind–diesel–battery system, it was \$0.281/kWh.

Table 3.1.4 shows the different HRES-OFF configurations according to latitudes between the Tropics of Cancer and Capricorn (that is, $-23° \leq$ latitude $\leq +23°$). There is a marked tendency to use solar energy (alone or with wind energy) as the main form of renewable energy in simulated or implemented HRES-OFF. The battery is the main energy storage strategy to meet energy demands at times when the supply of energy from renewable sources is insufficient. Likewise, there is a preference for PV–wind–diesel–battery systems (16 investigations), followed by PV–diesel–battery (9 investigations) and PV–wind–battery systems (7 investigations), as the main power generation strategies for remote areas. Finally, few studies considered marine-based energy sources as renewable HRES-OFF sources. Two studies evaluated wave energy [53, 141] and three considered tidal energy [41, 78, 132]. One study analyzed the flywheel as an energy storage system in combination with batteries, taking advantage of the high energy density that this system provides and the high depth of discharge, which are favorable characteristics in the transition between renewable energy sources and the storage system.

Subtropical Zone

Table 3.1.5 shows the HRES-OFF configurations of the 52 studies we found that evaluated different hybrid systems in tropical zones, that is, between the latitudes $+23°$ and $-23°$: $+23° <$ Latitude $\leq +36°$ and $-23° >$ Latitude $\geq -36°$. As in the tropical zone, PV and wind systems are the main renewable resource in HRES-OFF, accounting for 88.5 % and 67.3 %, respectively. Biomass energy appears to be more important in this zone, with six studies, which is twice the number for the tropical zone. There were no studies that considered tidal energy as a renewable HRES-OFF resource. Three studies considered waves as a potential energy source [145, 146, 147]. A study in the subtropical zone applied exergy analysis to an ocean thermal energy conversion system (OTEC) to determine the optimal evaporation and condensation temperatures of different working fluids [148]. Three Japanese islands isolated from the electrical grid were considered in an investigation to define the optimal configuration of a HRES-OFF PV-Wind-Diesel-Battery system, using hourly data on solar radiation and wind speed over a year (Senjyu et al. 2007) [47]. A genetic algorithm was used in this study to determine the cost of the hybrid system.

Rehman et al. (2012) [16] optimized a hybrid PV-Wind-Diesel system, thus reducing fuel consumption by a conventional autonomous system, without affecting the energy required in a remote community in Saudi Arabia. HOMER obtained an optimal configuration to produce electrical energy, with 26 % from wind, 9 % from solar and the remainder from five diesel generators. Offshore wave and wind resources on the Canary Island of Fuerteventura were evaluated using eleven measurement sites, as well as the optimal areas for installing wave/wind farms, taking into account wave height, energy period and predominant wave direction around the island, bathymetry, environmental areas and the distance to ports (Veigas et al. 2014) [145].

Dekker et al. (2012) [17] determined that the most technically and economically feasible approach to providing electricity to an off-grid system in six distinct climatic areas in South Africa. The authors determined that the optimal area in South Africa for a hybrid PV-Diesel-Battery system is the subtropical coastal region. The results indicate that the proposed system not only functions better than conventional autonomous system in terms of costs based on six simulations, but also had better results in categories of electricity, fuel consumption and emissions released to the atmosphere. A study that evaluated the feasibility of installing a hybrid PV-Diesel-Battery system in southern Algeria found that transforming the current autonomous conventional system to a hybrid system would represent a savings of 54,100 liters of fuel per year, which would represent a 90.4 % reduction in fuel consumption (Khelif et al. 2012) [149]. Ismail et al. (2013b)[150] investigated the feasibility of using microturbines as a backup to a PV-Battery system. The optimal size of the hybrid system was determined with the aid of an algorithm (mathematical model of the HRES-OFF components), with a minimum energy cost based on the optimal angle of inclination and azimuth angle for the solar panels. A comparison of microturbines and conventional diesel-based generators as backup systems showed that

Tabla 3.1.5: Evaluated off-grid hydro systems in subtropical areas ($+23° <$ Latitude $\leq +36°$ y $-23° >$ Latitude $\geq -36°$).

PV	Wind	Biomass	Biogas	Small Hydro[a]	Wave	OTEC[b]	Fuel Cell	Micro-Turbine	Diesel	Battery	Pumped Hydro Storage	H_2	ORES[c]	Ref.
✓	✓								✓	✓				[47, 88, 151, 152, 153] [154, 155, 156, 157, 158] [93, 159]
✓	✓								✓					[16, 22]
	✓				✓									[145, 146]
✓									✓	✓				[17, 58, 149, 160, 161] [79, 162, 163]
✓								✓		✓				[150]
	✓										✓			[82, 164]
✓	✓			✓						✓				[74]
✓	✓									✓				[165, 166, 167, 168, 169] [170, 171] [3]
✓							✓					✓		[172]
	✓								✓					[76]
✓		✓							✓	✓				[173]
✓			✓							✓				[174]
✓		✓								✓				[175]
✓										✓				[176, 177]
✓		✓	✓	✓					✓	✓				[178]
✓	✓	✓	✓	✓						✓				[179]
	✓				✓				✓	✓				[147]
✓	✓												✓	[180]
✓	✓	✓		✓					✓					[181]
✓	✓			✓					✓	✓				[96, 99] [1]
✓						✓	✓					✓		[148]
✓	✓								✓	✓		✓		[182] [2]
✓	✓	✓								✓				[183]

[a] Includes Mini- and Micro-hydro systems; [b] Oceant Thermal Energy Conversion (OTEC); [c] Ocean Renewable Energy Storage (ORES); [1] The author evaluated four independent configurations: Hydro-Battery, PV-Battery, Wind-Battery and diesel; [2] Hydrogen is employed by the diesel generator; [3] This study was carried out in an educational with access to an electricity grid.

microturbines have a lower energy cost. A study in Iran determined the feasibility of a hybrid PV-Wind-Diesel-Battery system for an area with a significant energy demand in Shiraz (9.9 MWh/d) (Baneshi et al. 2016) [151]. With the aid of HOMER software, the optimal system was configured and analyzed for two scenarios, one off-grid, and the other on-grid.

Table 3.1.5 shows that batteries are the main storage strategy, appearing in 80.77 % of the studies overall, and 86.49 % of studies dealing with tropical areas. Pumped hydro storage and hydrogen systems are less common in subtropical areas. [180] proposed ocean renewable energy storage (ORES) for offshore and onshore wind systems, having the advantage that such systems can be installed at great depths (up to 800m) and serve as anchors for offshore wind generators.

Temperate Areas

Table 3.1.6 shows the configurations used for HRES-OFF in middle and high latitudes between $+36° < \text{Latitude} \leq +63°$ and $-36° > \text{Latitude} \geq -63°$. Solar and wind energy are the most widely used renewable resources. Wind energy was assessed in 80.9 % of 42 studies and solar energy was assessed in 76.2 %. Biomass, biogas and small hydro were each assessed in a single study. Marine-based energy sources received more attention in temperate zones than in the other climatic zones, accounting for 16.7 % of studies. Tidal energy was assessed in two studies [184, 185] and wave energy in five [43, 186, 187, 188, 189]. Batteries continue to be the most widely used technique for energy storage in HRES-OFF, representing 69.1 % of studied systems. Hydrogen and pumped hydro storage are more common at middle and higher latitudes, representing respectively 16.7 % and 14.3 % of the studied systems.

A study on Lesbos Island in Greece used HOMER software to optimize an off-grid hybrid Wind-Diesel system without the integration of a storage system, resulting in a high COE associated with an operating reserve of 50 % of wind power generation (Giannoulis et al. 2011) [46]. The technical feasibility of wave-based electrical generation on St. George Island on the Bering Sea coast of Alaska was evaluated. The island was obtaining electrical energy from a generator, and the authors sought to lay the foundation for specific design and control elements essential in Wave-Diesel hybridization of small remote power grids. The assessment of the island's wave potential yielded an average of 28 kW/m, which could meet 9 % of the island's energy demand (Beatty et al. 2010) [186].

An assessment was made of an initiative for an isolated community on the small Greek island of Agathonisi to have autonomous electrical energy and potable water based on local non-conventional renewable resources. The proposed hybrid PV-Wind-Biogas-Battery system, optimized by HOMER, could meet electrical, heating and potable water demands through a reverse osmosis desalination plant, with a five-day autonomous period. Wind energy provided the major contribution at 50 %, followed by solar and biogas energy at 30 % and 20 %, respectively (Kaldellis et al. 2012) [48]. Yilmaz et al. (2017) [55] made a technical and economic analysis of a hybrid PV-Diesel-Battery system to identify the system's optimal size. Using HOMER, the

Tabla 3.1.6: Evaluated off-grid hybrid systems in temperate areas (+36° < Latitude ≤ +63° y −36° > Latitude ≥ −63°).

PV	Wind	Biomass	Biogas	Small Hydro[a]	Wave	Tidal	Fuel Cell	Flywheel	Diesel	Battery	Pumped Hydro Storage	H_2	CAES[b]	Ref.
	✓								✓					[46]
					✓				✓					[186]
✓	✓		✓							✓				[48]
✓									✓	✓				[18, 21, 51, 55]
✓	✓								✓	✓				[19, 190, 191, 192, 193] [98]
✓	✓									✓				[194, 195, 196, 197, 198] [62, 199, 200]
	✓								✓		✓			[72, 201]
✓	✓						✓		✓	✓		✓		[202]
	✓				✓					✓				[187] [1]
✓	✓										✓			[203]
✓	✓			✓					✓	✓				[204]
	✓						✓					✓		[205]
	✓								✓	✓				[77]
	✓					✓			✓		✓			[184]
✓	✓				✓				✓	✓				[188]
	✓				✓				✓	✓				[189]
✓	✓								✓	✓		✓	✓	[94]
✓	✓													[86]
	✓	✓												[206] [2]
✓	✓						✓			✓		✓		[207, 208]
✓							✓	✓	✓	✓	✓			[209] [3]
✓					✓				✓					[43]
✓	✓						✓					✓		[83]
✓						✓	✓							[185] [4]
✓	✓										✓	✓		[210]

[a] Includes Mini- and Micro-hydro systems; [b] Compressed Air Energy Storage (CAES); [1] The author considered an ideal battery (without loss); [2] The author studied a small dairy cattle farm with grid connection; [3] The author studied different storage devices such as: Lead-Acid battery, Na-S battery, flow battery, flywheel, pumped hydro and fuel cells; [4] A heat storage tank was installed in the power system. It was not used to store electricity.

authors determined that 84.6 % of total energy could be generated by solar panels and that the hybrid system could reduce carbon emissions by 44 tons per year.

A study in Russia that proposed the design of a multi-purpose hybrid PV-Diesel-Battery system (Bortolini et al. 2015) [18] identified the average power output of a PV plant, the capacity of the storage system (battery) and the optimal technical configuration to reduce the levelized cost of electricity (LCOE) and the carbon footprint of energy (CFOE). The results showed that the best environmental scenario is a PV plant with an average power output of 95 kW_p, and a storage capacity of 200 kWh (8 Ah), resulting in a CFOE of 0.374 kg CO_2eq/kWh (50 % savings). A study by Gan et al. (2015) [19] developed a tool to optimize a hybrid PV-Wind-Diesel-Battery system, with the objective of helping investors to decide between batteries and diesel generators given the availability of local renewable resources and the demand for energy. The results show that a PV-Wind-Diesel system has a lower COE (0.677 £/kWh). In contrast, the PV-Diesel system has a COE of 1.55 £/kWh, more than double that of the Wind-Diesel (COE = 0.724 £/kWh) and PV-Wind-Diesel systems for total autonomy. The comparison of a Wind-Diesel and PV-Wind-Diesel system shows that twenty additional solar panels would result in a 33 % reduction in storage capacity.

Results by Population

Some 15.5 % of the evaluated studies indicate that the main economic activity of the community is primary: farming, fishing, mining, logging etc. Tourism is the main activity of 11.3 % of communities, while 64.3 % of the studies did not indicate predominant economic activity of the relevant communities. The remaining percentages are specific cases that include research centers, a base transceiver station (BTS), small scale industries, among others.

Some 76 of the evaluated investigations provided complete population and daily energy use data (Figure 3.1.5). Seven investigations analyzed HRES-OFF in communities with more than 20,000 inhabitants, six of these on islands and one continental. The study with the largest number of inhabitants was on the island of Sandwip in Bangladesh (Figure 3.1.5), although this study did not represent the highest daily demand for electrical energy with 93,000 kWh/d [41]. The study that represented the highest level of energy consumption was that of [81], in which the authors considered five energy demand scenarios for Cozumel Island, Mexico in 2018, 2020, 2024, 2035 and 2050. Cozumel Island is the target for developing sustainable tourism to improve the quality of life of the island's inhabitants. One of the strategies in this process is developing a PV-Wind-Diesel system.

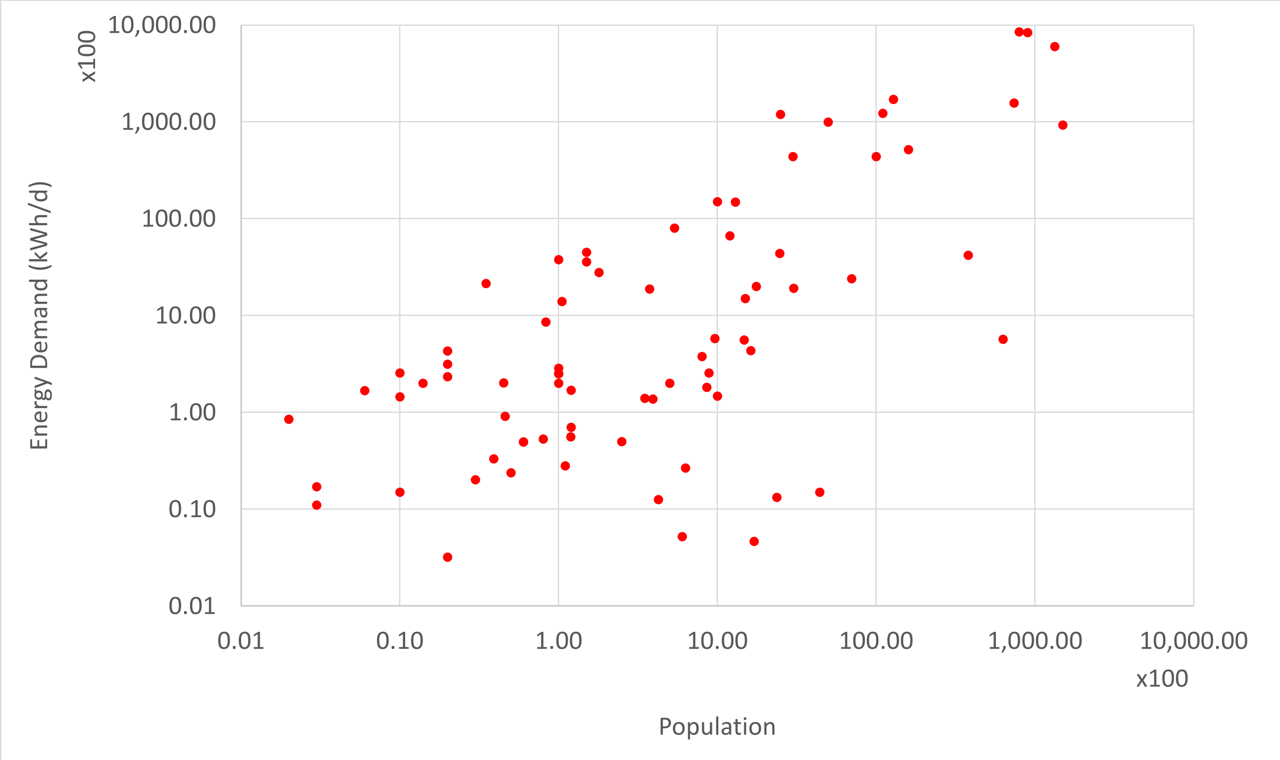

Figura 3.1.5: Daily energy use versus the number of inhabitants. The result of 76 studies with information available.

Of the 76 investigations, 46.1 % involved providing electricity to isolated communities with no more than 200 inhabitants (Figure 3.1.5), while 7.9 % involved communities with 200 to 500 inhabitants, 11.84 % dealt with communities with populations between 500 and 1000 inhabitants. The percentages were 18.4 %, 2.6 %, 5.3 % and 7.9 % respectively for communities with populations of 1000–5000, 5000–10,000, 10,000–50,000 and over 50,000.

Results by Type of Energy Storage

HRES-OFF energy storage strategies ensure an ongoing supply of electrical energy at times when energy production by renewable sources is low or highly intermittent. Diesel generators remain the preferred HRES-OFF backup strategy, and were employed 103 of the 168 studied cases. The principle of a battery-based backup system is simple, the excess energy generated by renewable energy sources is stored in the battery, using load regulators to appropriate charge and discharge levels. The strategy was different in some investigations [45, 61, 178], with a backup system (diesel generator) to supply the required level of energy and, in turn, charge the batteries of the hybrid system. In the latter case, the renewable energy source does not supply power to the batteries.

The most widely used type of battery in the evaluated HRES-OFF is lead-acid owing to it technological maturity, easy acquisition, low cost and wide use in different applications worldwide. Some 80.4 % of the publications analyzed in this paper involved the use of batteries, either alone or in combination with another energy storage method (Figure 3.1.6). In second place were HRES-OFF without any type of energy storage, that is, in these cases renewable energy sources are the only means used to meet electric power demand. The lack of a storage system can result in oversizing the electrical generating system or more use of diesel generators to meet energy demands in the context of limited availability of appropriate renewable resources. Thirdly is hydrogen fuel cells using an electrolyzer, followed by solid oxide fuel cells (SOFC), which provides electrical energy from stored hydrogen when the energy demand is greater than the supply from renewable sources. Some 7.7 % of the studies considered pumped hydro storage, which takes advantage of favorable topography. Only a few investigations, around 2 %, dealt with HRES-OFF that used flywheels [142, 209], ORES [180] or CAES [94] as the main energy storage methods.

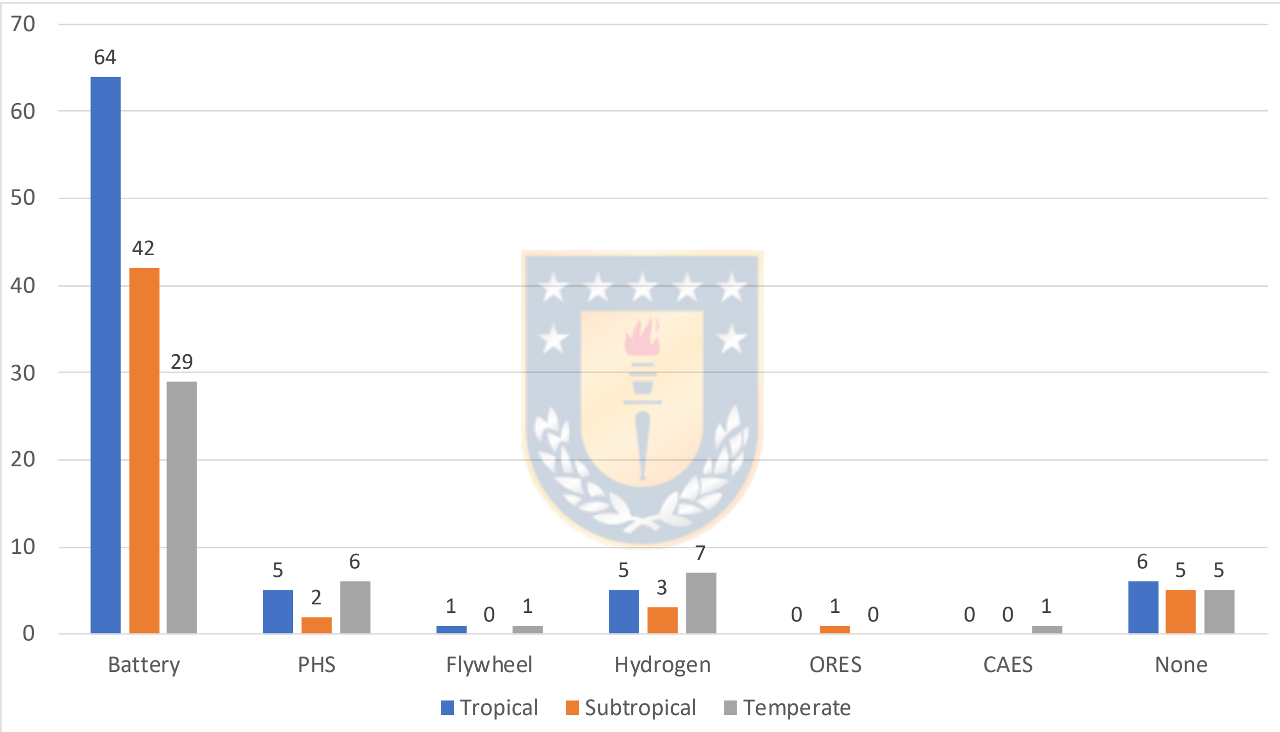

Figura 3.1.6: Main energy storage technologies used in HRES-OFF worldwide.

Trends

Based on the 168 selected articles from among a total of approximately 250 articles for the period 2002–2019, the trend worldwide in HRES-OFF for remote communities is toward using solar and wind energy (Figure 3.1.7). Although one of the objectives of establishing local energy generation systems is to reduce dependence on fossil fuels, thermal units are still used as backup systems owing to the recognized intermittent character of renewable resources and the low plant factors associated with renewable energy conversion technologies. As noted above, the technological maturity, broad commercialization and availability of the resource are the main advantages of the sun and wind over other renewable resources. Although hydroelectricity is widely known and used, its use is problematic in island and coastal areas because of the low availability of water, which in some places is even inadequate to meet requirements for human consumption. The use of marine energy sources in HRES-OFF is weak owing to economic, technological and developmental aspects noted above. There is little use of marine-based energy sources due to economic, technological and developmental factors already mentioned. However, since 2013, there has been more interest in marine-based energy resources for communities with low energy demand.

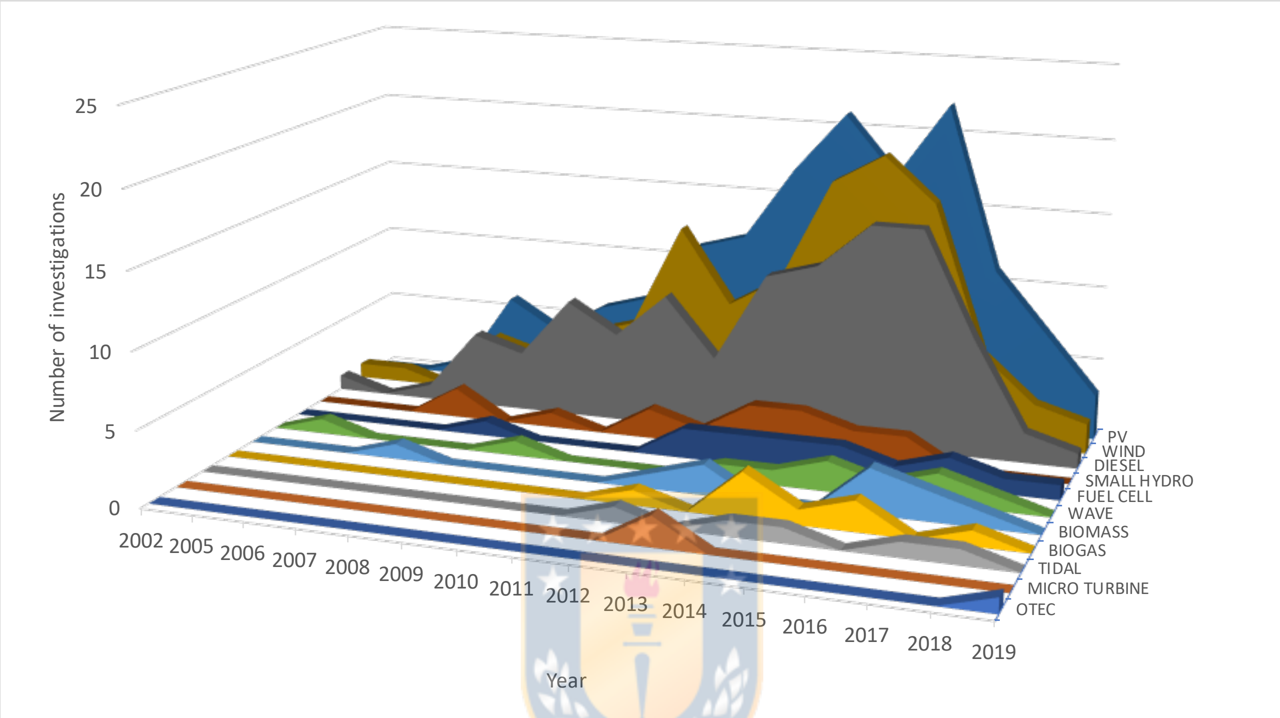

Figura 3.1.7: Trends in HRES-OFF evolution. The vertical axis represents the number of articles published annually. Note that if an article describes more than one technology, it is counted more than once.

The battery is categorically the most widely used storage system used in HRES-OFF (Figure 3.1.8). The number of studies in which batteries formed part of hybrid systems began to decrease in 2016. There is growing interest in using hydrogen as a more dynamic option HRES-OFF. Since 2010, at least one study has presented water pumping storage systems (PHS) as an alternative in areas with topography conducive to storing water at high altitudes. There is more interest among coastal and island communities in pumped hydro energy storage using seawater, the lower reservoir is the sea and only favorable topography is needed for storage at high altitudes. It is evident that storage systems in marine environments require more research and are in a very early stage of development.

The trend in recent years (2017–2019) is also in the number of the articles found suitable for review (Figure 3.1.9). The change in the number of articles published in recent years could reflect a change in interest in off-grid systems rather than in renewable energy sources.

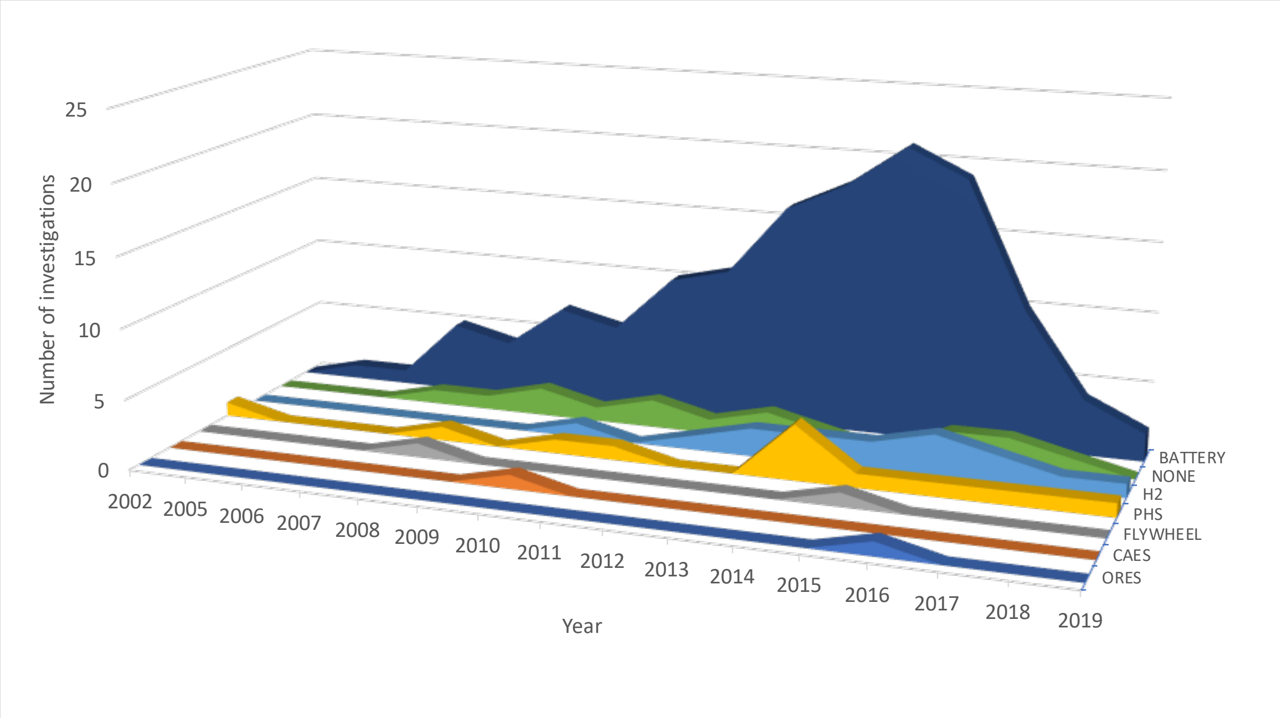

Figura 3.1.8: Trends in the use of different HRES-OFF energy storage systems. The vertical axis represents the number of articles published annually. Note that if an article describes more than one technology, it is counted more than once.

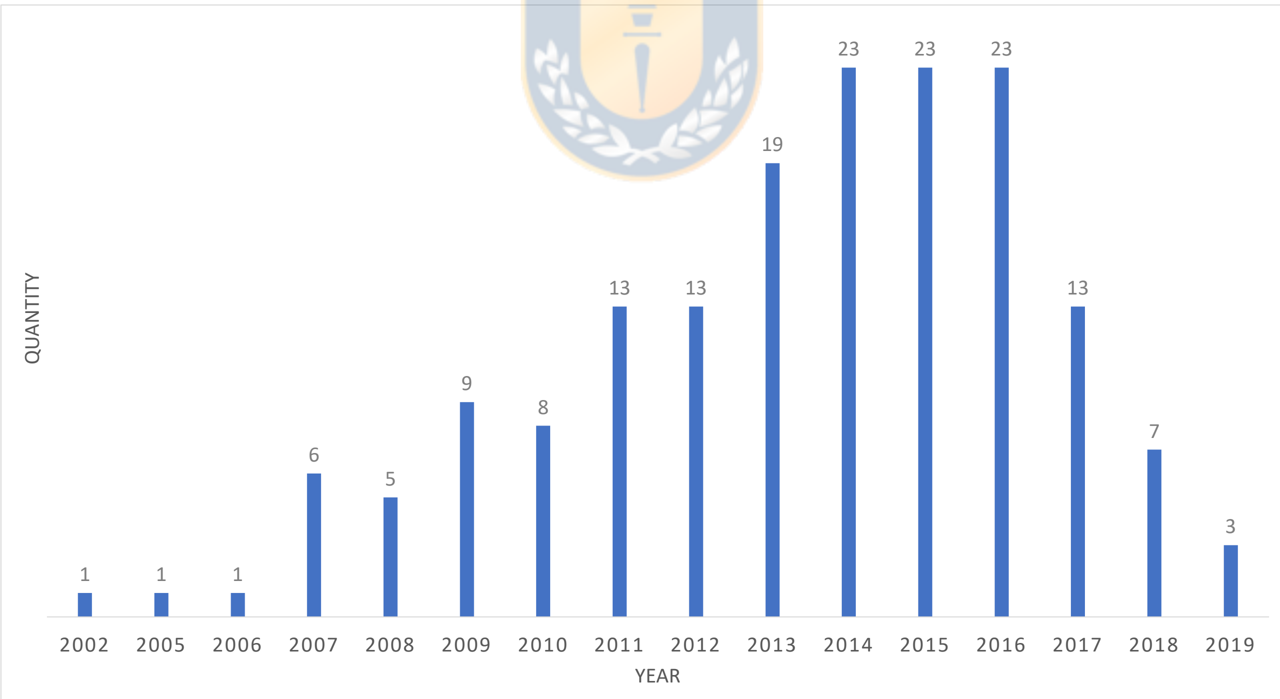

Figura 3.1.9: Total number of studies by year of publication analyzed in this bibliographic review.

Discussion

Unlike fossil fuels, most renewable resources are more equitably distributed and be used widely in different latitude. Energy production by renewable resources (hydro, solar, wind, geothermal, biomass and marine energy) increased globally from 93,776 TWh in 1965 to 667,349 Twh in 2018, which represents an increase of 712 % [211]. The International Energy Agency (IEA) stated that renewable resources, including hydroelectricity, accounted for 25.3 % of global electrical generation matrix in 2017 [212].

Correctly defining an HRES-OFF requires a precise evaluation of local renewable resources and characterization of the energy demand profile. Given this, appreciating the geographic location of subject communities of HRES-OFF studies is an important step in understanding the potential of renewable resources. Communities located on island or within a kilometer of a coast have access to marine energy resources like wave, tidal, salinity gradient and OTEC. These communities lack year-round access to water hydro energy resources and have limited access to biomass and geothermal energy, but do have access to strong offshore winds and ever-present sunlight. In contrast, isolated inland communities have more access to biomass and water resources appropriate for small-scale hydro power, high and low enthalpy geothermal energy source, and certainly, ample and widespread use of solar radiation and wind.

Differences in latitude are associated with greater or lesser potential of renewable resources. Solar rays are almost perpendicular in the tropical zone, which allows a greater availability of direct and diffuse radiation on the earth's surface. At higher latitudes, solar radiation passes through a more air mass (AM), which decreases the amount of useful solar radiation. Wind energy is employed almost everywhere in the world on both land and on the high seas. However, the use of this resource is not distributed uniformly. Its use is erratic and not very predictable, and the best wind regimes are not always located close to energy consuming centers [213]. The potential of wave energy is greater at middle and high latitudes, that is, in subtropical and temperate zones. According to [214], densities of annual potential greater than 50 kW/m are found in coastal areas or inner seas in Australia, the United States, Chile, New Zealand, Canada, and South Africa, which is 44 % of available theoretical potential, as estimated in the same study. However, the 2.1 TW of theoretical potential in waves is far from being drawn upon because of: i) the lack of technological convergence in the design of wave energy converters (WEC), ii) gaps in environmental legislation, iii) limited private investment, and iv) the lack of coastal infrastructure with connections to submarine cables [215]. Likewise, tidal and offshore wind energy face barriers similar to those faced by wave energy, with the difference that the technology of energy extraction is a stage of mature development and has been sufficiently tested. According to [216], tidal energy is used around the world, while the energy potential of OTEC is largely exploited in tropical areas where the temperature difference the ocean surface and depths of more than 1000 m are on the order of 20 degrees. Extraordinary levels of difference between low and high tide are found in middle and high latitudes, with difference of 7.5 to 13 m in Canada, Russia, Australia and the United States, and of 6 to 7 m in Argentina, Great Britain, Mexico and India, the latter two located in tropical areas [217].

Geothermal energy has an uneven distribution globally, and its presence is often at depths too great for practical use[218]. Exploratory drilling and test wells are too expensive to allow for identifying geothermal potential in a given area[219]. As well, the high costs and highly qualified staff required in the operational of geothermal plants make this option unfeasible for remote communities that have low energy demands and low population density. These difficulties in implementing and operating HRES-OFF are clearly related to the lack of studies that consider geothermal energy as a viable renewable resource in off-grid energy systems. Biomass is represented by a wide range of fuels. The concept of biomass includes solids, liquid fuels, and several gases. There are drawbacks to biomass energy in terms of availability and sustainable renewal of the resource for island and coastal communities, as well as concern about the use of potential food crops as sources of biomass energy and resulting air pollution, depending on the technology used in energy conversion [220]. Consequently, there has been limited integration of biomass into HRES-OFF, and has been represented mainly by the use of livestock manure, which through anaerobic conversion technique provides methane for use in electric generators or food preparation (Figure 3.1.10).

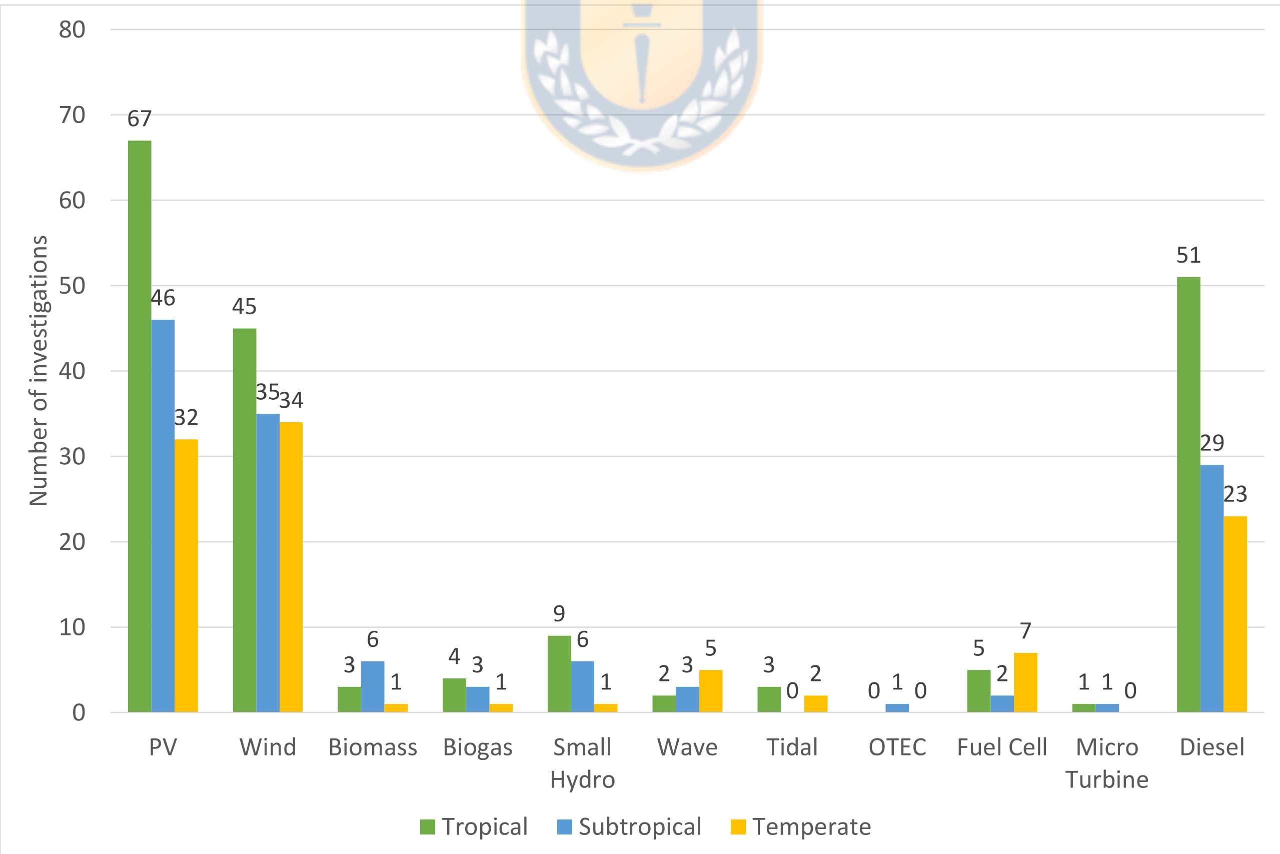

Figura 3.1.10: Evaluated sources of primary HRES-OFF energy worldwide.

Technical and Economic Aspects of Conversion Technology

According to [221], the main factors that have helped lower solar panel costs and increase their commercial use are lower primary material costs, a substantial increase in the production of solar panels in China, technological innovations and increased investment at the industrial level. Similarly, wind turbines are occupying an increasing role in the energy matrices of several countries, encouraged mainly by economies of scale, learning curves, higher plant factors that reduce the levelized cost of energy (LCOE) and an increase in supply with the emergence of wind turbine factories in China [213].

Run-of-the-river systems with a capacity of 10 MW are considered small-scale hydro power (SHP). According to [222], the main benefits of SHP are high efficiency, proven and reliable technology, long-term usefulness and appropriateness to the electrification needs of rural areas. Certain political, economic and social conditions are required to establish SHP, such as financing loans to developers and landowners, training of local personnel in the different stages of operation and maintenance and transfer of technologies to local developers [223]. Likewise, this same study concluded that the economic success of SHP systems depends on the load factor and the associated load, that is, the demand for electrical energy must be associated with commercial and industrial activities, not just domestic demand. In this sense, and highlighting that the economic activities of the studies referenced in this review are associated with agriculture, fishing, farming and tourism (where there is no special electrical energy requirement), SHP solutions are not an economically viable option, since they would be working with load factors of around 10 %, which would extend the period of return on investment.

Generating electrical energy from marine sources is in the early stages of development, with the exception of tidal barrage. Wave energy presents several difficulties in its use and integration in energy matrices. Some of these difficulties are: i) a wide range of designs and prototypes that have not lead to technological convergence, ii) the evaluation of coastal systems based on the establishment of wind farms[224], iii) anchoring systems for offshore installations, iii) extreme climatic events that threaten the integrity of WEC, and iv) the need for more research into environmental impacts and biofouling. Tidal energy has a promising future reflected in electrical generation systems established in countries like France, Canada, the United States, South Korea, China, and Russia. These systems employ tidal barrage technology, which has been used for several years to deliver electrical energy to national transmission networks. Turbines for tidal currents and waves are still in their infancy [225]. Among the main limitations of this technology is difficulties in installing systems and transmitting the electricity that is generated, environmental impacts, biofouling and maintenance requirements [226]. Microturbines best fit the distribution power generation approach. According to [227], microturbines offer several advantages, including lower initial investment (CAPEX), lower operating costs (OPEX) and less impact on the environment. In contrast, generating electrical energy by OTEC technologies and salinity requires more investigation and prototype tests [228] to ensure participation in future power generation systems. Government policies to increase the use of renewable energy source in energy matrices should promote the development of marine energy, which has a significantly higher energy potential than current world energy demand.

Population and Economic Activities

Most of the reviewed studies did not make reference to the main economic activity of the relevant community. An analysis by country identified that 24.4 % of the studies deal with developed countries as represented by member countries of European Community (including Great Britain), Japan, the United States, Canada, Australia, Russia and South Korea (Figure 3.1.3). In contrast to developed countries, where the basic energy needs of the population tend to have been met, there are still gaps in access to energy among the poorest and most isolated groups in developing countries. According to [229], access to energy has positive effects on health care, education, incomes, and development. Nevertheless, the low demand for energy in remote communities implies a high cost to electricity, making access to energy for the poorest families more difficult [230]. In this regard, the poorest families commonly use biomass and kerosene for cooking and lighting. The use of kerosene and paraffin involves the emission of contaminating gases that are dangerous to human health. According to [174], the gases emitted by kerosene can cause cancer and tuberculosis in women and children. Thus, alternatives to biomass (when it is not sustainable), liquid and solid fuels like paraffin and kerosene, can improve the quality of life of families.

Key Findings

There is a lack of research on the integration of marine energies as active resources of HRES-OFF in insular/coastal communities. The OTEC theory was conceptualized in the 19th century, however, its implementation in HRES-OFF is evidenced in only one article ([148]). Focusing research efforts on better working fluids and heat exchangers can increase the overall efficiency of the OTEC process. On the other hand, there is much to explore and investigate in the simulation of WEC, tidal turbines and salinity gradient as active renewable resources of HRES-OFF. Only 15 articles studied wave and tidal energy in HRES-OFF (Figure 3.1.10), a very low integration index considering that almost half of the 168 articles focus on island communities, which can take advantage of this type of energy.

61 % of HRES-OFF investigations still propose genset as backup systems. The use of fossil fuels has adverse effects on human health and the environment, in addition to maximizing the energy dependence of isolated and island communities. Therefore, research efforts in sustainable energy solutions, based on local renewable resources, should be increased. The investigations [103, 124, 126, 146, 203] deepen the diversification of energy mix towards 100 % energy autonomy communities. However, the use of fossil fuels is exacerbated if only HRES-OFF research from the

Southern Hemisphere is analyzed (Table 3.1.3). In this hemisphere, 81 % include genset in their case studies. Added to this is that remote and island communities in the Southern Hemisphere are poorly studied (Figure 3.3.10).

Conclusions

The development of communities is closely related to ongoing access to electrical energy. Electrical energy is a fundamental pillar of the economic and social development of communities, because of which it is common to find the highest indices of poverty and the low levels of technological development in rural communities. The geographic dispersion of communities in remote and rural areas hinders the provision of electrical energy through conventional electrical generation and transmission techniques owing to the high cost of extending electric transmission grids. Electricity is a vital tool for the economic participation and social wellbeing of rural communities. Areas without electricity have limitations in essential infrastructure, like schools, medical centers, communication and access to potable water. Fossil fuel-based electrical generation is commonly used in these cases, particularly diesel-based systems, given that this is relatively inexpensive, the technology is widespread and the time required to construct an electrical central is relatively short. However, remote communities often do not have easy access to fossil fuels, and owing to their isolation, the system may lack maintenance, which can result in harmful effects for human health and the environment.

Our review was focused on 168 articles published between 2002 and 2019 on the use of off-grid hybrid electrical generation systems as a response to the need to decrease consumption of and dependence on fossil fuels through the integration of different nonconventional renewable resources. HOMER was used in the majority of studies as a methodological tool to analyze cases. The subjects of the analyzed studies were concentrated geographically in the northern hemisphere, mainly in Asia. The majority of the studies dealt with HRES-OFF in tropical or subtropical zones. Photovoltaic arrays and wind turbines, alone or together were the main renewable resources used in HRES-OFF (Tables 3.1.4–3.1.6), associated fundamentally with their technical, operational and economic advantages. These systems use batteries as the main method to store energy, while diesel systems are the preferred option as the preferred backup system in the context of intermittent supply of renewable energy. At higher latitudes, HRES-OFF can make better use of other sources of renewable energy like wind energy for non-coastal areas and wave and tidal energy in coastal areas. However, our review found a small number of studies that included marine-based renewable resources as an energy source for coastal communities.

3.2. Impacto de las fuentes de información en los HRES off-grid

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Too many solar panels? Oversizing or undersizing of hybrid renewable energy systems based on different sources of information

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Abstract

This research evaluates the impact of information sources on the feasibility of a Hybrid Renewable Energy System (HRES). Due to their isolation and low population density, island communities satisfy their demand for electricity through thermoelectric plants. Diesel is the main fossil fuel used. This fuel must be imported, which translates into high logistics and operating costs. HRES are a feasible solution, integrating renewable resources, thermoelectric plants, and energy storage systems. The proper characterization of the variability of a renewable resource is decisive in the feasibility of an HRES. We used three sources of information on solar radiation and wind speed: the NASA Power Database (Case a), results of atmospheric and solar radiation models (Case b) and prospecting campaigns for wind and solar resources (Case c). The main findings point to an undersizing in the three best solutions: PV-Diesel, PV-Diesel-Battery and PV-Wind-Diesel-Battery with data from Case a, compared to measurements on site (Case c). On the other hand, a clear oversizing of the main architectures obtained with HOMER is evidenced, when using information sources from Case b compared with data from Case c. Therefore, the feasibility of an HRES begins with the selection of the information source of local renewable resources.

Introduction

The sun and the wind share the common features of being available and widely distributed sources of renewable energy for the continents and island territories. They are natural resources that can be used as primary sources in energy transformation processes. Independently, solar irradiation and wind speed are physical phenomena that have a variability inherent to their nature, explained by: i) stochastic behavior at different time scales [231], ii) cloudiness, particulate matter, air temperature [232] and natural or artificial obstacles, iii) the orography that produces a high spatio-temporal variability in magnitude and wind flow [233]. Hence, using solar and wind resources independently may present great difficulties in terms of oversizing of the distributed generation system [234], inability to meet energy demands and high installation costs. In order to counteract these drawbacks, several authors have investigated HRES in conjunction with energy storage systems to meet the energy demands of remote communities in mid-high latitudes [235, 236, 237, 238].

Variations in the estimation of solar radiation can be a decisive factor in the feasibility of an HRES project [239]. These variations can also affect the capacity factor of a wind project. Two different sources of information on renewable resources are available: both short-term and long-term records. Usually, short-term records are associated with equipment installed for periods of time of one year (e.g., meteorological towers). Short-term records imply a small space-time coverage; this can be compensated for more accurately in the measurements. Long-term records are linked to results from numerical wind prediction models or satellite sensors. Therefore, selecting an adequate source of information to characterize renewable resources is essential.

Simulating and optimizing HRES with different sources of information, unequivocally allows to deduce that there will be a set of different results, a quick conclusion supported by experience or common sense. However, have those results that experience and common sense warns us about been quantified? What is the range of variability in the technical and economic indicators of each “optimized HRES”?, or in other words, what is the percentage of oversizing or undersizing in the “simulated and optimized HRES”? Answering this question is the main objective of this research.

Studies in other areas of knowledge have focused on analyzing and quantifying the impact of the different sources of information that feed a model. Although the importance of the wind product used to feed a wave model is well known, the quantification of the main wind and wave products ERA-Interim vs CFSR was only recently carried out by [240], highlighting a better interannual consistency of ERA-Interim, a product that nevertheless underestimates the extreme wind values. In the oceanographic field, [241] studied the effect of different boundary conditions and initial conditions on the circulation patterns of the Humboldt current system, finding important differences depending on the temporal variability of the oceanic boundary conditions.

To the best of our knowledge, there is no detailed quantification to explain the technical and economic variation of HRES simulated and optimized, using different sources of information, such as: NASA Power Database, results of atmospheric and solar radiation models and measurements on site. Additionally, and as described in Section 2, there is a notable lack of studies that analyze sustainable energy systems in the southern hemisphere, especially in small island and remote communities that are energy-dependent on the mainland.

Thus, this research also aims to contribute to the solution of the energy challenges in island communities by analyzing the impacts of three different sources of solar radiation and wind speed data in the optimization of HRES.

Island communities around the world depend on fossil fuels to meet their electrical energy needs. They are energy-dependent on the mainland and have great limitations in the available space. In addition, their isolation and low population density make it impossible or too expensive to expand traditional electrical networks [1] or use submarine cables. Therefore, using microgrids or distributed generation systems are viable options for the generation of electricity in isolated and island communities [242]. The main energy resource used on islands is diesel fuel that powers internal combustion generators (gensets) in order to produce electrical energy. It is their technological maturity, reliability and low installation cost that made the genset a good alternative for small towns and island communities [243]. However, the use of diesel brings along certain disadvantages: high energy costs [244], air pollution [245], an impact on human health [246], high logistics costs and diesel power system operation. In addition to these disadvantages, there is also the growing concern about climate change and the measures being implemented worldwide to consolidate an energy transition. One strategy being implemented is the use HRES that integrate renewable primary resources, gensets and energy storage systems. According to [247] there are 1785 islands worldwide with a population between 1000 and 100,000 inhabitants. A general insular population of 20 million people is estimated. Island communities located at latitudes greater than +40° and lower than -40° have various challenges to face regarding their energy issues: i) complex and expensive logistics associated with importing fossil fuels for isolated thermoelectric systems, which in turn means energy-dependence, ii) the low penetration of HRES in isolated communities (including islands) which take advantage of local renewable resources, iii) the lack of studies that assess the technical and economic viability of HRES in island communities located in mid-high latitudes. Therefore, in order to analyze the effects on the feasibility of an HRES from different sources of information, an application has been made to a real case in Las Huichas Island (45° S), located in the XI Region of Chile.

Different methodologies for sizing and optimizing an HRES are described in the literature. The technical and economic feasibility of an HRES is a complex task that must consider, among other aspects: the stochastic behavior of natural resources, the minimization of the use of fossil fuels and its consequences, reducing the LCOE, determining an attractive Initial Capital and synchronize power generation, load and energy storage systems. To solve the above, some researchers develop multi-objective optimization algorithms applied to specific study cases [245, 248, 249]. However, and according to [1], there is a clear preference for the use of commercial software tools to simulate and optimize an HRES. The main software tool used is the Hybrid Optimization of Multiple Energy Resources (HOMER), developed by the National Renewable Energy Laboratory. This software uses hourly data from natural resources and optimizes the HRES based on Net Present Cost (NPC). On the other hand, RETScreen is a tool developed in Microsoft Excel, characterized by evaluating the reduction of greenhouse gases and specifying the life-cycle costs of the system. Another software tool is iHOGA, which is characterized by its low computational requirement and integrates mono or multi-objective optimization. HYBRID2 developed by Renewable Energy Research Laboratory is recommended to improve optimizations previously done with HOMER [250]. TRNSYS developed in Fortran allows to simulate transient system behaviors [251] for thermal and electrical systems. In this research, the well-known HOMER Pro tool will be used to simulate, optimize and discuss some sensitivity analysis.

The structure of this paper is as follows: Section 2 compiles a review of the scientific literature focused on HRES for island communities in mid-high latitudes. Section 3, made up of 6 subsections, explains the demographic, economic and energy characteristics of the insular community of Las Huichas island. Besides, it describes the software used in the simulation of HRES, relevant aspects of the information sources used in the island's renewable resource and technical and economic data of the main components of the proposed HRES. Section 4 summarizes the results found in the optimization and sensitivity analysis. Section 5 contains the discussion of the main findings. Finally, Section 6 presents conclusions and future work.

HRES in mid-high latitudes for island communities - A literature review

There is some research, mainly in the Northern Hemisphere, of simulated/installed HRES in island communities that are located at latitudes greater than +40° and lower than -40°. Figure 3.2.1 represents the geographic location of studies carried out in island communities and mid-high latitudes. 22 studies were identified in this literature review. 81.8 % evaluated wind turbines in the proposed HRES. 59.1 % integrated solar panels and 27.3 % analyzed some type of marine energy in the HRES architecture. More than half of the studies rely on thermoelectric plants for backup (Table 3.2.1). Additionally, the characterization of renewable resources is done with different sources. The criteria for selecting a specific information source is due to the availability of data in the study area or financing for the installation and maintenance of sensors.

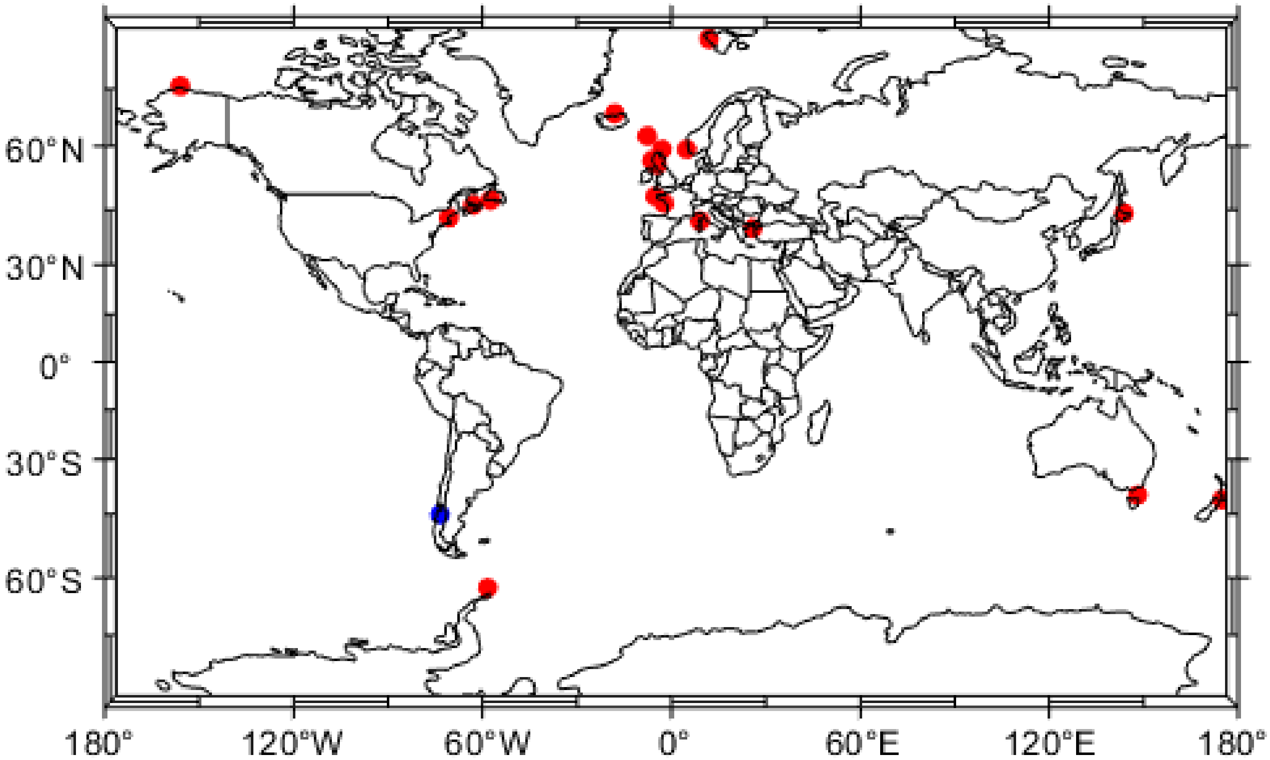

Figura 3.2.1: Geographical location of the HRES evaluated in mid-high latitudes (red circles). The blue circle corresponds to the geographical location of the Las Huichas island, Región de Aysén, Chile.

Out of these 22 studies, 10 characterized renewable resources with on-site measurements [185, 187, 195, 206, 252, 253, 254, 255, 256, 257]. However, some researchers use a specific information source for each renewable resource. On Eigg island, (56°54' N) Scotland, the authors analyzed the off-grid PV-Wind-Diesel-Small Hydro-Battery HRES installed on the island and used HOMER to identify opportunities for improving it [204]. Wind speed data is obtained from on-site measurements. However, solar radiation is characterized using satellite data. The French island of Ouessant (48°27'19" N) was evaluated in [184] with the purpose of measuring and optimizing a Wind-Tidal-Diesel-PHS hybrid system that minimizes polluting gas emissions on the island. The behavior of the wind was studied from observations at the site of interest. Regarding tidal information, the source used is not mentioned. On Flinders island (40°0' S), Australia, researchers proposed a novel optimization method for measuring the energy storage and management system of the PV-Wind-Tidal-Diesel-Battery HRES [258]. Wind regime and solar radiation were obtained from The Australian Government Bureau of Meteorology. The tidal data correspond to the results of numerical models of the ocean. Researchers in [259] studied a PV-Wind-Diesel-Battery system for Gökceada island (40°9'39" N), the largest island in Turkey. On-site measurements were used to characterize the wind in the area. Satellite data were used as a source of information to characterize solar radiation. In [260] the authors investigated a PV-Wind-Diesel-Boiler-Batteries HRES to integrate renewable energies into the electrical generation system of the Brazilian Antarctic Station (62° 5'S). Two different sources of

Tabla 3.2.1: Main primary energy sources, energy storage systems (ESS) and source of primary resources used in HRES of mid-high latitudes and island communities (n = 22 studies).

Ref.	Site (Latitude)	Energy Supply	Energy Storage	Status	Source of primary resources
[186]	St. George Island (56.58°N)	Wave-Diesel	None	Simulation	Numerical modeling.
[195]	Corsica Island (42.15°N)	PV-Wind	Batteries	Simulation	On-site measurements.
[187]	Yeu Island (46.72°N)	Wind-Wave	Ideal Battery	Simulation	On-site measurements.
[204]	Eigg Island (56.9°N)	PV-Wind-Diesel-SHP	Batteries	Installed	Solar radiation sourced from satellite data. Wind speed data from on-site measurements.
[205]	Mykines Island (62.10°N)	Wind-Fuel Cell	Hydrogen	Simulation	Calculations made in WindPro, based on MERRA mesoscale wind data.
[184]	Ouessant Island (48.45°N)	Wind-Tidal-Diesel	PHS	Simulation	Wind speed data from "Météo Bretagne" database. The source of tidal information is not indicated in the study.
[188]	Westray Island (59.3°N)	PV-Wind-Wave-Diesel	Batteries	Simulation	Wind and wave data from accurate numerical models. Source of the solar data is unclear.
[206]	Prince Edward (46.25°N) Island	Wind-Biomass	Grid	Simulation	On-site measurements.
[185]	Japan (44.16°N)	PV-Tidal-Fuel Cell	Heat Storage Tank	Installed	Solar radiation data was obtained from Japan's meteorological agency. Tidal data were taken from the Hydrographic and Oceanographic Department of Japan.
[258]	Flinders Island (40°S)	PV-Wind-Tidal-Diesel	Batteries	Simulation	Wind speed and solar irradiance profile were obtained from the Australian Government Bureau of Meteorology. Tidal data was obtained from numerical hydrodynamic modeling.
[254]	Star Island (42.97°N)	Wind-Diesel	Batteries	Simulation	On-site measurements.
[259]	Gökceada Island (40.16°N)	PV-Wind-Diesel	Batteries	Simulation	Solar radiation sourced from satellite data. Wind speed data sourced from on-site measurements.
[252]	Spitsbergen Island (78.92°N)	PV-Wind	Grid	Simulation	On-site measurements.
[260]	Comandante Ferraz Antarctic Station (62.08°S)	PV-Wind-Diesel	Batteries	Simulation	GHI from satellite measurements, wind speed from on-site measurements.
[261]	Corsica Island (42.15°N)	PV-Wind	Batteries	Simulation	Solar radiation was calculated with different math models. Source of the wind speed profile is unclear.
[262]	Ramea Island (47.51°N)	Wind-Diesel	Hydrogen	Installed	Unclear
[255]	Grimsey Island (66.55°N)	Wind-Diesel	Hydrogen	Simulation	On-site measurements.
[256]	New Zealand (41.16°S)	PV	Grid	Installed	On-site measurements.
[253]	Corsica Island (42.15°N)	PV-Wind	Batteries	Simulation	Meteorological data.
[19]	Scotland (55.90°N)	PV-Wind-Diesel	Batteries	Simulation	On-site measurements of wind speed data. Source of solar data is unclear.
[263]	Arctic (69.95°N - 71.5°N)	PV-Wind-Diesel	Batteries	Simulation	Source of hourly solar data: the USA National Renewable Energy Laboratory. Source of wind speed is unclear.
[257]	Utsira Island (59.3°N)	Wind	Hydrogen	Installed	On-site measurements.

information were used: on-site measurements to obtain the wind regime and solar radiation satellite data to characterize the incident solar radiation. In Bishopton (55°54'30" N) a small town located in the north east of Renfrewshire, Scotland, a study was performed that seeks to develop a computer tool to size off-grid HRES [19]. On-site measurements were used to determine wind behavior. The article does not indicate the source of solar radiation.

Some studies do not characterize renewable resources with on-site measurements. In [186] the authors simulated a Wave-Diesel hybrid system on St. George Island (56°35' N). The estimation of the wave resource is associated with data obtained from results of the US NOAA's numerical wave forecast model. Another study evaluated a hybrid system made up of wind, PV, gensets and batteries to meet the energy demand of offshore oil platforms in the Arctic (69°57'0" N - 71°30'0" N) [263]. In this study, solar radiation was obtained from the USA NREL. However, the source associated with the wind speed regime is not specified in the article. An investigation carried out on the island of Córsica (42° 9'N), defined two main objectives: i) defining an optimal HRES composed of PV-Wind that guarantees energy autonomy and, ii) analyzing the performance and optimal size of some architectures in different parts of the island [261]. To meet the objectives, the researchers calculated the incident solar radiation from mathematical models. The method for characterizing the wind is not indicated in the investigation. In Canada, specifically on Ramea island (47°31'10.29" N), the authors evaluated the Wind-Diesel system commissioned on the island and simulated a new system that includes a hydrogen module [262]. The source of information used to characterize the wind is not mentioned. On the island of Mykines (62°6'15" N) a study was carried out that aimed at comparing energy cost, convenience and environmental impacts of a Wind-Hydrogen system and a diesel-based generation system [205]. The estimation of the wind in the area is done with reanalysis data. Reanalysis is the combination of meteorological models and measurements of stations installed on the surface in order to determine the behavior of physical variables in the atmosphere and oceans.

Research Methodology

Primary Resource Data

Obtaining time series of horizontal global radiation and wind speed is not a trivial task. Some tools used to record data on wind speed and solar radiation are: buoys, meteorological stations, satellite sensors and numerical models. Some factors that influence the selection of one source of information over another are: i) the availability of spatio-temporal data in a place, ii) the financing for the installation of sensors (including O&M) or, iii) the correct use of climate numerical prediction models. However, each source has uncertainties that introduce variations in the characterization of the renewable resource, which may have effects on the economic [239] and technical evaluation of an HRES project.

Meteorological data are fundamental inputs to understand the dynamics and potential of renewable resources and their impact on HRES. Some authors use meteorological data from research programs and sensors installed on NASA satellites to determine the availability and variability of a renewable resource at a site of interest [264, 265, 266]. Another strategy available is the use of numerical models of meteorological prediction in order to establish the dynamics of a renewable resource in particular, e.g., results from the Weather Research and Forecasting (WRF) Model which make it possible to identify the wind resource potential in a geographic region [267]. However, there is research that establishes prospecting campaigns for renewable resources such as the sun and wind, and based on time series of measurements (usually one year), they analyze and simulate the performance of a particular HRES [254, 268]. Although estimates of surface solar irradiation from satellites is a widely used and well-developed method, its precision is lower than that obtained with equipment installed on the surface; in turn, the reanalysis, as a procedure to estimate the solar irradiation on the surface, has been described in several studies as overestimated, in addition to presenting biases when increasing the latitude of the territory under investigation [269]. The uncertainty associated with surface-installed sensors is due to little or inadequate maintenance of the sensors and the quality of the installed sensor [239].

Some characteristics of different sources of sun and wind information have been mentioned. Variations in the characterization of the renewable resource have direct implications on the technical and economic feasibility of an HRES. Therefore, a case study in the Chilean fjords has been selected to identify the technical and economic variations of a PV-Wind-Diesel-Battery HRES with the use of three (3) sources of information: i) the NASA Prediction Of Worldwide Energy Resources Database, ii) results of atmospheric and solar radiation models from the Chilean Ministry of Energy and iii) on-site measurements of solar and wind resources. The simulation and optimization of the proposed HRES is carried out with HOMER Pro software version 3.14.

Study area

Las Huichas island is an insular territory located in the northeastern part of the Chonos Archipelago, Aysén Region, Chile. It is located in between latitudes -45.1389 and -45.1659 and between longitudes -73.502 and -73.536 (Figure 3.2.2). There are three inhabited locations on the island: Puerto Aguirre (64 % of the population), Estero Copa and Caleta Andrade, with a total population of 840 inhabitants (according to the 2017 census). The main economic activity is artisanal fishing and the extraction of benthic resources. The electrical energy demand is met by a diesel-based thermoelectric plant which operates 24 hours a day. This power plant is installed in Caleta Andrade, and consists of two generator sets: one is a 288 kW Cummins and the other a 200 kW Caterpillar. The thermoelectric plant has a storage tank for 54,000 liters of diesel. Being an island community, there are only two means of access to and from the continent: i) maritime access used to supply food and essentials, including diesel and, ii) aerial access for private flights.

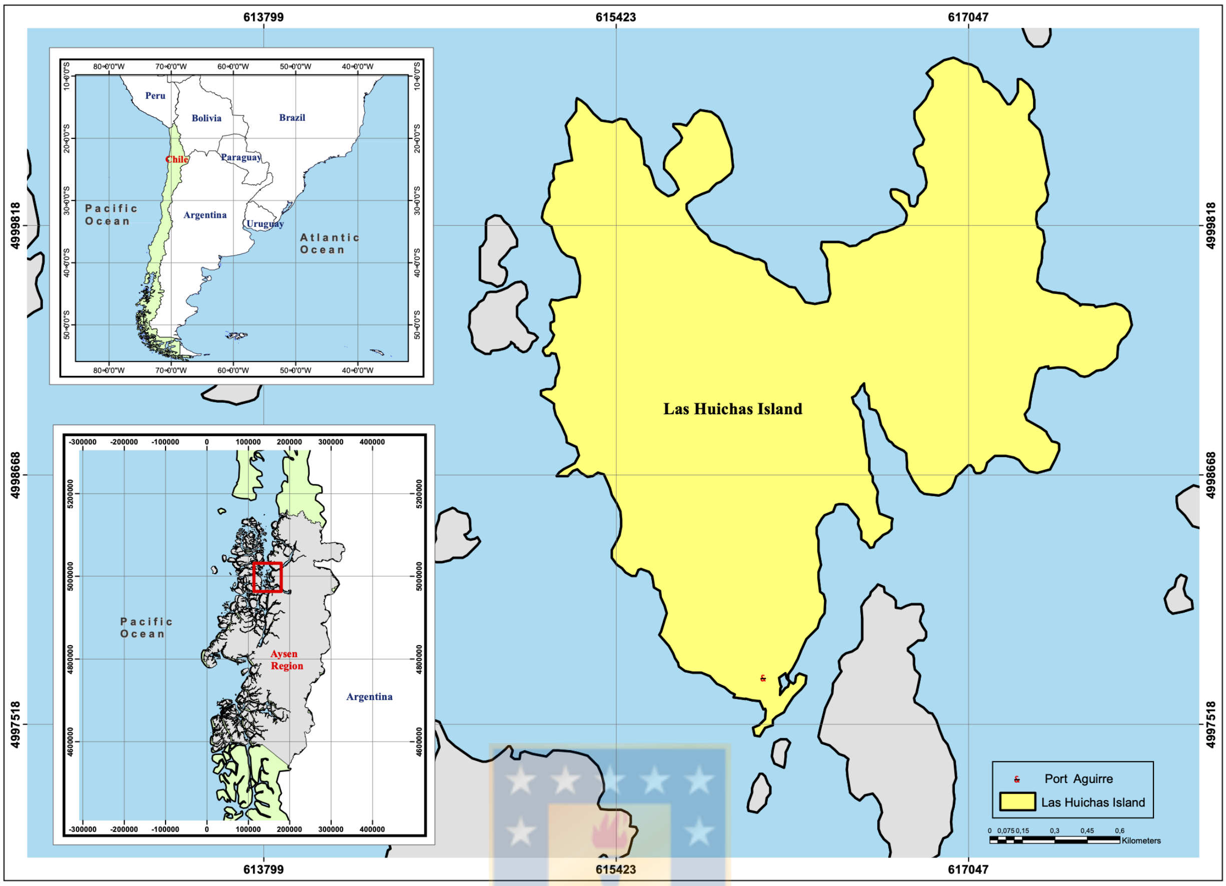

Figura 3.2.2: Location of Las Huichas island, Región de Aysén, Chile.

In 2018, the thermoelectric plant generated 981.8 MWh of electrical energy, according to the information provided by Edelaysen, the utility company in charge of generating and distributing electrical energy on the island (pers. comm.). Figure 3.3.11a shows the electrical energy consumption data of the island community. Peak energy consumption in the island community is located in the time slot between 19:00 and 20:00 (Figure 3.3.11b). The rates per kWh are higher than those established for communities on the mainland, due to the diesel import, transportation to the island and the low population density [270]. For example, the average value of a kWh on the island in 2018 was 0.271 \$/kWh (1 USD = 809 Chilean pesos [271]), according to the reports provided by Edelaysen. On the other hand, the average value in a major Chilean city around Santiago, the capital, was 0.132 \$/kWh [272], 51.3 % lower than the rate paid on the island. Finally, Figure 3.2.4 shows the historical price of a liter of diesel in the Aysén region. This figure results in an average value of 0.74 USD for each liter of diesel in the last eight years, a number that was used in the optimization process in HOMER Pro.

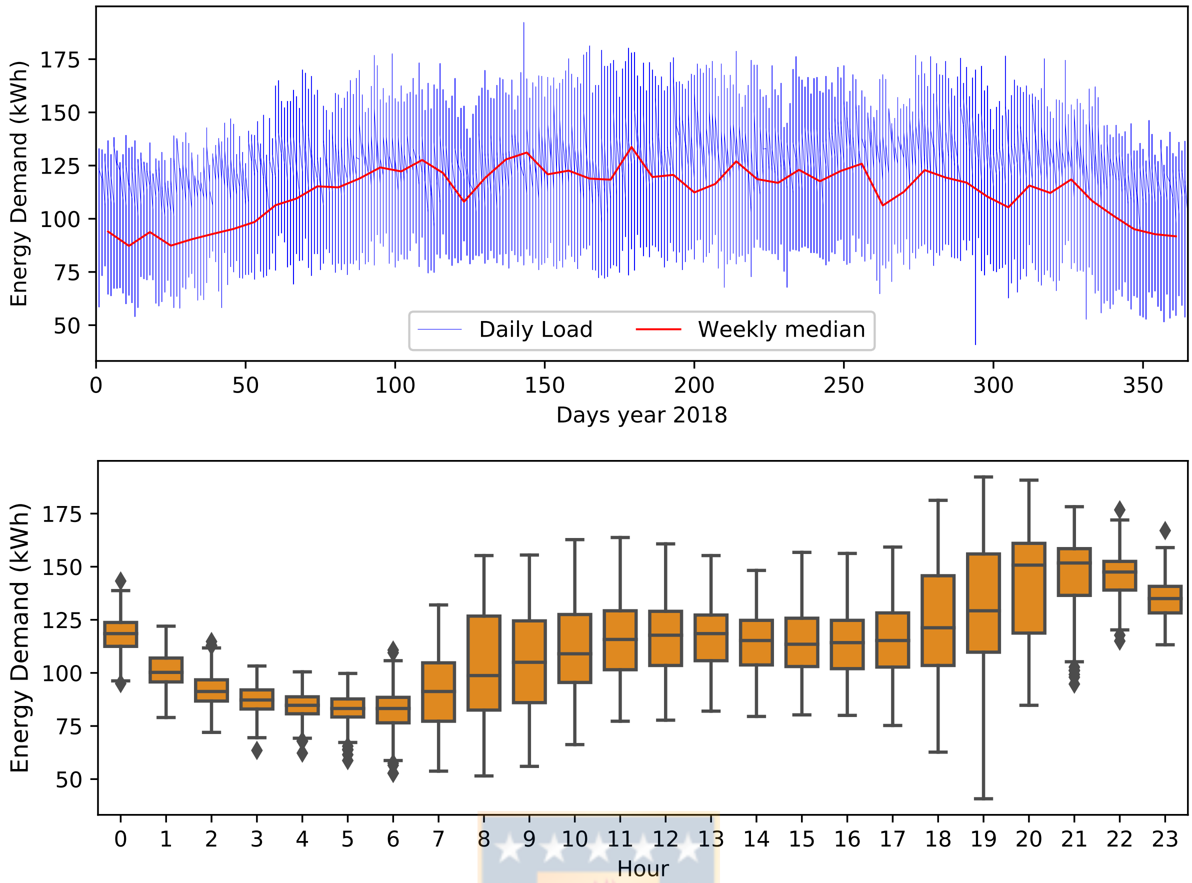

Figura 3.2.3: Power generated by the thermoelectric plant on Las Huichas island in 2018: a) hourly data series for a complete year of measurement (blue line) and data series with weekly median (red line), b) graphical representation of the median and quartiles of the hourly data for a complete year of measurement (outliers are represented by diamonds).

Data related to the load

In order to size and optimize the HRES of the island community, it is essential to have a load profile associated with the consumption of electricity on the island. Edelaysen is the company in charge of generating and distributing electricity to the three towns on the island. This company provided us with the electricity generation reports for 2018 with measurements every fifteen minutes, a time series that was later adjusted to hourly data. Average annual hourly and daily annual energy consumption is 112.07 kWh and 2689.77 kWh/day, respectively. Peak power in the evaluated year was 192.25 kW. During 2018 the island's thermoelectric plant had a *System Average Interruption Duration Index* (SAIDI) of 15,16 hours. In order to meet the energy demand on the island, 292,111 liters of diesel were imported in 2018. The approximate cost per import of diesel was $ 225,430.

Simulation and optimization software

Hybrid Optimization of Multiple Energy Resources (HOMER) from the National Renewable Energy Laboratory (NREL) version 3.14, was used to simulate eight variants of a hybrid system made up of: PV panels, wind turbines, gensets and Li-Ion batteries (Figure 3.2.5). HOMER uses wind speed hourly data (m/s), solar irradiation (kWh/m^2), ambient temperature (°C) and load profiles to simulate and optimize an on-grid and/or off-grid electricity generation system. Additionally, the size and price of each HRES component must be entered in HOMER, considering, among other aspects: initial capital, costs associated with O&M, replacement cost, lifetime, fuel, number of pieces of equipment and power of each device. With this information, HOMER is able to simulate and define the most economical and technically feasible HRES.

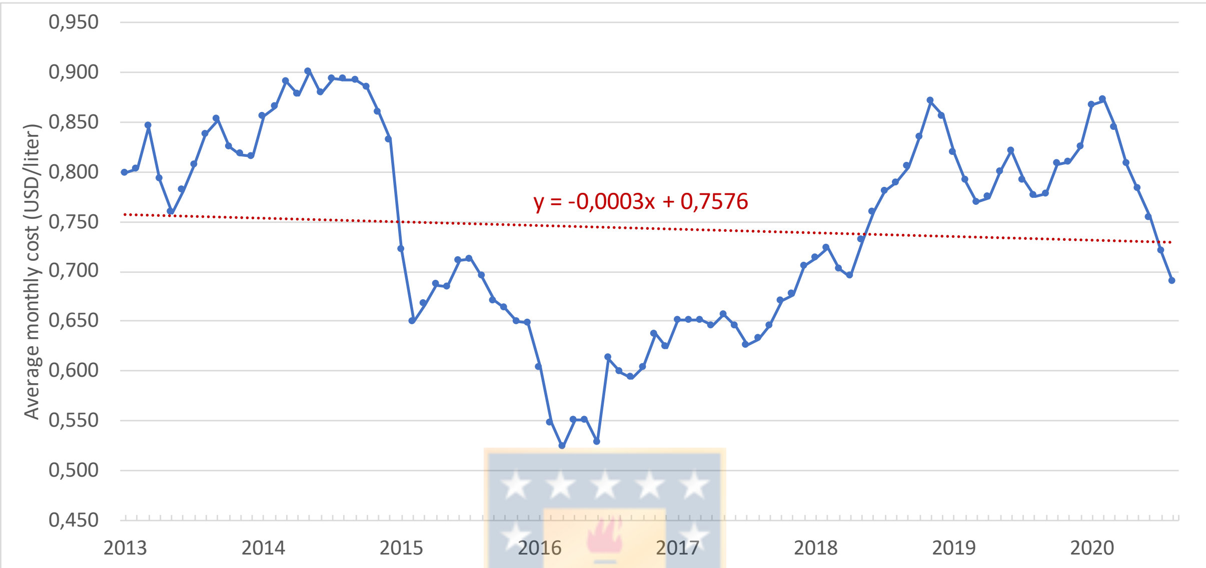

Figura 3.2.4: Historical price of diesel in the Aysén Region, Chile. The maximum, minimum and average value equals to 0.90, 0.52 and 0.74 \$/l, respectively. Data from [4].

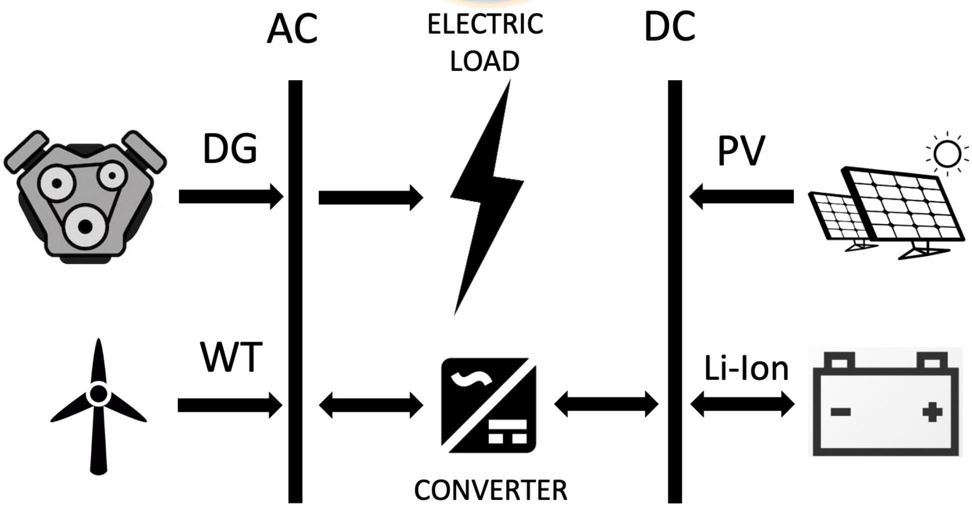

Figura 3.2.5: Schematic diagram of the hybrid PV-Wind-Diesel-Battery system simulated.

The levelized cost of energy (LCOE) is defined as the average between the total annualized cost of the HRES and the total annual energy served. On the other hand, the net present cost (NPC) indicates the current value of all costs associated with: installation, operation, maintenance and replacement, minus the current value of all income during the entire useful life of the HRES

[273]. These two economic variables are fundamental in HOMER to evaluate the economic feasibility of different HRES configurations. The mathematical development to calculate these economic variables is described in [259].

Data source for wind speed, solar irradiation and ambient temperature

Our research brings together three different sources of information to obtain the data related to wind speed and solar irradiation on the island, and in this way identify the variations in the sizing of the proposed HRES. The data sources used are:

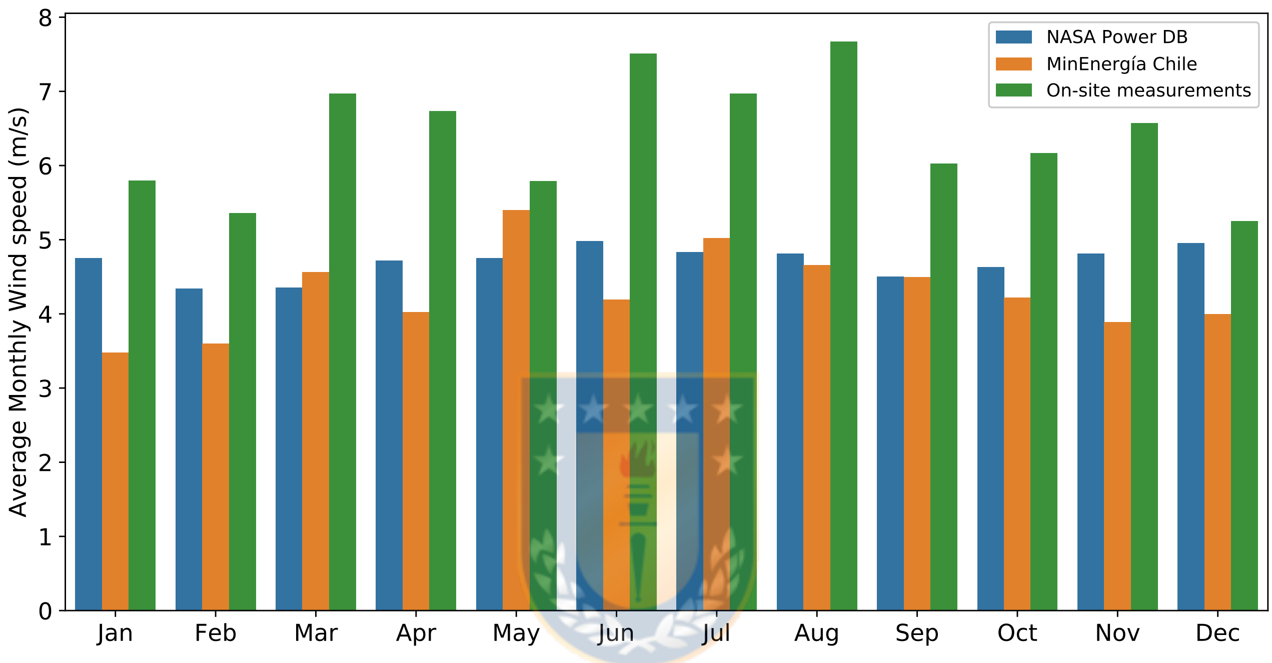

Figura 3.2.6: Average wind speed on Las Huichas island from different data sources: i) data from the NASA Power Database (blue bars), corresponding to a monthly average wind speed at 50 m above the surface of earth over a 30-year period (Jan 1984 - Dec 2013), for an Annual Average of 4.7 m/s ± 1.72, ii) data from the Wind Explorer of the Ministerio de Energía de Chile (orange bars), with an Annual Average of 4.3 m/s ± 2.4 and, iii) data associated with wind resource prospecting campaigns (green bars), with an Annual Average of 6.4 m/s ± 4.5.

- **Source 1.** Data from the NASA Prediction of Worldwide Energy Resources (NASA Power) Database [274], information source linked in HOMER to download wind speed data (blue bars in Figure 3.2.6), horizontal global irradiation (blue bars in Figure 3.2.7) and air temperature (blue bars in Figure 3.2.8). The data that HOMER downloads from the NASA Power Database correspond to monthly averages of wind speeds at 50 m above the surface of earth and from a period of 30 years (January 1984 - December 2013), monthly averages of global horizontal irradiation during a 22-year period (July 1983 - June 2005) and monthly averages of air temperature over a 30-year period (January 1984 - December 2013). The annual average of the wind speed time series and its standard deviation are 4.7 m/s and 1.72 m/s, respectively. In the case of solar irradiation the values are 2.83

kWh/m^2/day and 2.02 kWh/m^2/day and at an ambient temperature of 8.59°C and 3.27°C, respectively.

* **Source 2.** The Wind Energy Explorer (Explorador Eólico) of the Ministerio de Energía de Chile (Chilean Ministry of Energy) provides hourly results of the wind speed from the year 2015 (orange bars in Figure 3.2.6) from numerical modeling, using Weather and Research and Forecasting (WRF), at 20 meters above ground level [275]; the Solar Energy Explorer (Explorador Solar), also from the Ministerio de Energía de Chile, yields results associated with horizontal global irradiation (orange bars in Figure 3.2.7) and air temperature (orange bars in Figure 3.2.8), from solar radiation models [276, 277] made for the year 2015. In this case, the annual average of the time series associated with the wind speed and its standard deviation is 4.29 m/s and 2.4 m/s. Likewise, for solar irradiation the data are 3.17 kWh/m^2/day and 0.21 kWh/m^2/day and at an ambient temperature of 10.49°C and 3.5°C, respectively.

* **Source 3.** Measurements made on-site (Las Huichas island) from a wind and solar resource prospecting campaign (green bars in Figure 3.2.6 and Figure 3.2.7, respectively), carried out between August 22, 2005 and September 08, 2006, in which parameters were obtained for wind speed (20 m and 10 m above ground level), wind direction at 20 m above ground level and horizontal global solar irradiation at 3 m above ground level [278]. The annual average and standard deviation of the wind speed and solar irradiance time series are 6.4 m/s, 4.5 m/s and 3.13 kWh/m^2/day and 2.55 kWh/m^2/day, respectively.

In **Source 3** the wind speed data was selected at a height of 20 meters, because the chosen wind turbine has a height of 18 meters from the ground to the nacelle. The time series from the prospecting campaign are made up of measurements made with 10-minute time steps. Both series, wind speed and horizontal global irradiation, contain 50,789 measurement data, that is, there is a lack of 1,771 records to complete the 52,560 measurements that correspond to a year of data with the indicated time steps. Linear extrapolation was used to complete the two time series. In the case of **Source 2**, the time series contains 8,757 valid records, and the data associated with the last three hours of December 31 are missing. Therefore, the last valid value of December 31 was repeated in the three missing time registers. Completing the time series is a preliminary step to the simulation, since HOMER only recognizes time series that contain data for a full year.

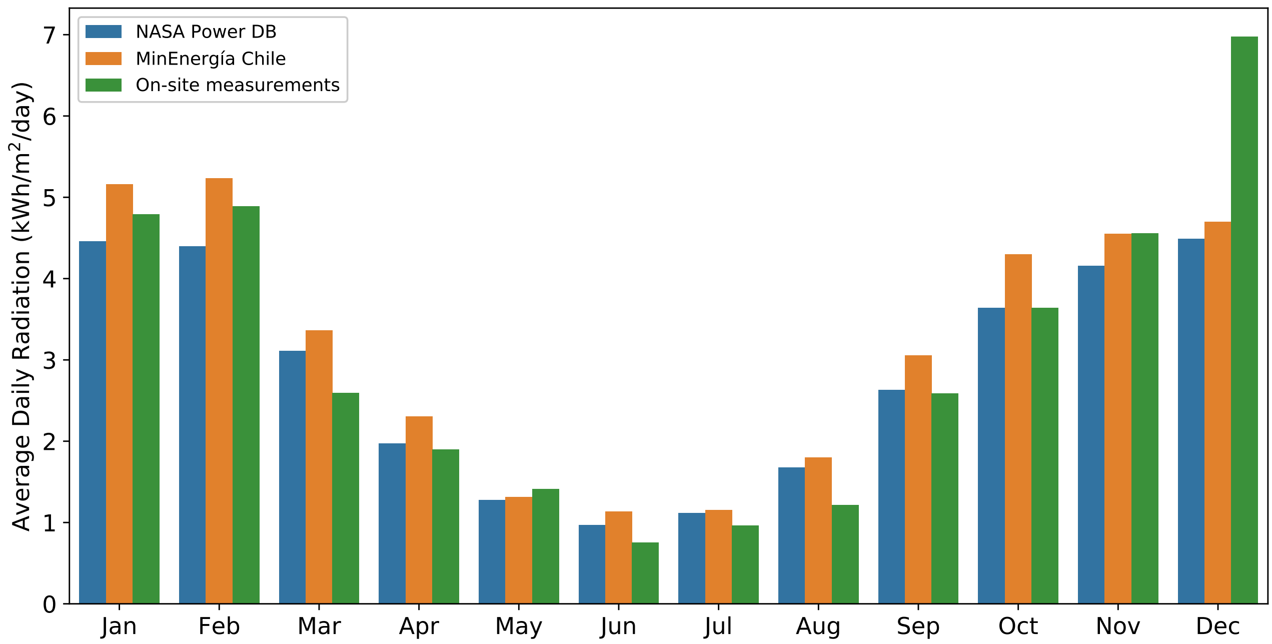

Figura 3.2.7: Average daily horizontal global irradiation on Las Huichas island from different data sources: i) using data from the NASA Power Database (blue bars), from monthly averages for global horizontal radiation over a 22-year period (Jul 1983 - Jun 2005), which provide an Annual Average of 2.8 $kWh/m^2/day \pm 2$, ii) with data from the Solar Explorer from the Ministerio de Energía de Chile (orange bars), resulting in an Annual Average of 3.2 $kWh/m^2/day \pm 0.21$ and, iii) with data obtained in prospecting campaigns of the solar resource (green bars), for an Annual Average of 3 $kWh/m^2/day \pm 2.6$.

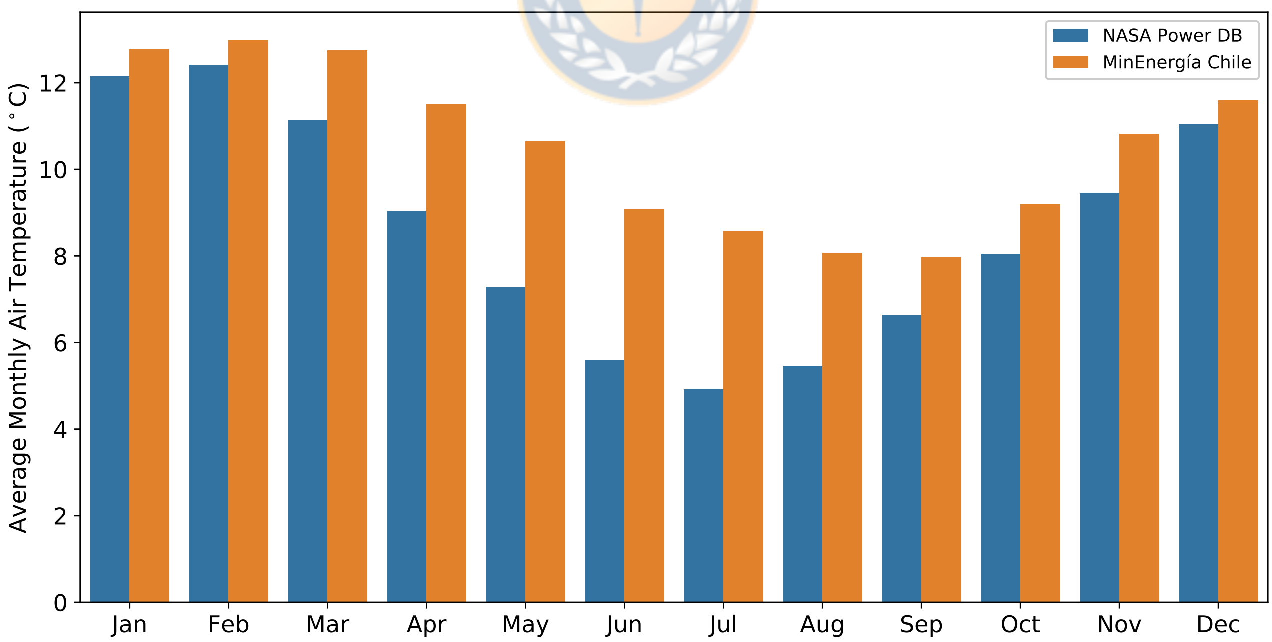

Figura 3.2.8: Monthly average air temperature from two data sources: i) using data from the NASA Power Database (blue bars) over a 30-year period (Jan 1984 - Dec 2013), resulting in an Annual Average of 8.6°C ± 3.3 and, ii) data from the Solar Explorer from the Ministerio de Energía de Chile (orange bars) resulting in an Annual Average of 10.5°C ± 3.5.

Regarding ambient temperature, two sources of information were used: the NASA Power

Database and the Solar Energy Explorer from the Ministerio de Energía de Chile (Figure 3.2.8). No data repositories associated with ambient temperature measurement campaigns were found on the island. In the case of ambient temperature, the results of atmospheric and satellite models from the Ministerio de Energía de Chile were used in the simulations corresponding to Cases *b* and *c*, in section 3.2.

Technical and economic data of the HRES

Table 3.3.2 shows the most relevant technical and economic parameters of the components for the proposed HRES: Wind Turbine, Solar Panel, Li-Ion Battery, Diesel Generator and Converter. To take advantage of the solar resource on the island, CanadianSolar's MaxPower CS6U-330 polycrystalline solar panels were selected, which have a nominal power of 330 W and are available at local distributors. The solar panel is configured without a solar tracking system, that is to say, it is positioned on a metal structure which gives it an adjustable tilt angle, which for the optimization base scenario was defined to be equal to the latitude of the island and directed towards the North ($\beta = 45.15°$, $\gamma = 180°$). Because the efficiency of a solar panel decreases as the ambient temperature increases [279], an analysis of the effects of ambient temperature on the performance of the panel was configured in HOMER for each simulation step.

To convert the kinetic energy of the wind into electrical energy, the Gaia-Wind 11kW 133 turbine was selected which has a rated power of 11 kW. This turbine has an adjustable cut-in and cut-out, although the standard configuration values are 3.5 and 25 m/s, respectively. Additionally, this turbine is designed for sites with average annual wind speeds of up to 7.5 m/s at rotor height. As in the case of solar panels, ambient temperature is an important physical parameter, due to its relationship with air density. This parameter, ambient temperature, can influence the turbine output power up to 20 % [280]. In the simulations carried out in HOMER, the effect of ambient temperature was considered in order to obtain more precise results in the electrical energy produced. On the other hand, the costs associated to the Initial Capital, O&M and Replacement cost were inquired with the manufacturer (pers. comm.).

The generation of electrical energy from renewable sources and the energy demand profile do not have an ideal behavior, where the periods of greatest power generation coincide with the greatest energy demand. Therefore, using an energy storage system (ESS) is vital to avoid oversizing the HRES system. During the times of the day in which there is an excess of electricity generation from renewable sources, the ESS will store said excess energy. On the other hand, when renewable energy sources cannot meet the demand for electrical energy, the ESS will supply the required electrical energy. In this research, the selected ESS corresponds to Li-Ion batteries mainly due to the fact that they have higher energy densities and have better efficiency during charge and discharge cycles, when compared to other types of batteries [281].

Tabla 3.2.2: Technical and economic parameters of the HRES components simulated in HOMER.

Parameter	Units	Value
Solar Panel CanadianSolar MaxPower CS6U-330P		
Rated Capacity	kW	0.330
Initial Capital	USD	206.67
O&M	USD	0
Replacement	USD	206.67
Efficiency	%	16.97
Lifetime	years	25
Derating factor	%	80
Wind Turbine Gaia-Wind 11kW 133 3-Phase		
Rated Capacity	kW	11
Initial Capital	USD	80000
O&M	USD/yr.	1600
Replacement	USD	66000
Hub Height	m	18
Lifetime	years	20
Diesel Generator CAT-250kVA-50Hz-PP		
Capacity	kW	200
Initial Capital	USD	0
O&M	USD/op. hour	0.03
Replacement	USD	60000
Fuel Price	USD/l	0.74
Minimum Load Ratio	%	25
Li-Ion Battery Generic 1kWh Li-Ion [ASM]		
Nominal Capacity	kWh	1
Capital (5 units)	USD	3500
O&M	USD	0
Replacement (5 units)	USD	3500
Initial State of Charge	%	100
Minimum State of Charge	%	20
Generic Converter		
Capacity	kW	1
Capital	USD	300
O&M	USD/yr.	0
Replacement	USD	300
Lifetime	years	15
Inverter Efficiency	%	95
Rectifier Efficiency	%	95

One strategy to respond to sudden changes to the electrical load side is the *operative reserve*. HOMER allows the definition of a percentage of surplus in the operating capacity of the HRES under evaluation, in order to respond to unexpected increases in the demand for electrical energy by the load. This ensures a continuous supply of electrical energy from renewable sources, in the event of changes that do not exceed the defined percentage of *operative reserve*. Table 3.2.3 shows the values defined in the *operative reserve* for the production of electrical energy associated with the sun and wind. In addition to this, it is established that the HRES must supply 100 % of the electricity demand, which translates into a loss of power supply probability (LSPS) of 0 %. Currently the inhabitants of the island have access to electricity 24/7, therefore, an energy solution with local natural resources should not reduce the conditions of comfort and quality of life of the island community.

Tabla 3.2.3: Technical and economic parameters configured in HOMER for each of the HRES architectures evaluated.

Item	Value
Optimization settings	
Maximum annual capacity shortage	0 %
Operative reserve as a percentage of load	10 %
Operative reserve as a percentage of solar power output	20 %
Operative reserve as a percentage of wind power output	30 %
Economics	
Nominal discount rate	8 %
Expected inflation rate	3 %
Project lifetime	20 years

Results

We used three sources of information on the availability and variability of renewable energies. Eight HRES architectures were simulated and optimized for the Las Huichas island community. In Case a (NASA Power Database), the data series are categorized as long-term records: 30 years of monthly averages of wind speed and air temperature (1984–2013), 22 years of monthly averages of global horizontal irradiation (1983–2005). The averaging process used in creating this data set effectively removes high frequency variability present in the data. Case b and Case c are short-term records. These cases represent the variability present in a specific period and as such might contain high frequency variability, due to dominant atmospheric processes present in that period such as El Niño Southern Oscillation (ENOS). In particular, Case b corresponds to the wind regime, solar radiation and ambient temperature for the year 2015 and Case c represents a year of measurements between 2005 and 2006.

Optimization

Eight different HRES architectures were simulated, each one fed with three sources of information for wind speed and solar irradiation, and two sources of information for ambient temperature. The load profile corresponds to the actual consumption of electricity on the island during 2018. The simulated HRES architectures were: PV-Diesel, PV-Battery, PV-Diesel-Battery, PV-Wind-Battery, PV-Wind-Diesel-Battery, Wind-Diesel-Battery, Wind-Diesel and Wind-Battery. The optimization results were categorized with the LCOE parameter, giving priority to the configurations that have the lowest LCOE. As a complement, fuel consumption, fraction of energy generated from renewables and autonomy of the hybrid system were evaluated as criteria for the selection of the HRES.

Table 3.2.4 shows the results obtained for the eight HRES configurations. The PV-Diesel-Battery hybrid system has the lowest LCOE ratings for all data sources: 0.207 \$/kWh in the case of NASA (Case a), 0.199 \$/kWh in the case of the Explorer from the Ministerio de Energía de Chile (Case b) and 0.210 \$/kWh with the data obtained from the on-site measurements of renewable resources (Case c). The PV-Diesel HRES follows these results closely with increases in the LCOE, for each case study, of 0.97 %, 1 % and 0.95 %, respectively. By including a wind turbine in the configuration with the lowest LCOE, the variation in the LCOE is 2.42 % (Case a), 2.01 % (Case b) and 0.48 % (Case c).

The Wind-Battery configuration does not have a feasible solution for Case a and Case b. In Case c, HOMER delivered a viable technical solution that is made up of 588 wind turbines, 10,251 Li-Ion battery units (giving it an estimated autonomy of 65 hours), with an LCOE of 5.25 \$/kWh, an initial investment of \$ 51.4 millions and an annual O&M cost of \$ 1.1 millions. Even though this system is 100 % renewable, that is, it does not use any primary source based on fossil fuels, it exceeds the available territory on the island for its installation.

The 100 % renewable PV-Battery system has two feasible configurations related to Case a and Case b. The LCOE varies between 0.417 and 0.632 \$/kWh. The supply of electrical energy to the load from the batteries can be extended for maximum periods of 45 hours (Case a) and 21 hours (Case b). Regarding the number of solar panels, the PV-Battery configuration requires the installation of 18,658 panels angled at $\beta = 45.15°$ (island latitude), the purchase and installation of 7,092 batteries and 206 kW in converters, all associated with the global horizontal irradiation series of Case a. Regarding Case b, the HRES topology is reduced to 15,916 solar panels, 3,357 batteries and there is an increase of 152 % in the minimum power required for the converters, compared to Case a.

The three remaining configurations: Wind-Diesel, Wind-Diesel-Battery and PV-Wind-Battery, have LCOE values of 0.230-0.285, 0.233-0.283 and 0.339-0.617 \$/kWh, respectively. In Cases a and b of the Wind-Diesel configuration, HOMER proposes an architecture made up of 13 wind turbines, a number twice higher than that proposed in Case c. A similar situation occurred in the Wind-Diesel-Battery configuration, with 12 wind turbines for the information sources associated with NASA and Explorer from the Ministerio de Energía de Chile, and 6 wind turbines considering results of on-site measurements (Case c). Lastly, the PV-Wind-Battery

Tabla 3.2.4: Summary of the optimization results for different hybrid power systems in HOMER. Cases with subscript *a* were simulated with data obtained from the NASA Power Database (Source 1). Subscript *b* corresponds to the optimization of the HRES with results of atmospheric and solar radiation models from the Ministry of Energy of Chile (Source 2), and subscript *c* are the results obtained from Source 3 (on-site measurements). The units in the Initial Capital and Operating Cost columns are in Thousands of USD ($\times 10^3$). The units in Total Fuel are in Thousands of liters. The NPC is given in Millions of USD ($\times 10^6$). The lowest LCOE is highlighted in bold.

	Architecture					**Cost**				**System**			
Case	PV Array (kW)	Wind Turbines	Diesel (kW)	Battery (Qty)	Converter (kW)	Initial Cap.[0] (M $)	NPC (MM $)	LCOE ($/kWh)	Op. Cost[1] (M $/yr.)	RF (%)	Total Fuel (M l/yr.)	Data	Autonomy (hours)
PV-Diesel hybrid power system													
1a	707	-	200	-	156	485.4	2.59	0.209	166.8	20.1	222.2	NASA Power	0
1b	953	-	200	-	157	637.6	2.50	0.201	147.2	28.7	198.2	WRF	0
1c	767	-	200	-	158	522.6	2.62	0.212	166.5	20.1	222.2	On site measu.[2]	0
PV-Battery hybrid power system													
2a	6157	-	-	7092	206	6724	7.82	0.632	86.9	100	0	NASA Power	45.2
2b	5252	-	-	3357	314	4732	5.16	0.417	34.1	100	0	WRF	21.4
2c	No feasible solutions found using on-site measured data.												
PV-Diesel-Battery hybrid power system													
3a	655	-	200	12	156	461.2	2.57	0.207	167.1	20.1	222.2	NASA Power	0.08
3b	892	-	200	12	157	608.4	2.47	**0.199**	147.3	28.8	198	WRF	0.08
3c	703	-	200	18	153	492.9	2.60	0.210	167.2	20.0	222.4	On-site measu.	0.12
Wind-Diesel hybrid power system													
4a	-	13	200	-	-	1040	3.53	0.285	197.3	20.6	231	NASA Power	0
4b	-	13	200	-	-	1040	3.51	0.283	196	21.3	229	WRF	0
4c	-	6	200	-	-	480	2.85	0.230	188	21.1	232.5	On-site measu.	0
Wind-Battery hybrid power system													
5a	No feasible solutions found using NASA Power data.												
5b	No feasible solutions found using WRF data.												
5c	-	588	-	10251	1335	51428	65.3	5.28	1099	100	0	On-site measu.	65.4
Wind-Diesel-Battery hybrid power system													
6a	-	12	200	30	106	1010	3.50	0.283	198	20.0	232	NASA Power	0.19
6b	-	12	200	24	96.8	1004	3.47	0.280	196	20.7	230	WRF	0.15
6c	-	6	200	6	85.0	510	2.88	0.233	188.2	21.1	232.5	On-site measu.	0.04
PV-Wind-Battery hybrid power system													
7a	7109	1	-	5637	250	6837	7.63	0.617	63	100	0	NASA Power	36.0
7b	3233	3	-	3237	215	3645	4.20	0.339	44.2	100	0	WRF	20.6
7c	3693	20	-	3087	231	5235	6.09	0.492	68	100	0	On-site measu.	19.7
PV-Wind-Diesel-Battery hybrid power system													
8a	631	1	200	18	166	532	2.63	0.212	166.4	21.7	219	NASA Power	0.12
8b	882	1	200	24	159	689	2.52	0.203	145	31.1	192.2	WRF	0.15
8c	642	1	200	27	160	542.4	2.62	0.211	165	22.9	216.1	On-site measu.	0.17

[0] Initial Capital; [1] Operating Cost; [2] On-site measurements.

HRES is 100 % supported on renewable energy sources that eliminate diesel consumption from the electrical energy production equation and, in turn, the emission of worrying and harmful greenhouse gases into the atmosphere. This configuration yields higher LCOE than those obtained in the two HRES systems mentioned above, however, it has a longer autonomy that ranges between 19.7 and 36 hours, a characteristic that the Wind-Diesel and Wind-Diesel-Battery solutions do not offer.

Sensitivity Analysis

The results presented in Table 3.2.4 correspond to the initial design conditions which can vary significantly in magnitude over time. In addition to that, using an angle of inclination on the solar panels equal to the latitude of the place minimizes the use of available radiation, directly affecting the economic viability of the project [282]. Therefore, a sensitivity analysis was implemented on three important design variables: diesel price, solar panel inclination and minimum renewable fraction (RF) of energy within the generated energy. In order to do this, the following design criteria were established:

- Diesel Price: Taking into account the historical records of the last 8 years [4], 5 possible scenarios were defined: 0.5 \$/l (historical minimum price), 0.6 \$/l, 0.7 \$/l, 0.8 \$/l and 0.9 \$/l (historical maximum price).
- PV Tilt Angle: Five angles of inclination were defined: 39.15° (angle with greater capture of solar irradiation in summer, when compared to the latitude of the island), 42.15°, 45.15° (island latitude), 48.15°y 51.15° (angle with greater capture of solar irradiation in winter, when compared to the latitude of the island).
- RF: technical design constraint that determines the minimum percentage of energy generated annually from renewables. Five scenarios were established that match the objectives of the Chilean energy policy: 20 % (goal by 2025) [283], 30 %, 40 %, 50 % and 60 % (goal by 2035) [284].

Table 3.2.5 summarizes the results obtained in the sensitivity analysis, categorized by architecture and the three case studies associated with different sources of information on wind speed, global horizontal irradiation and ambient temperature. From an LCOE analysis, the evidence shows that the PV-Diesel-Battery hybrid system has the lowest LCOE, oscillating between 0.149 - 0.156 \$/kWh for the three data sources, which represents a reduction of 25.12 % (considering the lower LCOE value) when compared to the result obtained in Table 3.2.4. The autonomy of this system is 0.04 hours for Case b, with 6 Li-Ion batteries, and 0.06 hours for Cases a and c provided by 9 Li-Ion batteries. The PV-Diesel configuration has an LCOE indicator very close to that obtained in the previous configuration. The results obtained were 0.154 \$/kWh in Case a, 0.149 \$/kWh in Case b and 0.157 \$/kWh in Case c. This system does not have batteries and so it does not offer any type of autonomy. In both configurations, PV-Diesel-Battery and

Tabla 3.2.5: Main sensitivity results in Homer. The units in the Operating Cost column are in Thousands of USD ($\times 10^3$). Cases with subscript a were simulated with data from the NASA Power Database (Source 1). Subscript b corresponds to the optimization of the HRES with results of atmospheric and solar radiation models from the Ministerio de Energía de Chile (Source 2), and subscript c are the results obtained from Source 3 (on-site measurements). The units in Total Fuel are in Thousands of liters. The NPC is given in Millions of USD ($\times 10^6$). The lowest LCOE is highlighted in bold.

	Sensitivity Cases			**Architecture**					**Cost**			**System**	
Case	RF (%)	PV Slope (°)	Diesel Fuel Price ($/l)	PV Array (kW)	Wind Turbines	Diesel (kW)	Battery (Qty)	Converter (kW)	NPC (MM $)	LCOE ($/kWh)	Op. Cost (M $/yr.)	Total Fuel (M l/yr.)	Autonomy (hours)
PV-Diesel hybrid power system													
1a	20.1	39.15	0.5	688	-	200	-	163	1.91	0.154	114	222.2	0
1b	20.1	39.15	0.5	588	-	200	-	153	1.85	**0.149**	114	222.3	0
1c	20.2	39.15	0.5	756	-	200	-	153	1.94	0.157	113.1	222	0
PV-Battery hybrid power system													
2a	100	39.15	0.5	6938	-	-	5940	226	7.60	0.614	66.5	0	37.9
2b	100	48.15	0.5	3826	-	-	4179	222	4.79	0.387	51.5	0	26.7
2c	No feasible solutions found using on-site data.												
PV-Diesel-Battery hybrid power system													
3a	20.0	39.15	0.5	647	-	200	9	162	1.89	0.153	114	223	0.06
3b	20.3	39.15	0.5	576	-	200	6	151	1.84	**0.149**	114	222	0.04
3c	20.1	39.15	0.5	717	-	200	9	159	1.93	0.156	113.5	222.1	0.06
Wind-Diesel hybrid power system													
4a	20.6	-	0.5	-	13	200	-	-	2.83	0.228	142	231	0
4b	21.3	-	0.5	-	13	200	-	-	2.82	0.227	141	229	0
4c	21.1	-	0.5	-	6	200	-	-	2.14	0.173	132	232.5	0
Wind-Battery hybrid power system													
5a	No feasible solutions found using NASA Power data.												
5b	No feasible solutions found using WRF data.												
5c	100	-	0.5	-	588	-	10251	1335	65.3	5.28	1099	0	65.4
Wind-Diesel-Battery hybrid power system													
6a	20.9	-	0.5	-	13	200	6	5.09	2.83	0.228	141.3	230	0.04
6b	20.2	-	0.5	-	12	200	6	4.69	2.74	0.221	141	232	0.04
6c	21.1	-	0.5	-	6	200	3	111	2.19	0.177	132.5	232.5	0.02
PV-Wind-Battery hybrid power system													
7a	100	45.15	-	7109	1	-	5637	250	7.63	0.617	63	0	36.0
7b	100	39.15	-	3328	3	-	3096	219	4.17	0.337	41.7	0	19.7
7c	100	39.15	-	3647	20	-	3069	233	6.05	0.489	67.4	0	19.6
PV-Wind-Diesel-Battery hybrid power system													
8a	21.3	39.15	0.5	628	1	200	9	160	1.96	0.159	114.1	219.6	0.06
8b	21.9	39.15	0.5	546	1	200	9	158	1.91	0.154	114	218.1	0.06
8c	24.2	39.15	0.5	743	1	200	18	152	1.99	0.160	110.2	212.5	0.12

[0] Operating Cost.

PV-Diesel, HOMER found that the angle of inclination must be lower than the latitude, that is to say, 39.15° instead of 45.15°. Similarly, the results of Table 3.2.5 show that low LCOE values are associated with low diesel prices per liter.

Now, if the RF in Table 3.2.5 is analyzed, the lowest LCOE are associated with numbers equal or slightly higher than 20 %, except in the cases of 100 % renewable configurations. Electricity generation systems based solely on renewable energies are associated with LCOE that vary between 0.337 - 0.617 $/kWh for PV-Wind-Battery architectures, 0.387 - 0.614 $/kWh for a PV-Battery HRES and 5.28 $/kWh (Case c) for the Wind-Battery system. These three architectures are capable of satisfying the demand for electrical energy on the island (LSPS = 0 %), using the sun and wind as primary resources. A relevant characteristic in these systems is the autonomy of the energy storage system. In the first system, that is, PV-Wind-Battery, the autonomy of electric power supply once the renewable energy sources are insufficient, is 36 hours for Case a and 19 hours in the other Cases. In the PV-Battery system the autonomy is 37.9 hours for Case a, almost two hours more than the previous system, 26.7 hours for Case b which represents 36 % more autonomy when compared to the PV-Wind-Battery system, and for Case c, HOMER did not find a viable solution. Although the Wind-Battery system has the longest autonomy of the eight systems evaluated (65.4 hours), it also has the highest LCOE of all the configurations with a value of 5.28 $/kWh.

Discussion

In this work we performed the optimization of eight different HRES architectures for Las Huichas island, Chile, with HOMER Pro v3.14 software using three different sources of information: a climatological data set, atmospheric model results from a specific year, and on-site observations from a specific year. The energy consumption profile of the 840 inhabitants of the island corresponds to the real consumption of the year 2018. The main primary resources involved in this research are the sun and wind, accompanied by an energy storage system (Li-Ion batteries) and a backup genset. We used three different sources of information in HOMER: the NASA Power Database (Case a), results of atmospheric and solar radiation models (Case b) and measurements made on the Las Huichas island (Case c). HOMER categorized HRES architectures that were feasible from a technical and economic perspective. Although the research focuses on mid-high latitude communities, and contrary to the common perception of very low solar irradiation at high latitudes, it is important to note that several studies have shown that incident solar irradiation at high latitudes can be even higher than the G_o under certain weather conditions [285, 286].

The results of the simulations demonstrate a convergence in three HRES architectures: PV-Diesel, PV-Diesel-Battery and PV-Wind-Diesel-Battery. The lowest LCOE and NPC economic indicators in these configurations were obtained with the data sources from the Wind Explorer

[275] and Solar Explorer [276] (Case b), followed by data from the NASA Power Database [274] (Case a) and, lastly, data from the wind and solar measurements on site [278] (Case c).

Using time series from different information sources causes significant variations in the optimization results of an HRES. While data obtained with numerical climate models (Case b) indicate that the lowest LCOE is 0.199 $/kWh (architecture PV-Diesel-Battery Table 3.2.4), data obtained from on-site measurements increase the LCOE at 0.210 $/kWh (Case c). Similarly, an RF of 28.8 % (Case b) is identified in the PV-Diesel-Battery HRES, much higher than the 20 % obtained with on-site sensor data (Case c), essential elements when evaluating the feasibility of any HRES project. From an environmental and social perspective, one of the greatest restrictions in island communities for the development and implementation of energy projects is the competition for land use [247], and the limited available surface area. Solar panels need large territories to produce a significant amount of electrical energy [26]. Regarding wind turbines, noise and visual pollution [26] are real issues that may not be tolerated by the community. According to the above, and highlighting that the results of the HRES PV-Diesel-Battery (Case b) confirm the lower LCOE (Table 3.2.4), this architecture in turn requires the installation of a greater number of solar panels on the island. This translates into the need to install approximately 2,704 solar panels in Case b, compared to 2,131 panels needed in Case c, which has the highest LCOE of this architecture.

Considering the growing environmental concerns associated with the use of fossil fuels [262, 268] and the technological maturity in the use of renewable resources [195], it is clear that HRES are an opportunity to guarantee: i) better air quality, ii) minimize risks from diesel use and iii) increase the energy independence of island communities. Sustainable electricity generation systems require less genset integration. In this regard, analyzing the annual fuel consumption in the PV-Diesel-Battery HRES, an additional 24400 l/yr. are used in Case c when compared to Case b. All the variations highlighted in the economic and environmental indicators of the PV-Diesel-Battery HRES are due solely to the sources of information used. Similar results can be obtained with the PV-Wind-Diesel-Battery HRES (Table 3.2.4).

Increasing the autonomy of the PV-Diesel-Battery and PV-Wind-Diesel-Battery HRES architectures reflects substantial increases in the LCOE, NPC and the installed power of the PV array. A 3-hour autonomy for the PV-Diesel-Battery system causes an increase in the LCOE of +146 % Case a, Table 3.2.5, +143 % Case b and +249 % Case c. Considering the three Cases, the NPC indicator has an increase that ranges between 142 % - 250 %. In the case of the PV-Wind-Diesel-Battery HRES the increases in the LCOE of each case study are: +144 % Case a, Table 3.2.5, +141 % Case b and +144 % Case c. The NPC in this configuration ranges between $ 2.69 and $ 2.85 millions.

Almost 50 % of HRES studies in island communities (Section 3.2), characterized local renewable resources with on-site measurements. In our research, Case c corresponds to short-term records (on-site measurements). These types of records characterize in detail the intraseasonal and seasonal dynamics. However, interannual or interdecadal climatic variations are beyond these types of records. Therefore, clear differences are established in the sizing of an HRES due to short-term and long-term records (Table 3.2.4). Analyzing the three best architectures: PV-Diesel, PV-Diesel-Battery and PV-Wind-Diesel-Battery, and establishing Case c as the base scenario, the following results can be highlighted:

- With data from NASA (Case a) there is an undersizing in the three best HRES configurations. For PV-Diesel the number of solar panels is 7.8 % less than Case c. The initial capital is less than the other cases and fuel consumption remains stable when compared to Case c. The insertion of batteries to the previous configuration reduces the number of solar panels to 1,985, 6.9 % lower than the figures obtained in Case c. The difference is smaller in the PV-Wind-Diesel Battery HRES, where the number of panels is reduced by 1.7 %.

- With data obtained from climatological models, there is an oversizing of equipment in the three best architectures (compared to Case c). The PV-Diesel configuration requires 24.3 % more solar panels to satisfy the same load as Case c. This increases the initial capital, however it reduces diesel consumption by 24,000 l/yr. due to the increase in RF. The HRES PV-Diesel-Battery is 26.9 % oversized in solar panels. Regarding initial capital, diesel consumption and RF, the behavior is similar to that explained in PV-Diesel. Lastly, including a wind turbine in the HRES causes a 37.4 % increase in the number of panels required, a difference that is explained by the low average wind speed (Case b) when compared to the high wind regimes obtained in Case c.

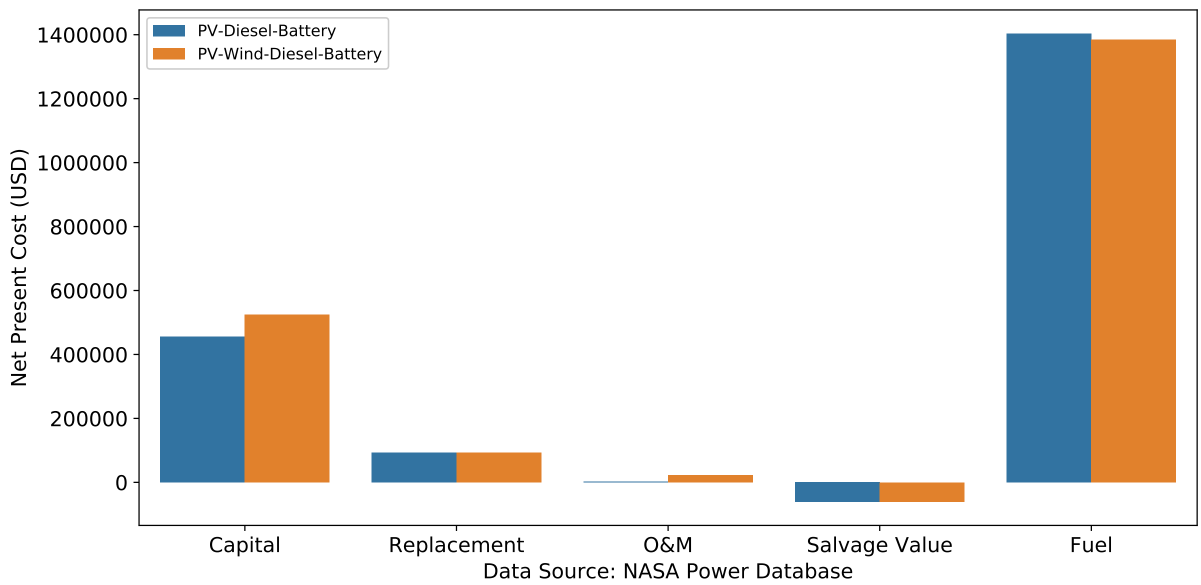

Figura 3.2.9: Net present cost of all costs involved in installation and O&M of the PV-Diesel-Battery HRES (blue bars) and the PV-Wind-Diesel-Battery HRES (orange bars) throughout the life of the project (Case a: NASA Power Database).

Table 3.2.5 presents the summary of the main results of the sensitivity analysis. These results reflect that the inclination of the solar panels must be at angles lower than the latitude of the island ($\beta = 39.15°$), which is explained by the higher irradiation indices in summer time (Figure 3.2.7), which in turn increases the amount of usable solar energy. Regarding the prices of diesel, the sensitivity analysis shows that diesel prices close to 0.5 $/l, reduce by about 25 % the LCOE economic indicator for the PV-Diesel-Battery and the PV-Wind-Diesel-Battery HRES architectures. Considering that the NPC indicates the total current price associated with all the costs of the HRES (installation, operation and maintenance) during its useful life [259], therefore, that is another indicator that decreases with low prices per liter of diesel. In the PV-Diesel-Battery configuration the NPC presents a reduction in the range of $0.63 - $ 0.68 millions (covering the three simulated cases). For the PV-Wind-Diesel-Battery HRES the NPC has a reduction that ranges between $ 0.61 and $ 0.67 millions.

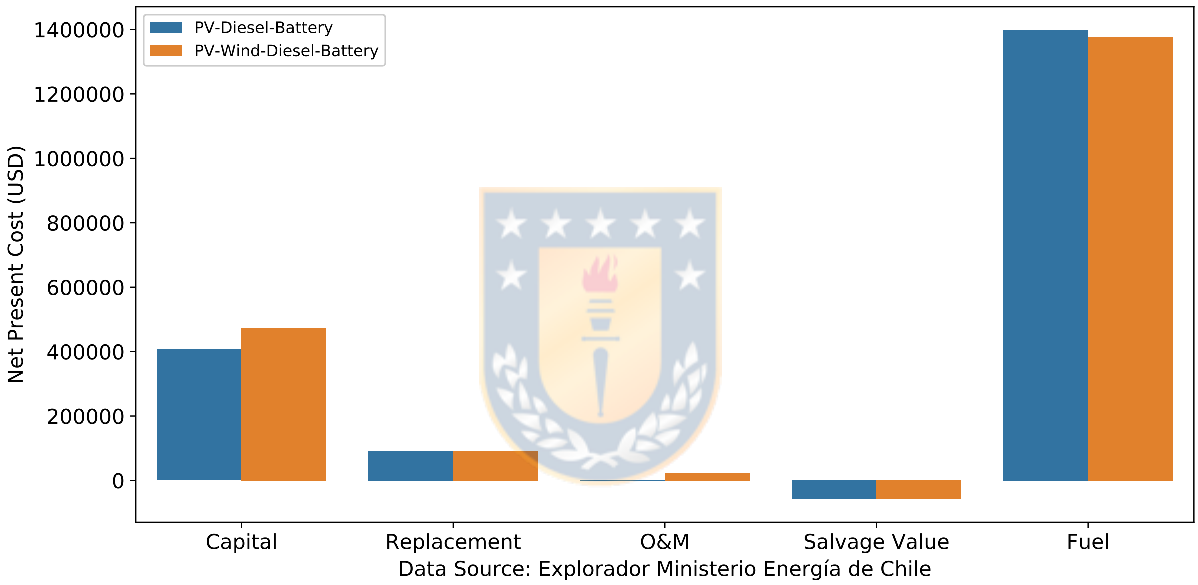

Figura 3.2.10: Net present cost of all costs involved in installation and O&M of the PV-Diesel-Battery HRES (blue bars) and the PV-Wind-Diesel-Battery HRES (orange bars) throughout the life of the project (Case b: Wind and Solar Explorer from the Ministerio de Energía de Chile).

Figures 3.2.9,3.2.10 and 3.2.11 disaggregate the total costs of the NPC, throughout the useful life of the project, for the PV-Diesel-Battery and PV-Wind-Diesel-Battery HRES architectures, from the different data sources. In Case a, that is, using data from the NASA Power Database (Figure 3.2.9), the costs associated with diesel consumption, initial capital and O&M for the PV-Diesel-Battery HRES and PV-Wind-Diesel-Battery HRES are: $ 1,404,168 and $ 1,385,341, $ 455,616 y $ 523,879, $ 2,615 and $ 22,802, respectively. Fuel consumption has the largest share of the NPC, with more than 70 % in both configurations. The initial capital corresponds to the acquisition of solar panels, a wind turbine, batteries and converters, since the genset and distribution lines are already installed on the island. Differences in the area of O&M between

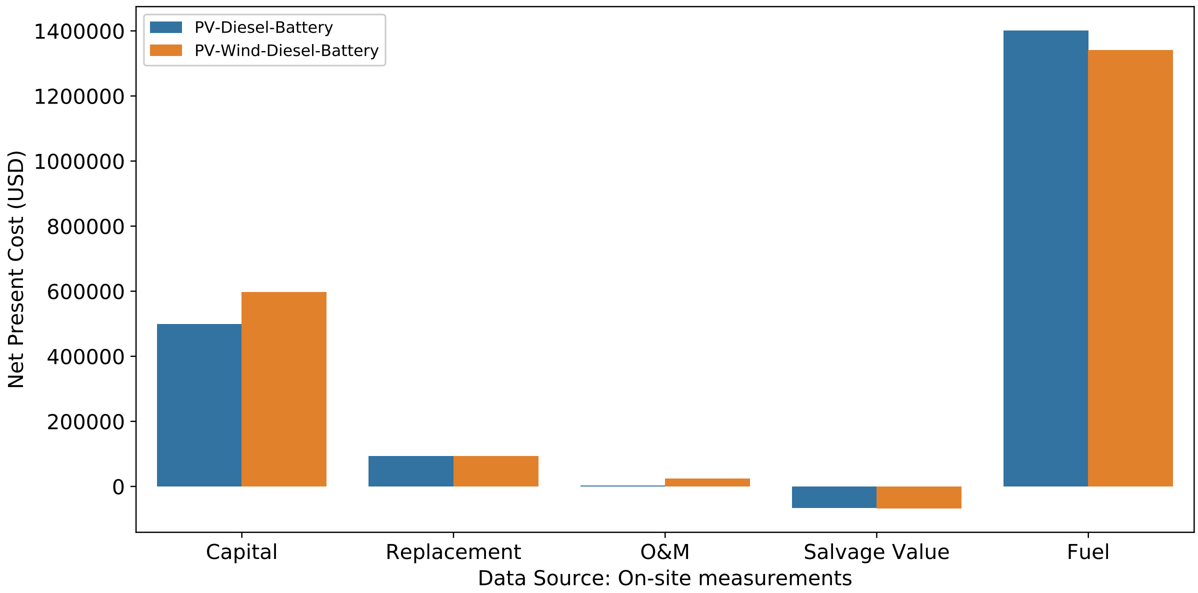

Figura 3.2.11: Net present cost of all costs involved in installation and O&M of the PV-Diesel-Battery HRES (blue bars) and the PV-Wind-Diesel-Battery HRES (orange bars) throughout the life of the project (Case c Prospecting campaigns for renewable resources from the Ministerio de Energía Chile).

both configurations, correspond to the maintenance cycles required in the wind turbine for the second configuration. In Case b (Figure 3.2.10), and when compared to the results of Case a, there is a decrease in fuel consumption costs of -0.45 % and -0.68 %, initial capital of -10.77 % and -9.83 % and O&M of -0.67 % and -0.06 %, for the PV-Diesel-Battery and PV-Wind-Diesel-Battery configurations, respectively. The main variation in the initial capital is based on the higher average solar irradiation indices in Case b, which translates into a lower number of solar panels required to generate the same amount of electrical energy. Regarding Case c (Figure 3.2.11), the costs associated with fuel consumption vary -0.21 % and -3.21 % when compared with Case a, the initial capital is the highest of the three sources of information, with numbers equal to $ 498,831 and $ 597,327 for the PV-Diesel-Battery and PV-Wind-Diesel-Battery systems and the O&M costs are slightly lower in the PV-Diesel-Battery HRES with $ 2,604 (compared with Case a) and the highest in the PV-Wind-Diesel-Battery configuration with $ 23,715 (for the three sources of data). According to the results of the sensitivity analysis, implementing a PV-Diesel-Battery HRES on the island reduces fuel consumption by 24 % (average of the three analysis Cases), reduces the LCOE by 25.6 %, promotes the use of renewable energies in the island's energy matrix by about 20.1 % and introduces around 0.05 hours of autonomy in the electricity generation system. In the possible scenario of implementing a PV-Wind-Diesel-Battery system, the reduction in fuel import is 25.8 % (average of the three analysis Cases), the LCOE is reduced by 24.4 %, renewable energies participate with about 22.5 % of the island's electric power generation and an operating autonomy of 0.08 is introduced, relatively better parameters than those obtained in the PV-Diesel-Battery HRES configuration.

The renewable energy fraction remains at a rate of 20 % for the lower values of the LCOE. The Figure 3.2.12 presents the evolution in the LCOE when the price of diesel (y axis) and the RF (x axis) change in the PV-Wind-Diesel-battery HRES Case c, considering a tilt angle of the solar panel equal to 39.15°. It can be seen in the plot that with percentages close to 20 % in the RF, the best architecture of the hybrid system is PV-Diesel-Battery, regardless of the price of diesel per liter. For any RF >24 % and with diesel prices oscillating between 0.50 - 0.70 \$/l, HOMER ranks the PV-Wind-Diesel-Battery HRES as the best energy solution. LCOE with ranges between 0.235 and 0.261 \$/kWh are mainly associated with PV-Wind-Diesel HRES, diesel prices above 0.70 \$/l and with an RF higher than 30 %.

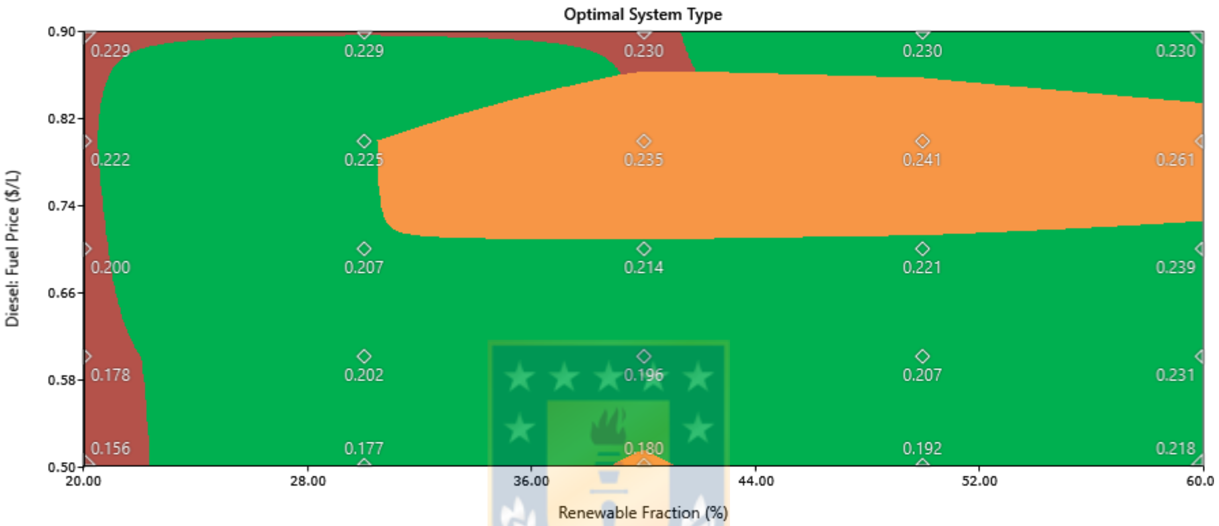

Figura 3.2.12: Effects of increasing the fuel price and the renewable fraction for the PV-Wind-Diesel-Battery HRES Case c, setting the tilt angle of the solar panels to $\beta = 39.15°$. On the y axis the historical variations in the price of diesel for the Aysén region are defined. The x axis represents increases in the fraction of energy generated from renewable resources. Overlapping values correspond to LCOE. The green area represents the PV-Wind-Diesel-Battery HRES, the orange area represents the PV-Wind-Diesel HRES and the red area represents the PV-Diesel-Battery HRES.

Conclusions and future work

The feasibility of an HRES begins with the selection of the method to characterize renewable resources. Short-term records (particularly on-site measurements during one year) are characterized by high precision in the measurement of physical variables, but their limited measurement time implies low spatio-temporal coverage. On the other hand, climatologies based on long-term records, such as the results of atmospheric and solar radiation models and satellite sensors, as they are an average, filter out the detail of interannual and interdecadal climatic variations. Whether to use short-term or long-term records depends on the availability of measurements/models in the study area, research funding, knowledge of the variety of data sources, or simply a decision of the researcher. Almost 50 % of HRES studies in island communities, characterized local renewable resources with on-site measurements [1]. However, as we demonstrate in this study, the number of solar panels in an optimized HRES can vary by as much as 40 %, depending on the method used to characterize the renewable resource.

In this work we evaluated three different sources of information on the availability and variability of renewable energies (sun and wind): the NASA Power Database (Case a), which is a climatological product, one year of data from atmospheric and solar radiation models (Case b), and one year of on-site measurements (Case c), made at Las Huichas island (45° S) . These information sources were used to simulate and optimize eight HRES architectures in the island community of Las Huichas, Chile. HOMER classified three architectures with the best economic and technical indicators: PV-Diesel, PV-Diesel-Battery and PV-Wind-Diesel-Battery. However, the variability of the information sources causes large changes in the feasibility of simulated HRES. The main technical and economic indicators evaluated in a HRES vary notably in each simulated case. Considering the three sources of information used in this research, the PV-Diesel system shows a variation range of 31.4 % in Initial Capital, 12 % in fuel consumption, 42.8 % in RF and 5.5 % in LCOE. The results are similar for the PV-Diesel-Battery configuration: 32 % in Initial Capital, 12.3 % in fuel consumption, 44 % in RF and 5.5 % in LCOE. Finally, the ranges of variation in the PV-Wind-Diesel-Battery configuration are: 30 % in Initial Capital, 14 % in fuel consumption, 43 % in RF and 4.4 % in LCOE.

On the other hand, the range of variability in the number of solar panels is of concern, especially for cases such as island communities with limited space. The largest number of solar panels are associated with the results obtained from atmospheric and solar radiation models (Case b). Based on NASA data (Case a) the PV-Diesel configuration requires 35 % fewer solar panels (compared to Case b). Simulating with on-site measurement records (Case c) shows 24 % fewer solar panels than Case b. In the PV-Diesel-Battery configuration the figures are similar with variability ranges of 36 % between Case a and Case b and 27 % between Case c and Case b. The most critical case is presented in the HRES PV-Wind-Diesel-Battery. Simulation results of Case b demand 40 % more solar panels than Case a and 37 % more than Case c. This translates into approximately 1500 m^2 of additional land for the installation of solar panels.

The sun and wind are not the only renewable resources available with high energy potential and with a more equitable distribution across territories compared to fossil fuels. Wave energy potentials at mid-high latitudes are much higher than those recorded in the tropics. Some places in the Northern and Southern Hemisphere present extraordinary levels of tidal ranges in mid-high latitudes, a physical phenomena that can be exploited by the use of an HRES. Our literature review indicated that there is a lack of use or evaluation of marine renewable energy in HRES. In a subsequent publication, wave and tidal energy, along with traditional resources (sun and wind), will be integrated as renewable resources in hybrid renewable energy systems, considering their variability and data availability.

3.3. Optimización de HRES off-grid con recursos renovables marinos

El contenido de esta sección corresponde al manuscrito del tercer artículo en preparación. *Se presentan los resultados preliminares y el trabajo futuro en esta línea de investigación.*

Sistemas híbridos de energía renovable en microrredes insulares: el papel de las energías marinas

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Abstract

Más de 600 millones de personas carecen de acceso a energía eléctrica en el mundo. Esta cifra cobija a poblaciones instaladas en zonas rurales, insulares y remotas. Atender la demanda energética de estas comunidades exige soluciones de generación descentralizada. Los sistemas híbridos de energía renovable (HRES, por sus siglas en inglés) son una solución sustentable que emplea recursos renovables locales. Esta característica es apropiada para atender cargas de baja potencia, además de acelerar el tránsito de un modelo importador de energía a economías rurales independientes energéticamente. Recursos renovables con alto potencial energético están concentrados en los océanos: olas y corrientes mareales. Sin embargo, integrar estos recursos renovables marinos en HRES es un trabajo pendiente en la literatura. Las investigaciones en HRES tienen una profunda atención en plantas PV y turbinas eólicas. Adicionalmente, los software más usados en la literatura no contienen módulos específicos y dedicados a simular HRES con energías marinas. Por lo tanto, esta investigación aborda estas brechas, analizando técnica y económicamente HRES con energías marinas, a partir de un novedoso algoritmo que simula y optimiza configuraciones HRES. A partir de una función multiobjetivo, la optimización lineal dimensiona una solución HRES que minimiza el indicador técnico (LPSP) y económico (LCOE). El mayor potencial de las olas y las corrientes mareales se enfocan en zonas de alta latitud. En ese sentido, se analiza un caso de estudio en los fiordos chilenos donde se simulan y optimizan 4 configuraciones HRES: WEC-BESS, TT-BESS, PV-BESS y WT-BESS. Los resultados indican que dispositivos ***overtopping*** y ***attenuator*** poseen los mejores índices de

LCOE, bajo diferentes escenarios de LPSP (0 %, 3 % y 5 %). Soluciones TT-BESS alcanzan indicadores LCOE competitivos con sistemas PV-BESS, cuando el flujo mareal promedio es superior a 1.55 m/s.

Introducción

La energía eléctrica es un pilar fundamental en el desarrollo social y económico de las comunidades. De acuerdo al banco mundial, el 9.5 % de la población mundial (2020) no tiene acceso a energía eléctrica. Este porcentaje (∼733 millones de personas) se puede desagregar en dos grandes grupos: población urbana con alrededor de 132 millones de personas y, el grupo más preocupante, población rural con 601 millones de personas [287]. Aunque existen esfuerzos del sector público y privado para reducir esta pobreza energética, conectar la población rural con métodos de transmisión tradicionales es exageradamente costoso [288]. Sin embargo, existen soluciones competitivas y sustentables para producción de energía eléctrica en zonas aisladas. Los sistemas híbridos de energías renovables (HRESs) son microrredes en aplicaciones off-grid y on-grid que aprovechan el potencial de diversas fuentes renovables: sol, viento, biomasa, energías marinas, etc., y la combinan con sistemas de almacenamiento de energía: Battery Energy Storage System (BESS) [289], Pumped Hydro Storage (PHS) [290], producción y uso de H_2V (Hidrógeno Verde) [291], Compressed Air Energy Storage (CAES) [292], Ocean Renewable Energy Storage (ORES) [180], flywheels [293], entre otros. Algunas soluciones HRES son diseñadas con pequeños generadores diesel que atienden la demanda de energía en períodos donde las energías renovables son insuficientes [294]. Por lo tanto, estos sistemas energéticos son versátiles, robustos y están presentes en la cercanía de los centros de consumo, incrementando la fiabilidad de los sistemas eléctricos. Los HRES han sido investigados ampliamente en la literatura científica, sin embargo, un reciente y extenso estudio analizó las tendencias de los HRES a nivel mundial, resaltando entre otros aspectos: i) existe una profunda atención en los HRES PV-Wind-Diesel a nivel mundial, ii) más del 90 % de las 168 investigaciones analizadas se concentran en el hemisferio norte, iii) hay una brecha significativa en la investigación y evaluación de las energías marinas en HRES off-grid para comunidades costeras, iv) 16 investigaciones se encuentran en latitudes del hemisferio sur y ninguna considera algún tipo de energía marina en los HRES simulados [1]. Estos hallazgos, sumado a las diversas estrategias para reemplazar los combustibles fósiles y mitigar el cambio climático, crean un escenario propicio para simular y analizar HRES integrados con energías marinas, evaluar su factibilidad técnica y económica y contribuir a la reducción de la probreza energética en pequeñas comunidades insulares o costeras.

Alrededor de 2400 millones de personas están asentadas en una franja de 100 km desde la costa [38]. A su vez, el potencial energético de los océanos se ha estimado entre 45000 a 130000 TWh/año [33]. Este tremendo potencial puede suplir dos veces la demanda mundial de electricidad (28466 TWh/año - año 2021). Las actuales condiciones de demanda de energía versus potencial energético marino, favorecen la incorporación de las energías marinas a las soluciones

HRES "tradicionales": PV-Wind-Diesel-Battery, PV-Wind-Battery y PV-Diesel-Battery [1]. Además, la cercanía de los centros de consumo con las microrredes (HRES, Smart Grids, etc.), reduce las pérdidas por transporte de energía, incrementan la tolerancia ante posibles fallos [295] en la generación o distribución de energía y da mayor participación a los recursos locales renovables. Atender las necesidades energéticas de comunidades costeras/insulares, utilizando HRES con recursos marinos locales proporciona: i) independecia energética de las comunidades al minimizar el uso de combustibles fósiles foráneos, ii) mejoramiento de la calidad del aire al reducirse el uso de generadores diesel, iii) potabilización del agua marina toda vez que hay constante suministro de electricidad, iv) disminuir la pobreza energética de las comunidades más remotas y vulnerables, v) aporte significativo en la acción común por el clima.

En la actualidad existen diversos software para simular y optimizar HRES. Estas herramientas facilitan la integración de diversas fuentes de energía, cargas diferenciadas (electricidad y/o calor) y sistemas de almacenamiento, con el fin de optimizar la microrred y el dimensionamiento de cada dispositivo. El usuario puede definir los indicadores de evaluación con los cuales desea optimizar el HRES (funciones objetivo o multiobjetivo). Estos indicadores tienen gran influencia en el comportamiento y capacidad de todo el sistema. Los principales indicadores son: fiabilidad, económicos, emisiones atmosféricas y sociales, siendo los preferidos fiabilidad y económicos [24]. Las herramientas computacionales comerciales más ampliamente usadas en la literatura son HOMER, RETScreen, iHOGA, Energy Plan, TRNSYS, Hybrid2 [32] y sus características han sido evaluadas en diversas publicaciones [66, 296, 297, 298]. En [299] se indica que HOMER simula energías renovables marinas, e investigaciones como [40, 43] simulan y optimizan HRES con energías marinas usando HOMER. Sin embargo, HOMER, como las demás herramientas mencionadas, no posee un módulo específico y detallado para cada energía marina. Luego, homologar el funcionamiento de dispositivos marinos con los módulos disponibles en estas herramientas, puede llevar a imprecisiones en los resultados, además que las condiciones iniciales de diseño son muy limitadas para el usuario. En este sentido, y sumado a la poca integración y evaluación de energías marinas en HRES, es evidente la escasa disponiblidad de software para simular y optimizar energías marinas, oportunidades que se convierten en las principales motivaciones de este trabajo.

El presente estudio aborda estas carencias analizando técnica y económicamente un HRES con energías marinas a partir de un algortimo construido con el lenguaje de alto nivel Python. En este algoritmo confluyen 5 módulos independientes cada uno encargado de un recurso renovable o sistema de almacenamiento de energía: i) *módulo wave* encargado de analizar 3 dispositivos WEC (Wave Energy Converter) mediante las matrices de potencia y el estado del mar en pasos de tiempo de 1 hora, ii) *módulo tidal* donde se simula la respuesta de una turbina marina (TT) para velocidades bajas de corriente mareal, iii) *módulo solar* que utiliza un modelo anisotrópico para determinar la radiación solar global incidente en superficie inclinada, iv) *módulo viento* donde se utiliza una miniturbina eólica para evaluar su producción de energía eléctrica y, v) *módulo BESS* encargado de evaluar la carga y descarga de las baterías, evitando su sobrecarga y degradación acelerada. Estos cinco módulos alimentan un módulo central (*optimización)* encargado de la optimización lineal, considerando las series de tiempo de la carga (un año de datos horarios de consumo), caracterización de los recursos renovables (series de tiempos horarias anuales) y condiciones iniciales de diseño, utilizando dos funciones objetivo: Loss of Power Supply Probability (LPSP) y Levelized Cost Of Energy (LCOE).

De acuerdo con los propósitos introducidos, nuestro trabajo está organizado de la siguiente manera: Sección 2 ilustra la configuración del HRES propuesto, define la metodología de funcionamiento del algoritmo diseñado, describiendo la lógica de control para la producción y despacho de energía. La Sección 3 describe analíticamente cada uno de los módulos que componen el algoritmo y describe las funciones objetivo, mientras que la Sección 4 presenta un caso de estudio en los fiordos chilenos (hemisferio sur), incluyendo la caracterización de los recursos renovables y datos de entrada. Los resultados obtenidos se describen ampliamente en la Sección 5. Para finalizar, la última Sección 6 explica el trabajo futuro y los pasos a seguir en la investigación de HRES con recursos renovables marinos.

Arquitectura HRES

EL HRES propuesto en esta investigación se describe en la figura 3.3.1. La configuración general se compone de energías renovables tradicionales: paneles fotovoltaicos (PV), miniturbinas eólicas, energías marinas poco integradas en HRES: WEC y TT, almacenamiento de energía con baterías Li-Ion y convertidores AC/DC, DC/DC y DC/AC para acoplar adecuadamente la generación con la carga. Se integran cuatro fuentes de energía renovable disponibles en comunidades insulares/costeras, que tributan al mejoramiento y diversificación del patrimonio energético de estas poblaciones, incrementando su independencia energética y reduciendo sustancialmente el uso de combustibles fósiles importados.

El HRES PV-Tidal-Wave-Wind-BESS representa un sistema robusto que reduce la variabilidad de la energía producida al combinar recursos renovables complementarios. Esta integración trae diversos beneficios: i) aprovechamiento de altos potenciales energéticos de energías marinas, especialmente en latitudes medias-altas, ii) reducir el impacto del comportamiento estocástico de la radiación solar y velocidad del viento [300], lo que mejora la operatividad del HRES, iii) reducción del ruido generado por las centrales termoeléctricas instaladas al ser reemplazadas por sistemas más silenciosos, vi) incremento de los factores de carga (capacity factor) de las turbinas eólicas debido a vientos offshore más fuertes y con menor turbulencia [145], v) eliminación de fuentes fijas contaminantes que emiten gases efecto invernadero a la atmósfera.

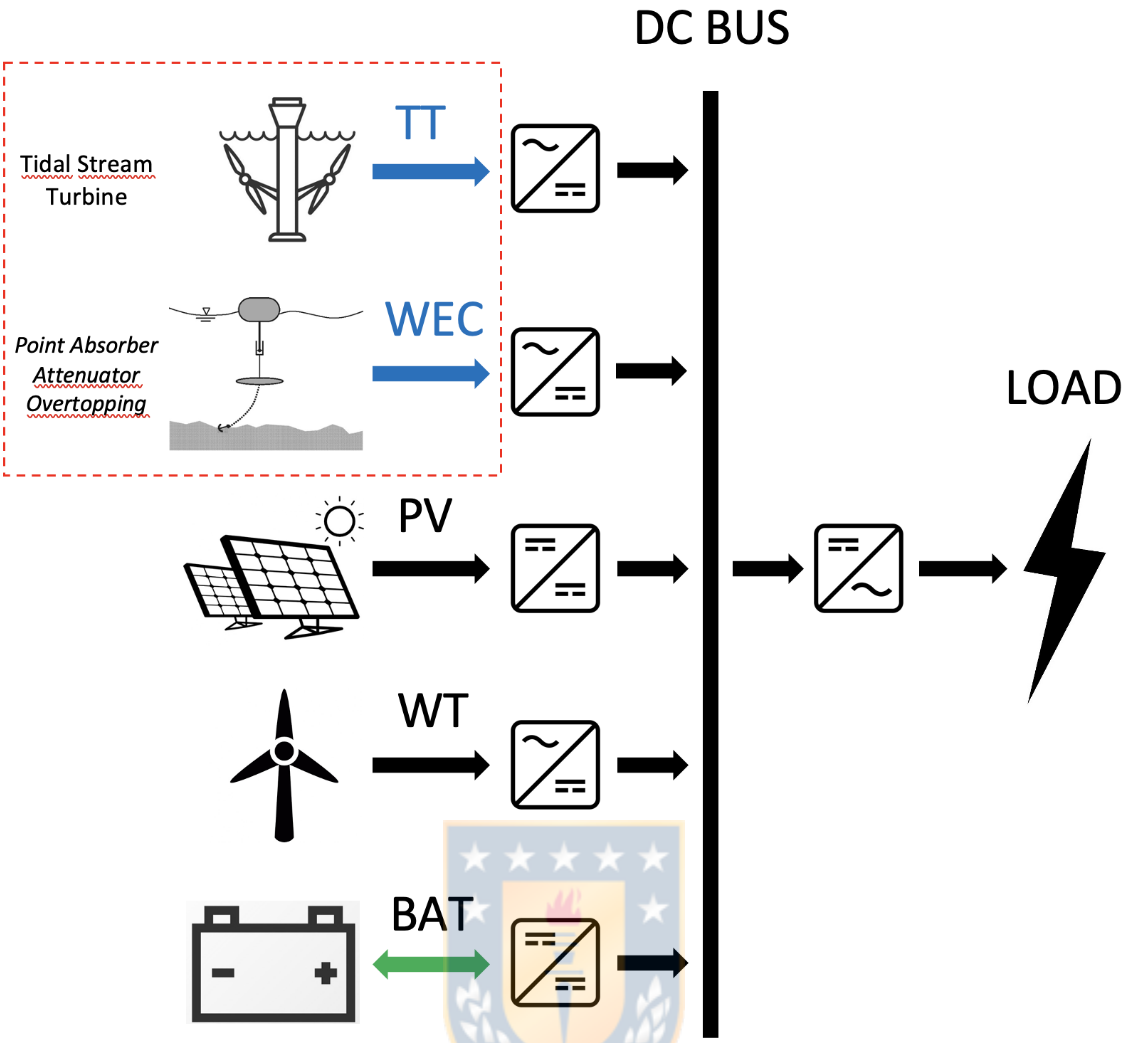

Figura 3.3.1: Diagrama esquemático de la arquitectura HRES propuesta en este estudio.

Cinco funciones o módulos alimentan una función central que se encarga de simular y optimizar el HRES, de acuerdo a parámetros técnicos definidos por el usuario. Dichos parámetros corresponden a número mínimo y máximo de dispositivos a evaluar por cada renovable, parámetros técnicos, gastos de capital (CAPEX) y gastos de operación (OPEX) de cada dispositivo, autonomía deseada (en horas), LPSP mínimo (ver Fig. 3.3.2). El proceso de simulación recibe y entrega información con pasos de tiempo de 1 hora, y requiere series de tiempo de mínimo un año. Esta última característica busca capturar los cambios intraestacionales de las variables físicas que rigen el comportamiento de cada recurso.

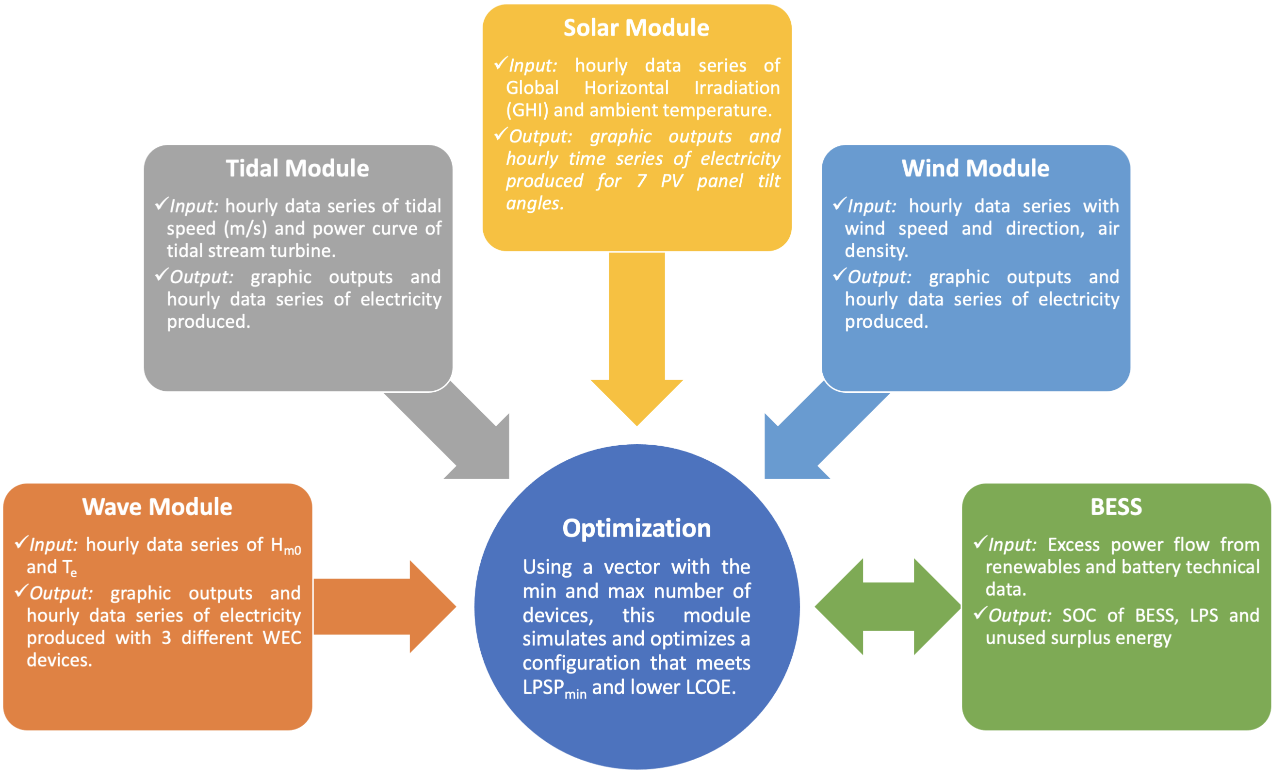

Figura 3.3.2: Flujo de información entre las funciones o módulos desarrollados en el nuevo algoritmo. Descripción general de las entradas y salidas de cada uno de los cinco módulos que alimentan la función de optimización.

El algoritmo es una herramienta de optimización que simula cientos de configuraciones en búsqueda de los valores mínimos de las dos funciones objetivo. Por lo tanto, antes de evaluar la necesidad de un BESS en una configuración, el módulo central de optimización analiza si el recurso renovable en valoración (planta PV, WT, WEC o TT), es suficiente para atender la demanda de la carga. Si no se cumplen las funciones objetivo, el algoritmo integra el BESS a la simulación con el objetivo de: i) satisfacer las condiciones de diseño y funciones objetivo, ii) reducir el dimensionamiento de la solución, iii) complementar y diversificar el flujo de energía desde dos fuentes diferentes: los dispositivos de transformación del recurso y el BESS.

Desde una perspectiva global el algoritmo está representado en el flujograma de la figura 3.3.3. Allí se resume el flujo de energía a través del sistema para atender una determinada carga E_L. Cada uno de los módulos de energía exporta un archivo de texto al módulo central de optimización. Este archivo contiene registros horarios de la energía eléctrica producida, desde cada recurso renovable. En cada hora de simulación, se valida si la energía proveniente de cada fuente renovable: olas, $E_{WEC,h}$, corrientes mareales, $E_{TT,h}$, sol, $E_{PV,h}$ o viento, $E_{WT,h}$, es suficiente para satisfacer la carga. El flujo de energía desde la generación hacia la carga crea dos escenarios principales:

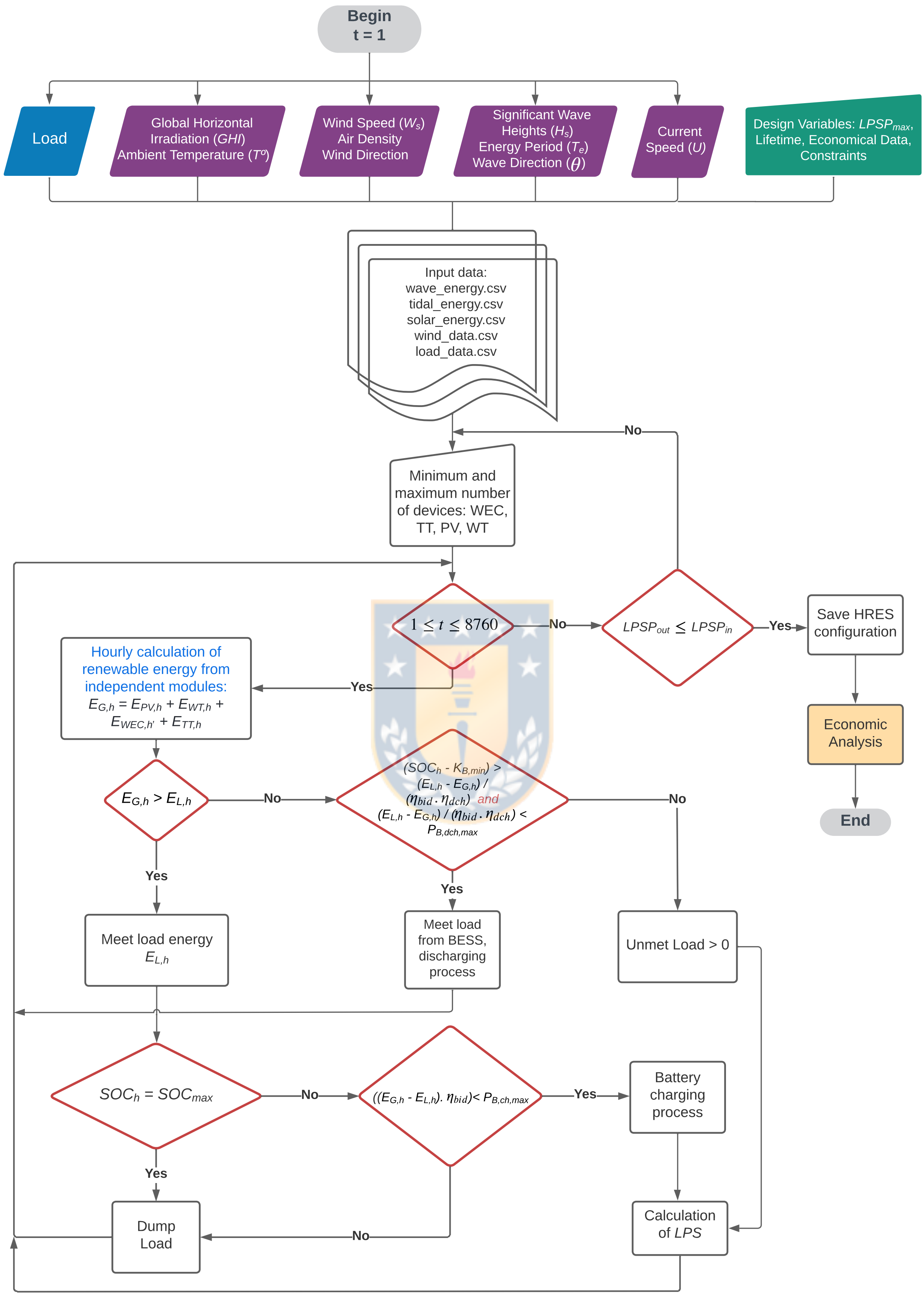

Figura 3.3.3: Diagrama de flujo del algoritmo que simula y optimiza HRES considerando series de tiempo horarias anuales.

- ***Escenario a. En caso que la energía producida sea mayor a la requerida por la carga***, el algoritmo atiende la carga y comunica a la función BESS los eventos con excesos de energía. En este momento, la función BESS valida si el State Of Charge (SOC_h) del banco de baterías ha alcanzado su valor máximo ($K_{B,max}$). Si la respuesta es afirmativa, el exceso de energía es dirigido a cargas de baja prioridad o dump loads. De lo contrario, y previo al inicio del proceso de carga, se examina si la potencia adicional generada no excede la potencia de carga de la batería $P_{B,ch,max}$, situación que puede degradar rápidamente el BESS y reducir su vida útil.
- ***Escenario b. En caso que la energía producida sea insuficente para atender la demanda***, es una situación que obliga al algoritmo a validar el SOC del BESS y establecer la potencia máxima de descarga requerida en la condición $(E_{L,h} - E_{G,h}) / (\eta_{bid} \cdot \eta_{dch})$. Si el BESS contiene la energía necesaria y no se excede la potencia máxima de descarga, se inicia el proceso de descarga de las baterías. De lo contrario, el módulo de optimización atenderá la carga parcialmente y se calcula la cantidad de carga perdida o no atendida (LPS).

Una vez se evaluan las condiciones de energía generada, $E_{G,h}$, y $E_{L,h}$ en cada paso de tiempo, se procede a calcular la carga no atendida, que para el ***Escenario a*** es igual a cero. Implementar sistemas de almacenamiento de energía en un HRES reduce el sobredimensionamiento del sistema [294]. Por lo tanto, excesos de energía pueden ser almacenados en el BESS para cubrir picos inesperados de consumo o incrementos sostenidos de electricidad, por ejemplo, en horas de la noche donde la demanda de energía se incrementa y la energía solar desaparece, es fundamental que energía almacenada en las baterías satisfaga la carga. Además, el BESS puede utilizarse como estrategia de control en la regulación de voltaje y frecuencia para microrredes [301]. La carga y descarga del BESS es controlada por el convertidor bidireccional DC/DC, dispositivo que protege las baterías de la degradación por sobrecarga o descarga excesiva. En esta primera publicación se analizarán 4 configuraciones HRES: WEC-BESS, TT-BESS, PV-BESS y WT-BESS. Asociado a la configuración WEC-BESS, se analizarán 3 dispositivos WEC cada uno con un mecanismo diferente de conversión de energía. Respecto al HRES TT-BESS se simula y analiza el comportamiento de una turbina marina acompañada de un sistema de almacenamiento de energía con baterías Li-Ion. Todos los HRES se alimentan con una serie de datos que representan un año de consumo de una comunidad insular ubicada en los fiordos chilenos.

Modelo Analítico

Modelo Undimotriz

Una de los mayores potenciales energéticos del océano se encuentra en las olas. De acuerdo a [302] el potencial energético de las olas se estima en 29500 TWh/año. Cifra que en la teoría es suficiente para cubrir la demanda actual de energía eléctrica (28466 TWh/año [303]). Determinar el potencial energético de las olas en un área específica, implica caracterizar tres parámetros físicos: altura de ola (m), período de ola (s) y dirección de ola (°). Conocer las condiciones de ola en cada estado de mar (para cada paso de tiempo h), se realiza a partir de expresiones matemáticas derivadas de los momentos espectrales del espectro de ondas:

$$H_{m0} = 4{,}004\sqrt{m_0} \approx 4\sqrt{m_0} \tag{3.3.1}$$

$$T_e = \frac{m_{-1}}{m_0} \tag{3.3.2}$$

$$\theta_m = \arctan \frac{\int_0^{2\pi} \sin\theta \; S(f,\theta) \; df \; d\theta}{\int_0^{2\pi} \cos\theta \; S(f,\theta) \; df \; d\theta} \tag{3.3.3}$$

Donde H_{m0} es la altura significativa de ola (m), m_{-1} y m_0 son los momentos espectrales -1 y 0 de la onda, respectivamente, T_e es el período de la ola (s), θ_m es la dirección media de la ola (°) y $S(f,\theta)$ corresponde a la densidad de energía espectral que representa la distribución de energía según la frecuencia, f (Hz), y la dirección, θ (°). m_{-1} y m_0 se pueden obtener a partir de la expresión del n-ésimo momento espectral m_n ($m^2 Hz^{-n}$) [304]:

$$m_n = \int_0^{2\pi} \int_0^{\infty} f^n S(f,\theta) \; df \; d\theta \tag{3.3.4}$$

La densidad de potencia de las olas, P_{WEC} (kW/m), puede ser calculada para cada estado del mar, usando la expresión de aguas profundas:

$$P_{WEC} = \frac{\rho_s g^2}{64\pi} \cdot T_e H_{m0}^2 \tag{3.3.5}$$

Donde ρ_s es la densidad del agua del mar que correponde a 1025 kg/m^3 y g es la aceleración gravitacional (m/s^2).

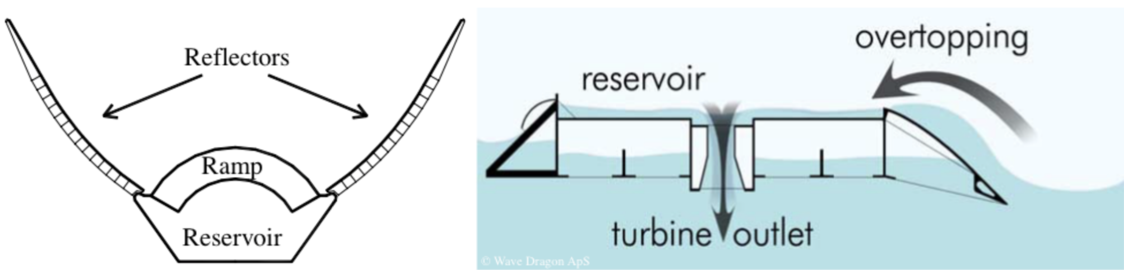

Figura 3.3.4: WEC tipo ***overtopping***: Wave Dragon. La imagen de la izquierda representa los principales componentes; la imagen de la derecha describe el principio de funcionamiento del dispositivo marino. Tomado de [5].

Tres dispositivos WEC fueron evaluados en este trabajo: Wave Dragon (Fig. 3.3.4), Pelamis (Fig. 3.3.6) y Archimedes Wave Swing (AWS - Fig. 3.3.8). El primero es un dispositivo del tipo ***overtopping***, que posee dos reflectores que dirigen las olas hacia una plataforma central que actúa como embalse. Las olas entrantes incrementan su altura gracias a los reflectores, maximizando la cantidad de agua que ingresa al embalse central, la cual posteriormente, regresa al océano a través de turbinas kaplan de baja altura [305]. Estas turbinas producen energía eléctrica que es enviada a costa a través de cables submarinos. Para examinar la producción de energía eléctrica con este dispositivo, se simuló un Wave Dragon con una potencia nominal de 6 MW. La matriz de potencia del Wave Dragon, para diferentes condiciones de ola incidente (H_{m0} y T_e), es mostrado en la Fig. 3.3.5.

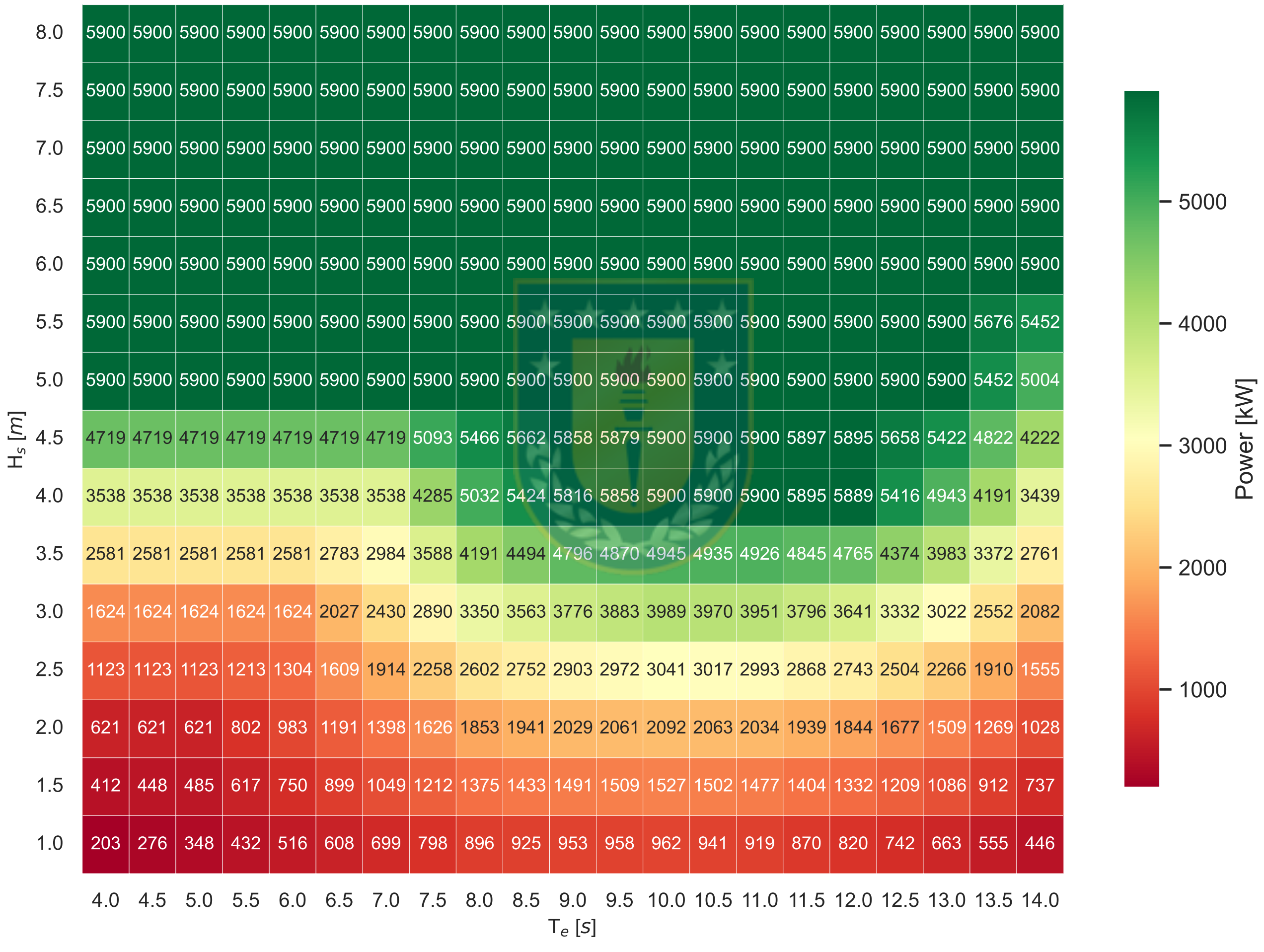

Figura 3.3.5: Matriz de potencia del dispositivo Wave Dragon. Potencia nominal de 6 MW.

El segundo dispositivo es un WEC semisumergido tipo ***attenuator*** con forma de serpiente. Este dispositivo está construido a partir de varios segmentos cilíndricos que aprovechan el movimiento de la olas para producir energía eléctrica. Al interior de los 3.5m de diámetro de cada segmento, se encuentra el generador hidráulico que funciona con aceite a alta presión, para transformar la energía mecánica en energía eléctrica. En este trabajo se consideraron unidades Pelamis con potencia nominal de 750 kW y longitud de 15 m. En la Fig. 3.3.7 se muestra la matriz de potencia del Pelamis utilizado en el algoritmo.

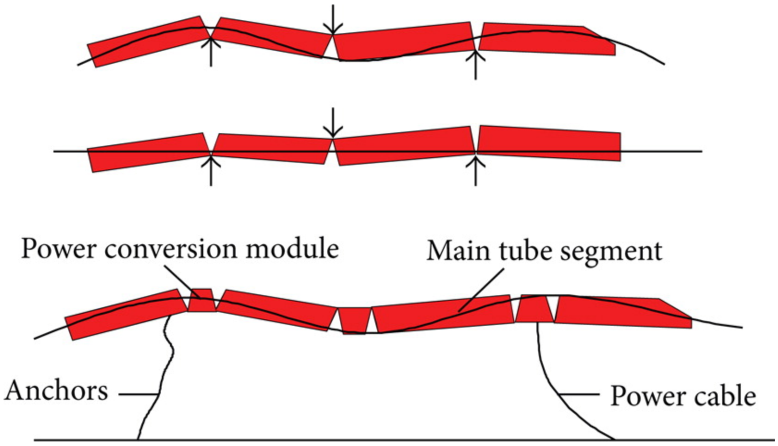

Figura 3.3.6: WEC tipo ***attenuator***: Pelamis. Principio de funcionamiento del WEC. Tomado de [6].

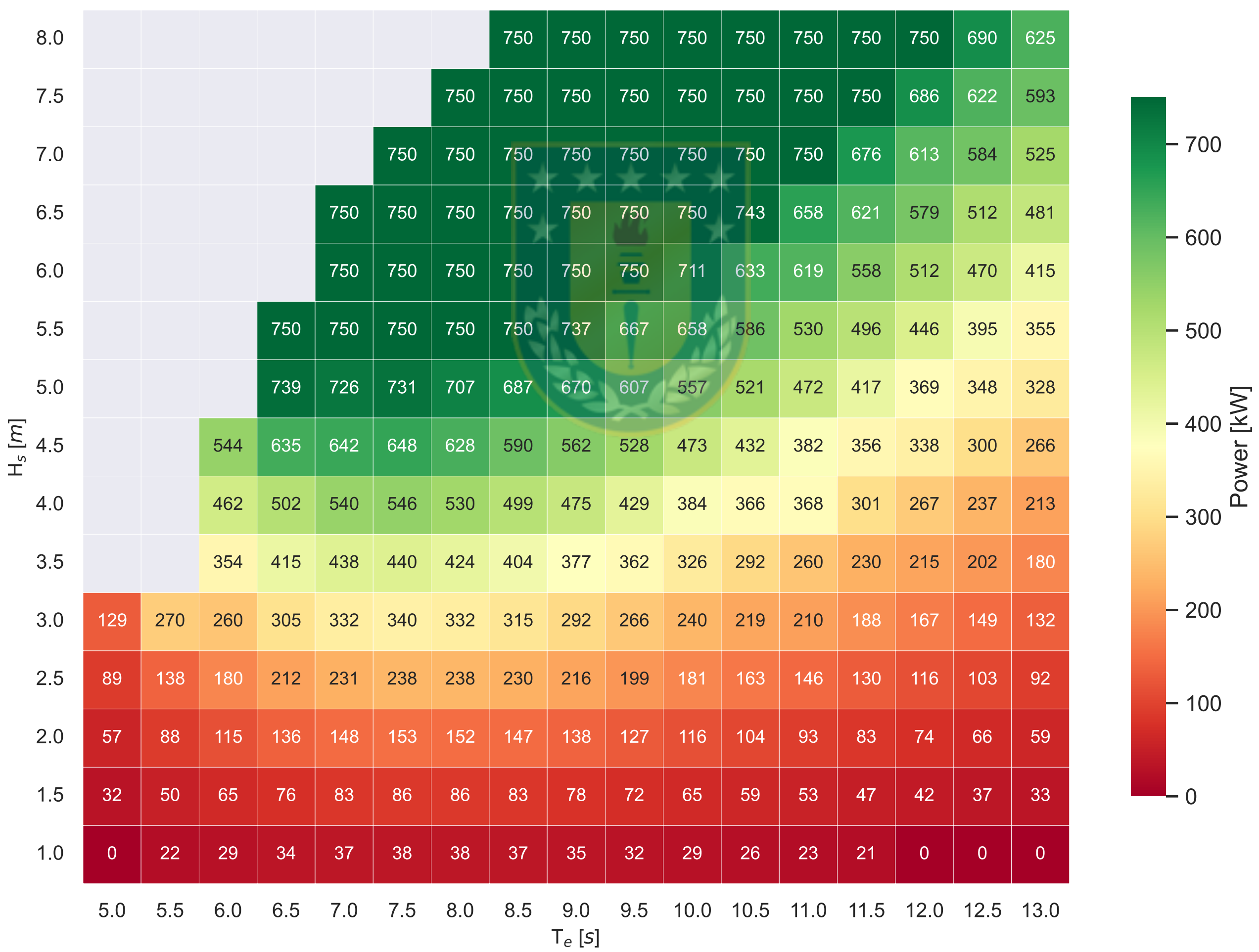

Figura 3.3.7: Matriz de potencia del dispositivo Pelamis. Potencia nominal de 750 kW. El color gris de los contenedores energéticos, indica las condiciones de estado del mar donde el dispositivo no produce energía eléctrica.

El último WEC considerado en la arquitectura HRES corresponde al AWS que es del tipo ***point absorber***. El AWS está completamente sumergido y anclado al lecho marino. En su diseño están involucrados dos cilindros principales: Un cilindro exterior que se mueve en dirección vertical (arriba → abajo, abajo → arriba) por la influencia de las olas y un cilindro interior estático que se encuentra sujetado al fondo marino. Al interior de los cilindros hay aire que se presuriza una vez el cilindo superior desciende. Los imanes fijos en el cilindro superior interactuan con la bobina del cilindro inferior, lo que induce una corriente eléctrica en la bobina, produciendo electricidad [306]. Las especificaciones del AWS simulado en el HRES de este trabajo son: 2.4 MW de potencia nominal, diámetro de 9.5m y longitud de 35 m. La matriz de potencia del AWS se presenta en la Fig. 3.3.9.

Modelo Mareomotriz

El fenómeno de las mareas es el resultado de la interacción de la Tierra, la Luna y el Sol. La fuerza de atracción gravitatoria y la cinemática entre estos cuerpos celestes es responsable del cambio en el nivel y desplazamiento de la marea. La luna tiene una mayor influencia en la generación de las mareas debido a su mayor cercanía a la Tierra. Cuando los tres astros están alineados se producen las denominadas spring tides, las mareas más altas dentro del ciclo lunar. Cuando el sistema Tierra, Luna y Sol describe un triángulo rectángulo se obtienen mareas con las amplitudes más bajas del ciclo lunar denominadas neap tides. A partir del incremento en el nivel del mar y el movimiento de las mareas, es factible técnica y económicamente producir energía eléctrica. A continuación se explican brevemente las dos principales técnicas de aprovechamiento de la energía mareomotriz [307]:

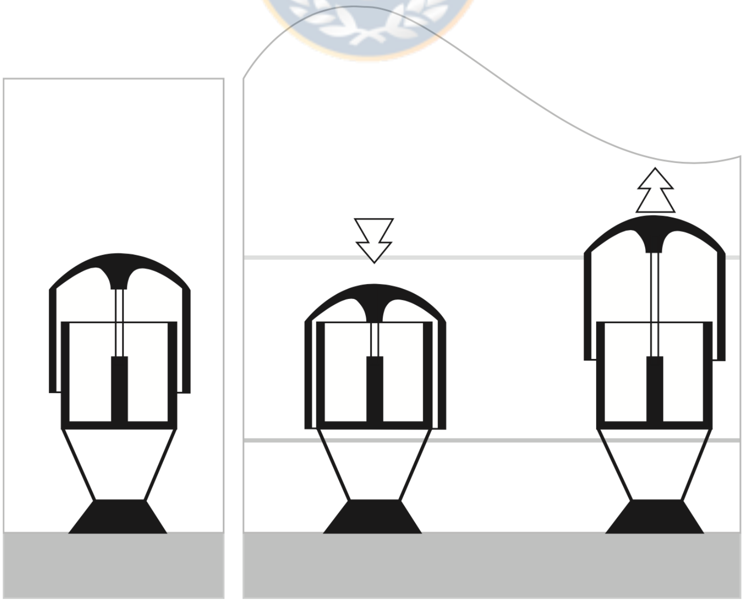

Figura 3.3.8: WEC tipo ***point absorber***: AWS. Se ilustra el principio de funcionamiento del dispositivo marino cada vez que la columna de agua varía sobre el WEC sumergido. Tomado de [7].

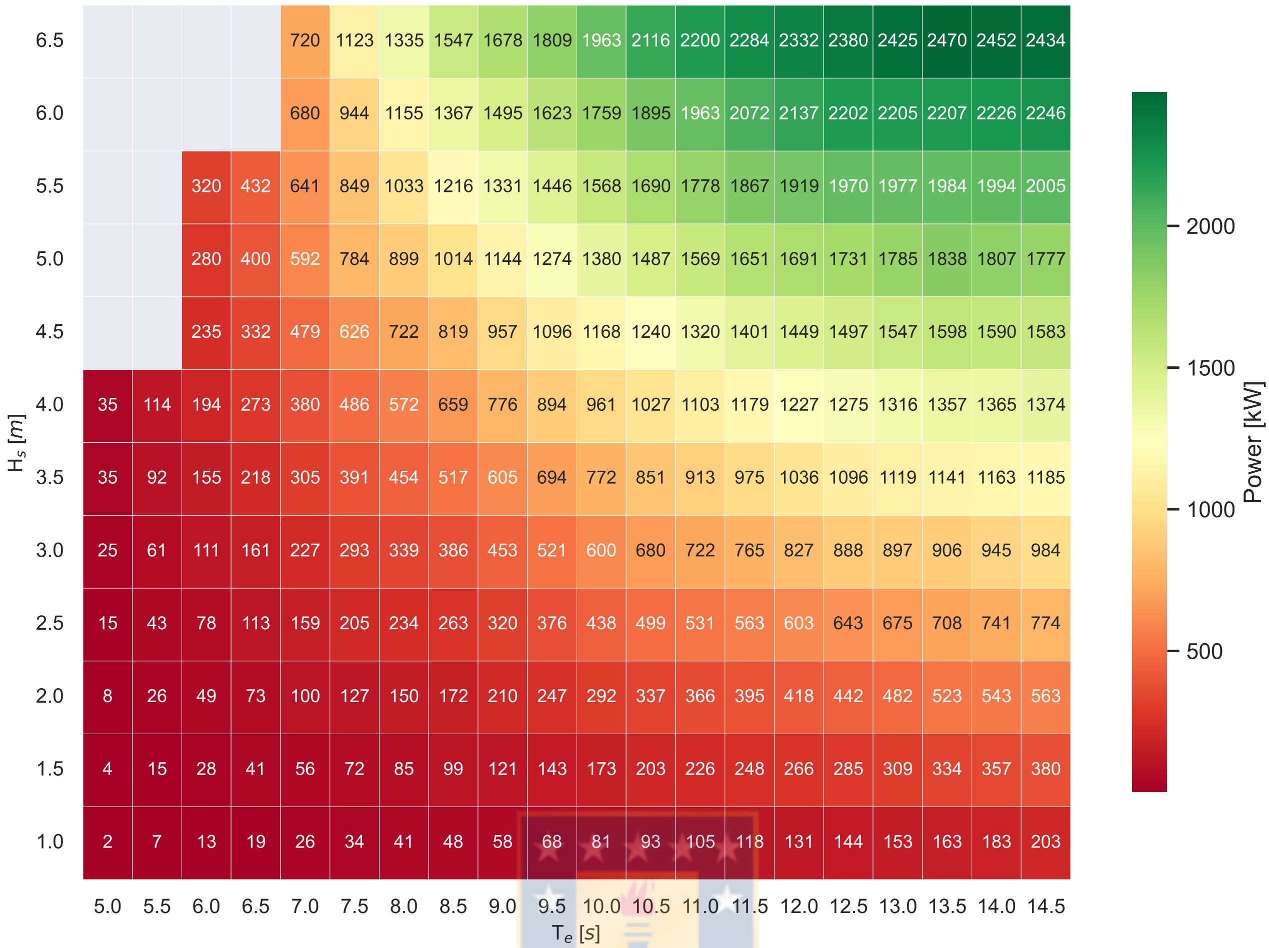

Figura 3.3.9: Matriz de potencia del dispositivo Archimedes Wave Swing (AWS). La potencia nominal es de 2.4 MW. El color gris de los contenedores energéticos, indica las condiciones de estado del mar donde el dispositivo no produce energía eléctrica.

- ***Rango Mareal***. Producir energía eléctrica a partir del rango mareal, es un proceso similar al funcionamiento de la energía hidroeléctrica. Su implementación se realiza en geometrías semicerradas como lo son las bahías, donde se facilita la acumulación de agua del mar, construyendo una presa en la apertura de la bahía. En cada uno de los ciclos de la marea, el agua que fluye hacia la costa (flood current), es almacenada en la presa hasta alcanzar su altura máxima de diseño. Terminado el período de flood current, se utiliza la energía potencial del agua contenida, para ser transformada en energía eléctrica:

$$E_p = \frac{1}{2}\rho_s \cdot Agh^2 \tag{3.3.6}$$

Donde A representa el área de la cuenca (m^2) y h es la altura (m). La potencia eléctrica promedio máxima ($\overline{P}$) que se obtiene con la turbina es:

$$\overline{P} = \frac{E_p}{\tau} = \frac{\rho_s \cdot Agh^2}{2\tau} \tag{3.3.7}$$

Donde τ representa el período de la marea (12h 25m ciclo semidiurno, 24h 50m ciclo diurno). Producir electricidad solo en pleamar, reduce los factores de planta de estas centrales. Por lo tanto, es posible maximizar su rendimiento y la sincronización entre los peak de consumo y generación, si se utilizan métodos de generación dual: pleamar y bajamar [308].

- ***Corrientes de marea***. Este método transforma la energía cinética contenida en la corriente mareal. El proceso de generación de electricidad se lleva a cabo con la instalación de turbinas marinas, dispositivos que tienen el mismo principio de funcionamiento que los aerogeneradores. La potencia de la turbina marina tiene una dependecia matemática igual a la usada en la turbina eólica:

$$P_{TT} = \frac{1}{2}\rho_s \cdot A \cdot g \cdot U^3_{tide(t)} \cdot C_p \cdot N_{TT} \tag{3.3.8}$$

  Donde A corresponde al área de barrido de las aspas (m^2), U es la velocidad horizontal de la corriente mareal para cada paso de tiempo (t = 1 hora), C_p es el coeficiente de potencia de la turbina de corriente mareal y N_{TT} es el número de turbinas marinas instaladas.

Instalar turbinas marinas en zonas donde el paso del agua es restringido por pequeños canales, maximiza la producción de electricidad, dado que se incrementa la velocidad de la corriente mareal. Este tipo de condiciones geográficas son comunes en los fiordos y bahías. En ese sentido, y valorando el menor impacto ambiental que comprende instalar turbinas marinas, se examinó la cantidad de energía producida por corrientes mareales en el algoritmo diseñado.

Modelo PV

La energía eléctrica generada a partir de una planta PV depende directamente de la radiación solar incidente y la temperatura ambiente. Los factores de planta de un sistema PV aumentan a medida que se inclinan los paneles solares (tilt angle β) y se introducen mecanismos de seguimiento solar [309]. Sin embargo, los datos de radiación global horizontal (incluida la radiación difusa horizontal) son los más abundantes. La disponibilidad de mediciones de radiación solar en superficie inclinada es escasa [310]. Por lo anterior, es esencial utilizar modelos matemáticos para estimar las componentes de la radiación solar incidente en un plano inclinado. En este trabajo se utiliza el modelo anisotrópico Hay and Davies, Klucher and Reind (HDKR), un modelo ampliamente conocido y validado, donde se integran factores isotrópicos con factores de brillo circunsolar y del horizonte ([311]). En el Apéndice A se detalla el modelo analítico utilizado en el cálculo de la radiación solar incidente en superficie inclinada. Allí se describen, entre otros aspectos: las correcciones de la ecuación del tiempo, la variación longitudinal, hora solar y el HDKR's model.

A partir de los valores horarios de radiación solar incidente en superficie inclinada, y considerando la temperatura ambiente como una variable física relevante en el desempeño del panel solar, la potencia de salida del panel solar está dado por [151]:

$$P_{PV} = P_R f_{PV} \left(\frac{I_\beta}{G_{STC}} \right) \left[1 + \alpha_p \left(T_c - T_{STC} \right) \right] \tag{3.3.9}$$

Donde P_R es la potencia nominal del arreglo fotovoltaico (kW), f_{PV} es un factor de reducción de potencia, I_β es la radiación solar global horaria (W/m^2) en la superficie inclinada, G_{STC} es la irradiancia en condiciones de prueba estándar (STC 1000 W/m^2), α_p corresponde al coefciente de temperatura del panel (%/°C) proporcionado por el fabricante, T_{STC} es igual a 25°C y representa la temperatura de la celda fotovoltaica en condiciones estándar y T_c, en °C, es la temperatura de la celda fotovoltaica y viene dada por:

$$T_c = T_a + G_T \left[\frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \right] \left(1 - \frac{\eta_{PV}}{\tau\alpha} \right) \tag{3.3.10}$$

Donde $T_{c,NOCT}$ es reportado por el fabricante y corresponde a la temperatura de celda considerando $G_{T,NOCT} = 800$ W/m^2, $T_{a,NOCT}$ equivale a 20°C, η_{PV} es la eficiencia de conversión eléctrica del panel fotovoltaico y $\tau\alpha$ es el producto entre la transmitancia de la cubierta sobre el panel y la absorbancia solar del PV.

El convertidor DC/DC ubicado inmediatamente después de la planta PV, acondiciona la señal de voltaje que se entrega al bus DC, con una eficiencia η_{inv} como se indica a continuación:

$$P_{inv,out} = P_{PV} \eta_{inv} \tag{3.3.11}$$

Modelo Turbina Eólica

La energía cinética del viento puede ser transformada en energía eléctrica a partir de turbinas eólicas. Identificar el regimen de viento es indispensable para estimar la energía eólica en un determinado lugar. Resultados de modelos climatológicos [199] o mediciones de viento on-site [312], son técnicas utilizadas para caracterizar la velocidad del viento a una altura específica. Dicha altura de velocidad de viento no siempre coincide con la altura del nacelle del aerogenerador. Por lo tanto, el primer paso, previo al cálculo de energía eólica, es determinar el valor de velocidad de viento ajustado a la altura del nacelle. Dos técnicas usadas para extrapolar la velocidad del viento son:

$$U_{hub} \approx \begin{cases} U_{ref}\left[\dfrac{\ln\left(\frac{Z_{hub}}{Z_o}\right)}{\ln\left(\frac{Z_{ref}}{Z_o}\right)}\right] & , \quad \textit{Logarithmic Profile} \\ \\ U_{ref}\left(\dfrac{Z_{hub}}{Z_{ref}}\right)^{\alpha} & , \quad \textit{Power Law Profile} \end{cases} \tag{3.3.12}$$

Donde U_{hub} es la velocidad del viento a la altura del nacelle, U_{ref} es la velocidad del viento conocida desde una altura de referencia (Z_{ref}), Z_{hub} es la altura del nacelle, Z_o es la rugosidad de la superficie en metros (detalles en la Tabla 3.3.1) y α es el exponente de la ley de potencia. De acuerdo a [2] α tiene una alta variabilidad debido a su relación con parámetros como: tipo de terreno, temperatura, velocidad del viento, elevación, entre otros. Dos métodos empíricos para calcular α son: i) como función de la velocidad y altura Ec. 3.3.13 y ii) a partir de la rugosidad de la superficie Ec. 3.3.14.

Tabla 3.3.1: Rangos aproximados de la rugosidad de la superficie adaptado de [2] y [3]

Surface roughness values, Z_o (Ranges in meters)	**Terrain description**
≤ 0.003	Calm and blown open sea, snow surface and terrains very smooth.
>0.003 and ≤ 0.008	Flat grassland, parkland or bare soil.
>0.008 and ≤ 0.05	Rough pasture, fallow field and few isolated obstructions.
>0.05 and ≤ 0.104	Territories with crops, slightly undulating areas and small isolated trees.
>0.104 and ≤ 0.25	Fields with boundary hedges, many trees.
>0.25 and ≤ 0.54	Forests, houses and occasional agricultural structures.
>0.54 and ≤ 1.1	Urban or suburban areas with a density in the area of approximately 20 %.
>1.1	Densely populated cities with presence of buildings.

$$\alpha = \frac{0{,}37 - 0{,}088\ln\left(U_{ref}\right)}{1 - 0{,}088\ln\left(\frac{Z_{ref}}{10}\right)} \tag{3.3.13}$$

$$\alpha = 0{,}096\log_{10} Z_o + 0{,}016\left(\log_{10} Z_o\right)^2 + 0{,}24 \tag{3.3.14}$$

Sin embargo, estas aproximaciones (Eq. 3.3.13 y Eq. 3.3.14) complejizan el cálculo y aplicación de la Power Law, por lo que en esta investigación se adopta un valor de $1/7$, el cual es usado ampliamente en la literatura científica [313].

El nuevo régimen de viento extrapolado a la altura del nacelle, proporciona una dinámica más aproximada de la velocidad de viento a la altura deseada. Por lo tanto, es posible calcular la energía eléctrica que produce el aerogenerador en cada paso de tiempo ($\Delta t = 1$ hour). En este cálculo la curva de potencia del aerogenerador es fundamental. Dicha curva considera presión y temperatura ambiente estándar. Por lo tanto, es recomendable hacer la corrección indicada en la Eq. 3.3.15, en los casos que se posean mediciones horarias de la densidad del aire:

$$P_{WT} = \left(\frac{\rho_a}{\rho_{a,std}}\right) P_{WT,std} \tag{3.3.15}$$

Donde P_{WT} es la potencia producida por la turbina (kW), ρ_a es la densidad del aire medida en cada paso de tiempo (kg/m^3), $\rho_{a,std}$ es la densidad del aire a temperatura y presión estándar (1.225 kg/m^3) y $P_{WT,std}$ es la potencia producida por la turbina en condiciones estándar de presión y temperatura, tal como se indica en la siguiente ecuación:

$$P_{WT,std} = \begin{cases} 0 & \text{if } v \leqslant V_{cin} \text{ or } v \geqslant V_{cout} \\ P_r \left[\dfrac{v - V_{cin}}{V_r - V_{cin}}\right] & \text{if } V_{cin} \leqslant v < V_r \\ P_{WT,r} & \text{if } V_r \leqslant v < V_{cout} \end{cases} \tag{3.3.16}$$

Donde P_r es la potencia nominal del aerogenerador, v es la velocidad del viento en cada paso de tiempo.

Modelo BESS

El HRES debe satisfacer la energía requerida por la carga ($E_{L,h}$) en cada hora del año, de acuerdo a la siguiente expresión:

$$E_{L,h} \leq (E_{PV,h} + E_{WT,h} + E_{WEC,h} + E_{TT,h} + E_{BES,h}) \tag{3.3.17}$$

Donde la energía generada a partir de la planta PV ($E_{PV,h}$), WT ($E_{WT,h}$), WEC ($E_{WEC,h}$) o TT ($E_{TT,h}$), y como backup el BESS ($E_{BES,h}$), es calculada en cada paso de simulación. Los excesos de energía, provenientes de fuentes renovables, se utilizan en el proceso de carga del BESS. Toda la energía almacenada en el banco de baterías es utilizada en períodos donde las fuentes de energía renovable son insuficientes para satisfacer la carga. En cada paso de tiempo de simulación se deben garantizar dos condiciones del BESS:

$$C_{min} \leq SOC_h \leq C_{max} \tag{3.3.18}$$

$$C_{min} = (1 - DOD) \cdot C_{max} \tag{3.3.19}$$

Donde C_{min} es la capacidad mínima del BESS (kWh), C_{max} es la capacidad máxima del BESS (kWh), SOC_h el estado de carga del BESS para la hora h (kWh) y DOD es la profundidad de descarga del banco de baterías (%). Adicional a las dos condiciones anteriores, el banco de baterías del HRES debe dimensionarse acorde a los flujos de energía en la microrred. La capacidad del BESS (en kWh) se determina de acuerdo al número de horas de autonomía (AH) esperado (ver Eq. 3.3.20), es decir, el tiempo durante el cual el BESS es capaz de satisfacer la demanda de energía:

$$AH = \frac{(C \cdot \eta_{binv} \cdot \eta_{dch} \cdot DOD)}{E_{L,a}} \tag{3.3.20}$$

Donde C es la capacidad nominal del BESS (kWh), η_{binv} es la eficiencia del convertidor DC/DC bidireccional (%), η_{dch} es la eficiencia de descarga del BESS (%) y $E_{L,a}$ es la carga media horaria. Mientras el SOC_h cumpla la condición de la Eq. 3.3.18, el surplus de energía es desviado hacia el BESS. Aquí inicia el proceso de carga y el SOC_h se incrementa de acuerdo a la siguiente condición:

$$SOC_h = \min\left\{SOC_{h-1} \cdot (1-\sigma) + \left((E_{PV,h} + E_{WT,h} + E_{WEC,h} + E_{TS,h}) - \left(\frac{E_{L,h}}{\eta_{inv}}\right)\right) \cdot \eta_{binv} \cdot \eta_{ch} \ , \ C_{max}\right\} \tag{3.3.21}$$

Donde SOC_{h-1} es el estado de carga del BESS en el paso de simulación anterior, σ es la tasa de autodescarga horaria de la batería (%), acotado en este trabajo a 0.14 % por día, y η_{ch} es la eficiencia de carga del BESS (%). El flujo de energía desde las fuentes renovables hacia el BESS debe cumplir con ciertas limitaciones técnicas que eviten la sobrecarga y deterioro del BESS. Una de las restricciones es el límite máximo de carga de la batería, parámetro que depende directamente de la corriente de carga definida por el fabricante. Estas limitaciones en el flujo de energía también deben ser consideradas en el proceso de descarga del BESS.

Cuando el SOC_h alcanza su valor máximo, el proceso de carga termina y cualquier remanente de energía se deriva a cargas de baja prioridad o dump load. Si la carga exige mayor energía que la producida por las fuentes renovables, comienza el proceso de descarga. El BESS satisface la carga hasta que SOC_h disminuye a su nivel mínimo o la potencia requerida supera el límite de potencia de descarga de la batería. El nuevo SOC_h del BESS se calcula con la ecuación 3.3.22.

$$SOC_h = \max\left\{SOC_{h-1} \cdot (1-\sigma) - \left(\left(\frac{E_{L,h}}{\eta_{inv}}\right) - (E_{PV,h} + E_{WT,h} + E_{WEC,h} + E_{TS,h})\right) \cdot \left(\frac{1}{\eta_{binv} \cdot \eta_{ch}}\right) \ , \ C_{min}\right\} \tag{3.3.22}$$

Modelo del dimensionamiento del HRES

Cada una de las cuatro configuraciones: WEC-BESS, TT-BESS, PV-BESS y WT-BESS, es simulada a partir de un vector inicial que posee la cantidad de equipos a simular. Es decir, el usuario determina el número mínimo y máximo de WEC, TT, PV y WT, previo al proceso de optimización. En el caso que la energía producida por la fuente renovable y el BESS sea insuficiente para satisfacer la carga en determinada hora del año, se procede a determinar el Loss of Power Sypply (LPS), a partir de la Ecuación 3.3.23 [314].

$$LPS = E_{L,h} - (E_{G,h} + E_{BESS,h-1} - E_{BESS,min}) \cdot \eta_{inv} \tag{3.3.23}$$

Donde, $E_{BESS,h-1}$ es la energía contenida en el banco de baterías en la hora anterior $(h-1)$ y $E_{BESS,min}$ es el mínimo de energía restante admisible del banco de baterías para evitar la condición de sobredescarga. En ese sentido, una de las funciones objetivo establecidas en este trabajo, busca minimizar el Loss of Power Supply Probability (LPSP) del HRES optimizado. Este método se encarga de definir la cantidad mínima y óptima de WEC, TT, PV, WT y baterías que garanticen un suministro eléctrico constante a la carga [315]. Este indicador técnico es uno de los más empleados en la literatura para comparar la fiabilidad de varios componentes en un HRES [316]. Es por ello, que para un período de tiempo de un año, el LPSP se define como la relación entre la suma de los LPS horarios y la suma de la demanda de energía en el año de evaluación (Ec. 3.3.24).

$$LPSP = \frac{\sum_{i=1}^{8760} LPS_i}{\sum_{i=1}^{8760} E_{L_i}} \tag{3.3.24}$$

En resumen, si el flujo de energía se enmarca en el ***Escenario a*** el LPS es igual a cero, es decir, toda la carga fue atendida por el HRES, en el paso de tiempo correspondiente. Pero, si el flujo de energía es menor a $E_{L,h}$ (***Escenario b***), quiere decir que la carga no se satisface con la energía producida por la fuente renovable + BESS, por lo tanto, hay un déficit que se calcula de acuerdo a la Ec. 3.3.23. Una vez concluida la simulación anual, si el LPSP es mayor al LPSP definido por el usuario, el HRES es modificado y se reinicia el proceso de simulación.

Desde el punto de vista económico, el algoritmo analiza el Levelized Cost Of Energy (LCOE), un indicador económico utilizado para comparar el costo de energía de diferentes tecnologías de generación. El LCOE, expresado en $/kWh relaciona el valor actual del costo del proyecto (USD) con la energía eléctrica que produce durante toda su vida útil (kWh). Esto significa, que el LCOE incluye todos los flujos de dinero en el tiempo de vida del proyecto, tales como: capital inicial, gastos de operación y mantenimiento, costos de reposición de equipos e inflación a largo plazo. Para calcular el LCOE se utiliza la siguiente expresión matemática:

$$LCOE = \frac{C_{ann,tot}}{R_{prim} + R_{tot,grid,sales}} \tag{3.3.25}$$

Donde $C_{ann,tot}$ es el costo total anualizado, R_{prim} es la carga primaria (kWh/año) y $R_{tot,grid,sales}$ es el total de ventas a la red (kWh/año), que en este trabajo es igual a cero.

Caso de estudio

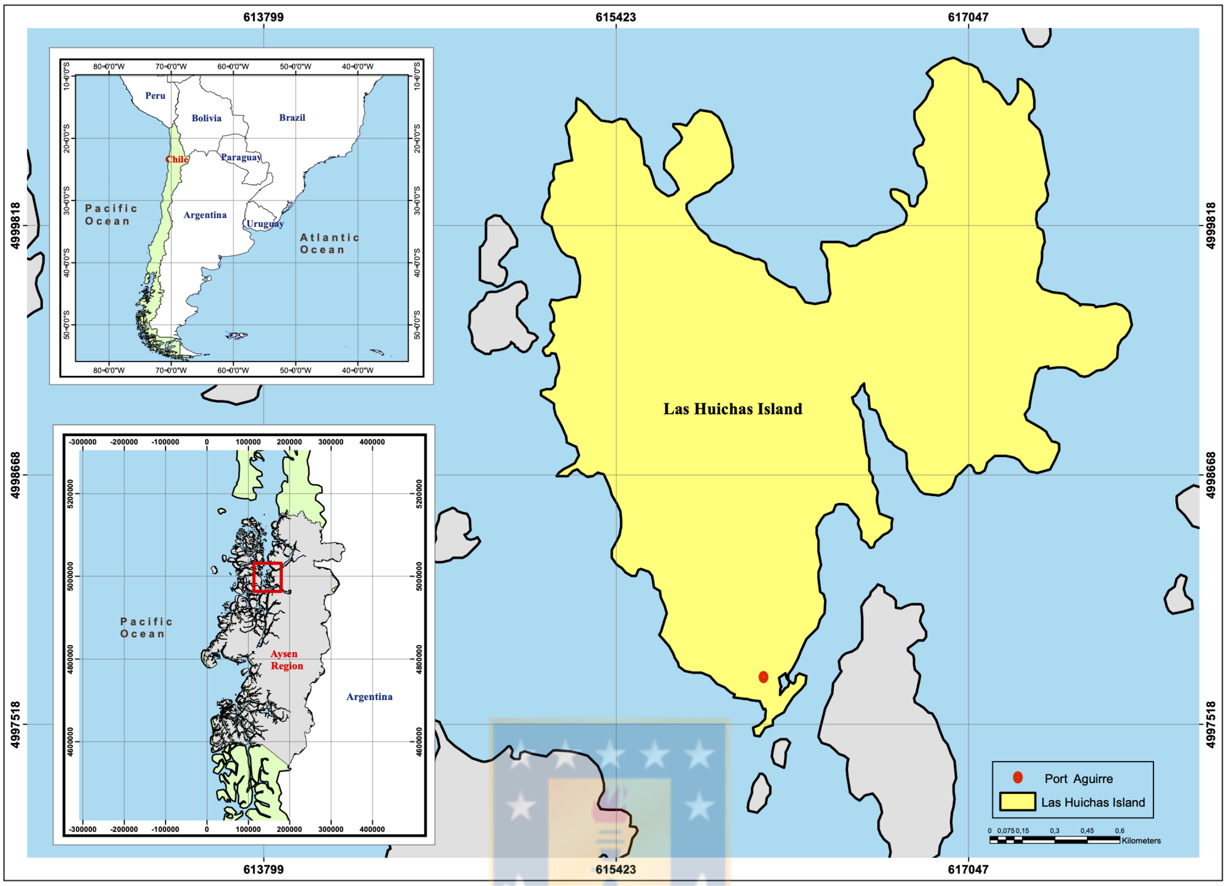

Figura 3.3.10: Ubicación de la Isla Las Huichas, Fiordos de Chile, Región de Aysén, Chile.

El algoritmo propuesto es usado para simular y optimizar cuatro HRES que satisfagan la demanda energética de la comunidad insular de la Isla las Huichas (45.15°S 73.52°O), ubicada en la parte noreste del Archipiélago de los Chonos, Región de Aysén, Chile (Figura 3.3.10). La isla tiene una población fija de 840 habitantes (datos del censo 2017) y posee una central termoeléctrica que proporciona electricidad las 24 horas del día.

Perfil de carga

La empresa encargada de la generación y distribución de energía en la isla (Edelaysen), indicó que para el año 2018 la central generó 981.8 MWh/año (pers. commun.). La Figura 3.3.11 representa la dispersión de datos horarios de consumo durante el año 2018. Las horas con mayor consumo se sitúan en la franja entre las 20:00 - 22:00. El promedio horario anual y diario anual de consumo de energía es de 112.07 kWh y 2689.77 kWh/day, respectivamente. La potencia peak en el año evaluado es 192.25 kW. El valor promedio del kWh en el año 2018 en la isla fue de 0.271 $/kWh.

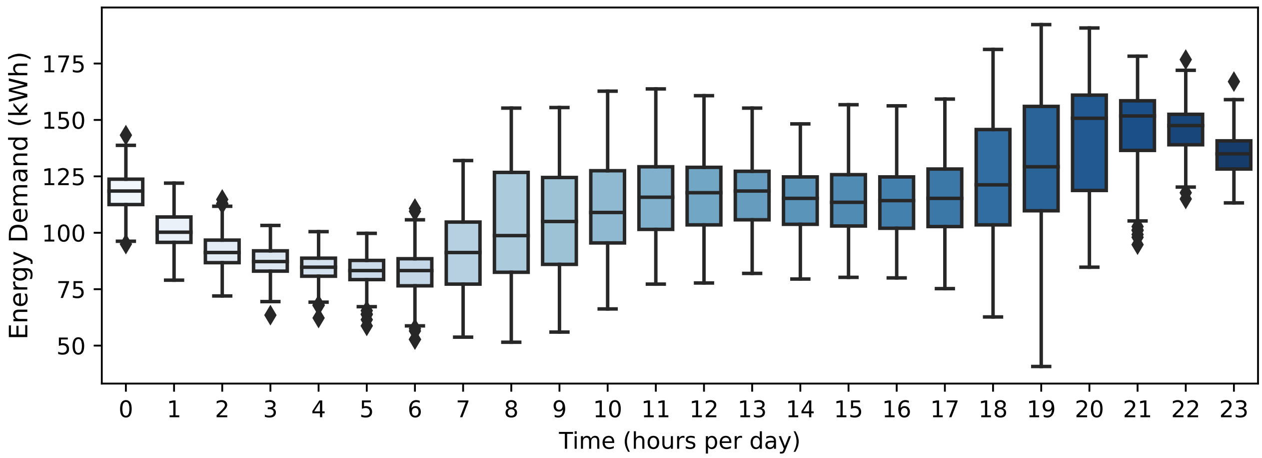

Figura 3.3.11: Energía generada por la central termoeléctrica de la isla las Huichas, año 2018. Representación gráfica de la mediana y los cuartiles de los datos horarios (los valores atípicos se representan con rombos).

Parámetros técnicos y económicos del HRES y caracterización de los recursos

La Tabla 3.3.2 resume los principales parámetros técnicos y económicos para los dispositivos WEC, TT, PV y WT y el sistema de almacenamiento de energía. El LPSP se define en 0 % en las cuatro configuraciones simuladas. Además, se establece una autonomía de 1 hora para satisfacer la carga a partir del BESS.

Tabla 3.3.2: Parámetros técnicos y económicos de los dispositivos empleados en la simulación de los cuatro HRES: WEC-BESS, TT-BESS, PV-BESS y WT-BESS.

Parameter	**Units**	**PV device**	**Wind device**	**Wave device**			**Tidal device**	**BES Li-Ion**
		CanadianSolar CS6U-330P	*Enair 200*	*Wave Dragon*[1]	*Pelamis*[1]	*AWS*[2]	*Schottel Instream*	*Battery Li-Ion*
Rated Capacity	kW	0.335	20	6000	750	2400	70	1 *(kWh)*
Initial Capital	USD	206.67	165000	14400000	2500000	6696000	1500000	700
O&M	USD	5	5000	720000	125000	12600	100000	0
Replacement	USD	206.67	95000	14400000	2500000	6696000	1500000	700
Efficiency	%	17.26	-	81	72	72	-	90
Lifetime	years	20	20	20	20	20	20	4
Derating factor	%	90	-	-	-	-	-	-
Hub Height	m	-	18	-	-	-	-	-
Initial State of Charge	%	-	-	-	-	-	-	100
Minimum State of Charge	%	-	-	-	-	-	-	20

[1] Datos económicos y técnicos tomados de [317]; [2] Datos económicos tomados de [318].

Los fiordos de Chile carecen de una red de equipos que caractericen el oleaje y corrientes mareales a lo largo de los numerosos canales. Una alternativa a las mediciones en terreno, es usar resultados de modelos de oleaje y del océano, para establecer las variables físicas que rigen cada recurso renovable marino. El Instituto de Fomento Pesquero, a través de su sitio web (http://chonos.ifop.cl), posee información oceanográfica relevante de los fiordos. En este recurso web, es posible descargar series de datos de corrientes mareales, resultado de las simulaciones del modelo hidrodinámico de malla flexible MIKE3 FM. Para alimentar el módulo de corrientes mareales, se descargó una serie de datos horarios anual en la coordenada 45.22°S 73.54°O, punto ubicado al sur de la Isla las Huichas. Dicha serie de datos informa que el promedio de velocidad de corriente mareal anual y valor máximo anual es de 0.44 m/s y 1.65 m/s, respectivamente. En lo referente a resultados de modelos de oleaje, no se encontraron en la zona de interés registros históricos o resultados de modelos numéricos del océano, por lo que se descagaron registros históricos de oleaje del Centro Nacional de Datos de Boyas (NDBC, por sus siglas en inglés) en la estación 32012 ubicada en el Pacífico Sur, al frente de las costas chilenas (https://www.ndbc.noaa.gov). La serie de datos horarios permite resaltar que el promedio de $H_{m0} = 2.16$ m y $T_e = 7.15$ s, con un percentil 90 de 2.93 m y 8.98 s, respectivamente.

De acuerdo al recurso web Explorador Solar de Chile [276] la irradiación solar global promedio en la isla corresponde a 3192.94 kWh/m^2/día. El Explorador Eólico de Chile [275], proporciona series de tiempo de mediciones y resultados de modelos climatológicos a lo largo del país. El promedio de velocidad del viento en la isla es de 6 m/s, con valores máximos de hasta 21.3 m/s en los meses de invierno (Junio - Agosto).

Resultados

Mediante un algortimo de optimización lineal se han simulado y optimizado cuatro configuraciones HRES en la isla Las Huichas, ubicada en los fiordos de Chile. Esta comunidad insular que depende energéticamente del continente, importa 54.000 l/año de diesel para cubir la demanda de energía de 982 MWh/año. Al ser una comunidad insular, existe un potencial energético asociado a olas y corrientes mareales cercano a sus costas, que hasta donde sabemos, no ha sido evaluado en ninguna solución energética HRES o en estudios similares en el país. El potencial de las olas y las corrientes mareales tiene mayores índices energéticos en las zonas de alta latitud. Por lo tanto, se analizan microrredes con energías marinas y energías tradicionales (sol y viento) acopladas a BESS, para determinar la factibilidad técnica y económica de estas soluciones sustentables. La configuración WEC-BESS se analiza para tres dispositivos undimotrices: Pelamis, AWS, Wave Dragon.

Solución WEC-BESS

El primer escenario de esta configuración corresponde a la simulación de un equipo Pelamis, de 750 kW de potencia nominal y un BESS de soporte para almacenar excesos de energía. Con un LPSP de 0 % (condición inicial de diseño), el algortimo optimizó una solución compuesta por 3 WEC y 4186 baterías (Fig. 3.3.12). La carga no atendida por el sistema corresponde a 3266 kWh/año lo que es equivalente a un LPSP de 0.3 % (Fig. 3.3.13). Esta pérdida de carga se enmarca en la época de verano, específicamente en el mes de enero. Con la instalación de 3 WEC y 4186 baterías hay un surplus de energía del 243 % de la energía consumida por la comunidad. Por último, el indicardor económico LCOE es de 1.82 $/kWh con un Costo Actual Neto (NPC, por sus siglas en inglés) de 24 millones de dólares.

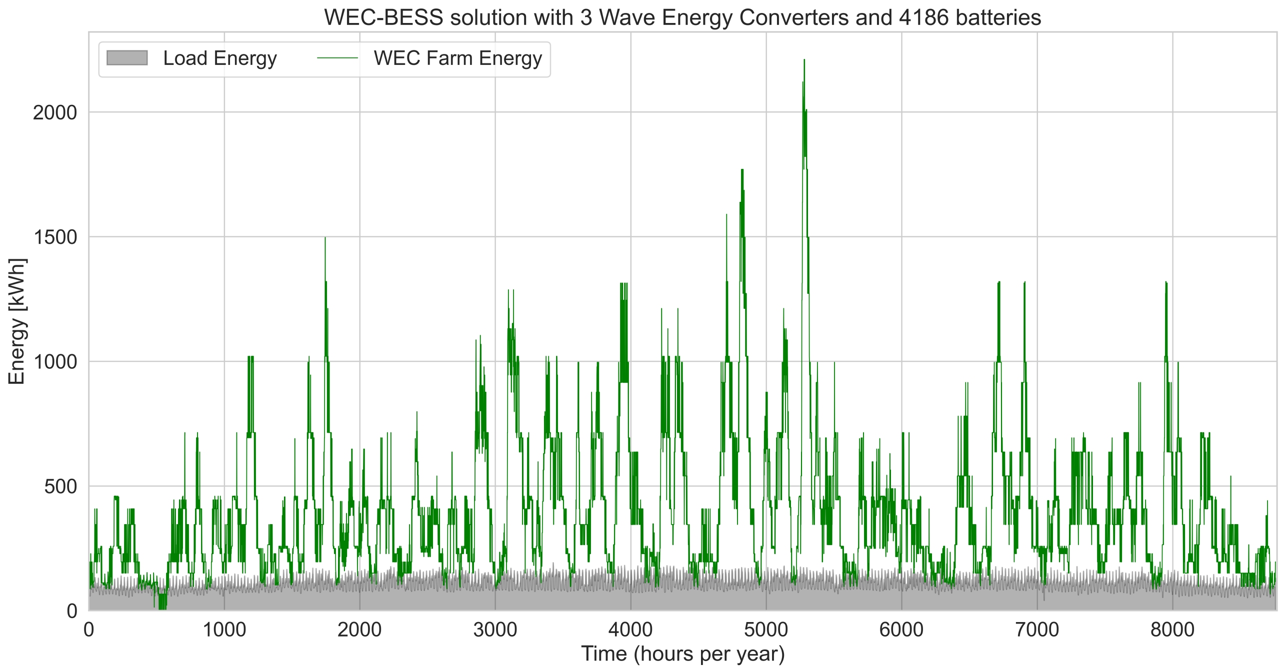

Figura 3.3.12: Simulación de la configuración WEC-BESS donde se resalta la energía horaria generada (verde) versus energía consumida (gris) en la comunidad insular. En este caso se simuló un dispositivo Pelamis con potencia nominal de 750 kW. El tiempo de autonomía de la solución renovable es de 1 hora. LPSP = 0.3 %.

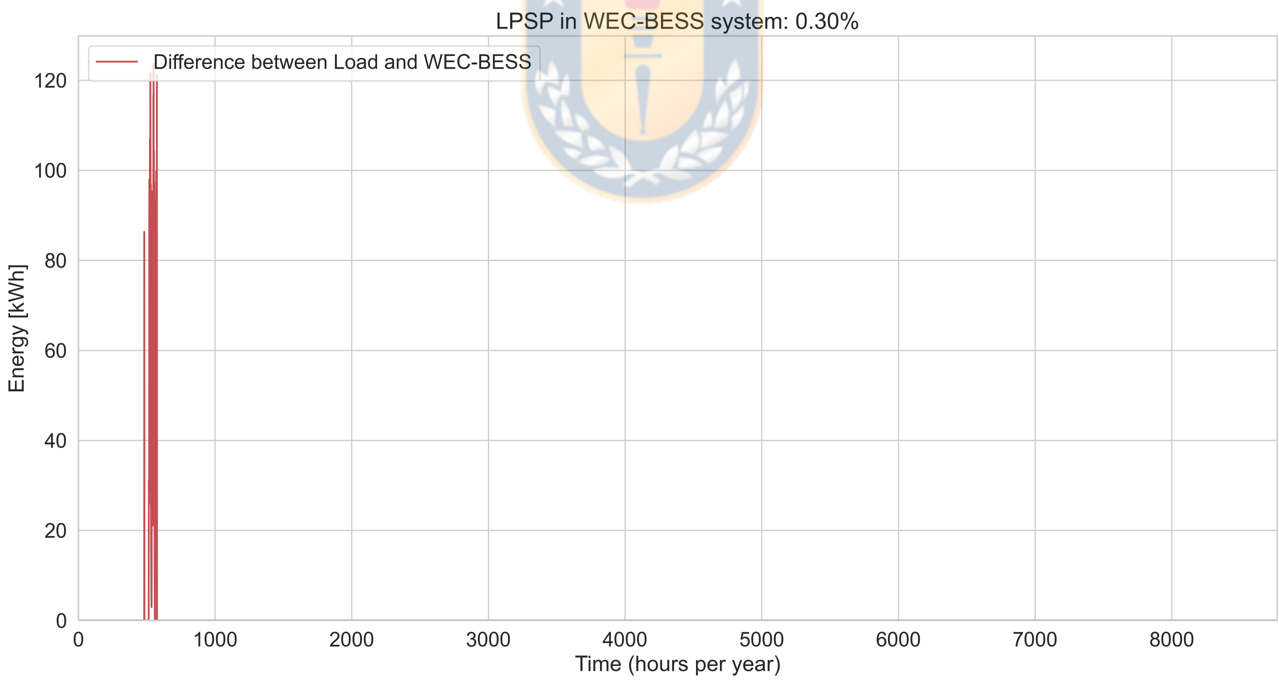

Figura 3.3.13: Carga no atendida durante el año de simulación del HRES WEC-BESS, usando un dispositivo Pelamis y un LPSP esperado de 0 %. El LPSP obtenido luego de la optimización del HRES fue del 0.3 %.

El surplus de energía obtenido con los equipos WEC es demasiado alto (ver Tabla 3.3.3) si se compara con la demanda de energía en la comunidad insular. Se obtuvieron porcentajes que oscilan entre el 127 % al 1135 % de la energía que consume la comunidad, es decir, una generación de electricidad anual “excesiva”. Este resultado permite concluir que: i) la potencia nominal de los dispositivos WEC sobrepasa en exceso la potencia peak diaria de la comunidad (391 % para el caso Pelamis), una condición de diseño que implica sobredimensionamiento, y por ende, un costo más elevado de la solución y, ii) puede presentarse una baja sincronización entre las horas de mayor consumo de energía y las horas de alta generación de electricidad. Por lo tanto, este tipo de resultados exhorta a que se evalúen dispositivos WEC de menor potencia nominal, si se consideran las características de consumo de la isla. Sin embargo, de manera complementaria, es importante resaltar que las comunidades insulares presentan serios problemas de acceso a agua potable. En razón de ello, una planta desalinizadora (funcionando como carga de baja prioridad) con una tasa de potabilización de 24 m^3/día, y un consumo de 4.38 kWh/m^3, podría trabajar a potencia nominal, con cualquiera de los 3 dispositivos WEC, y abastecer de 29 l/día de agua fresca a cada habitante de la Isla Las Huichas.

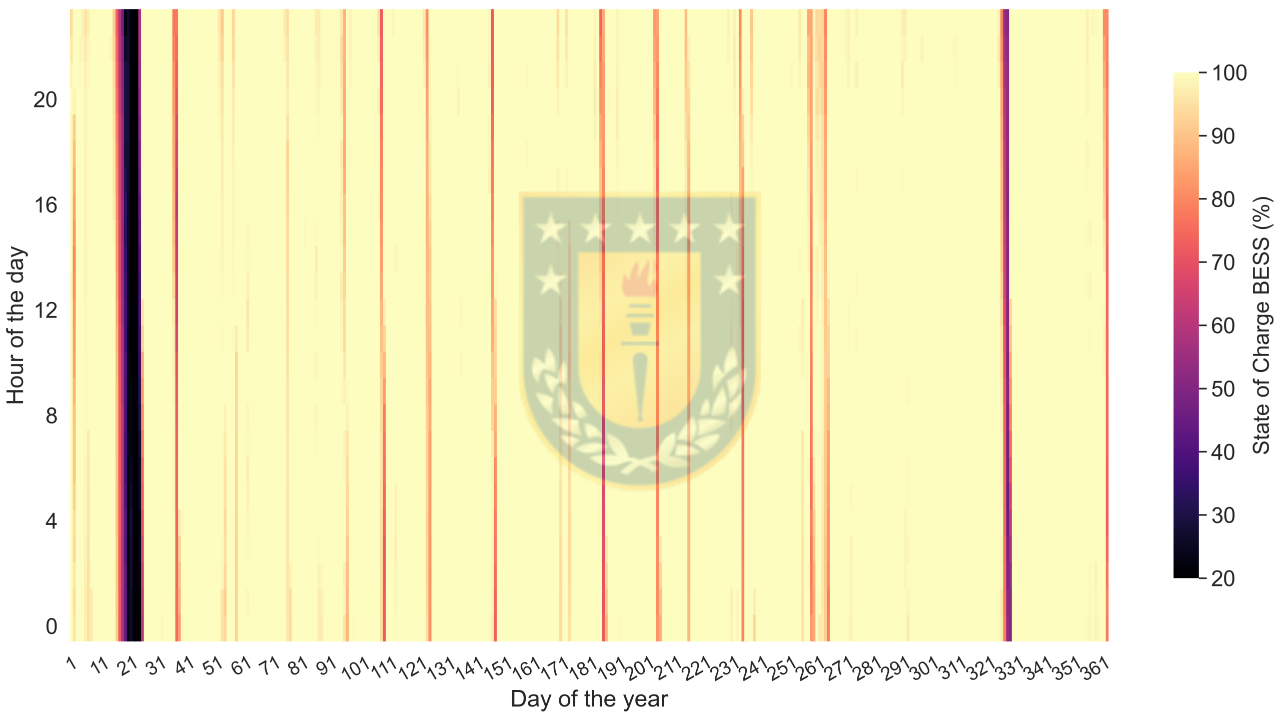

Figura 3.3.14: Surface Plot para determinar la variación del SOC durante un año de simulación. Las líneas negras indican un SOC del 20 %, límite inferior crítico que evita el deterioro acelerado del banco de baterías.

El comportamiento del banco de baterías está representado en la figura 3.3.14, donde las franjas de color negro corresponde a un SOC del 20 %, límite máximo de descarga para evitar el desgaste acelerado de las baterías. Aunque el banco de baterías tiene un aporte significativo en el mes de enero, la mayoría del tiempo el BESS mantiene un SOC del 100 %.

En la Tabla 3.3.3 se resumen los resultados de la optimización de HRES marinos. Allí, además de describir los indicadores LPSP y LCOE de los 3 dispositivos WEC, se desagregan las soluciones para 3 casos diferentes de LPSP: 0 %, 3 % y 5 %. Un caso particular se presenta con la solución

Wave Dragon, el cual no requiere sistema de almacenamiento de energía para cumplir con la demanda de energía y los LPSP definidos.

Tabla 3.3.3: Resumen de los resultados obtenidos en la simulación de los HRES de energía marina: WEC-BESS y TT-BESS. Cada configuración de HRES ha sido evaluado con tres diferentes LPSP: 0 %, 3 % y 5 %. Todas las simulaciones consideran una autonomía del BESS de 1 hora. LPSP in corresponde a la condición de diseño inicial y LPSP out representa el resultado del indicador luego de simular el HRES. Remarks resume la cantidad de dispositivos requeridos para suplir la demanda de energía y cumplir las condiciones iniciales de diseño.

Arquitecture	LPSP in/out (%)	WEC device	NPC (MM USD)[1]	LCOE (USD/kWh)	Surplus (MWh/yr)	Remarks
WEC-BESS	0/0.3	Pelamis	24	1.82	2381	WEC = 3, BESS = 4186
	3/1.4	Pelamis	18	1.35	1243	WEC = 2, BESS = 3437
	5/1.4	Pelamis	18	1.35	1243	WEC = 2, BESS = 3437
	0/0.4	AWS	57	4.18	2921	WEC = 4, BESS = 9882
	3/2.5	AWS	43	3.22	1944	WEC = 3, BESS = 7484
	5/2.5	AWS	43	3.22	1944	WEC = 3, BESS = 7484
	0/0.2	Wave Dragon	26	1.94	11144	WEC = 1, No BESS
	3/0.2	Wave Dragon	26	1.94	11144	WEC = 1, No BESS
	5/0.2	Wave Dragon	26	1.94	11144	WEC = 1, No BESS
TT-BESS	0/–	–	–	–	–	*No technically feasible solutions were found.*
	3/3.5	-	492	33.36	418	TT = 150, BESS = 17157
	5/5.4	-	454	31.64	324	TT = 138, BESS = 16291

[1] Million of US dollars.

El LCOE de la comunidad insular en el año 2018 alcanzó los 0.271 $/kWh, utilizando un sistema energético soportado por combustibles fósiles foráneos. Los resultados de la configuración WEC-BESS de la Tabla 3.3.3, anotan cifras de LCOE superiores a USD 1 por kWh generado. Cifras altas de LCOE con dispositivos WEC pueden obedecer a: i) duras condiciones ambientales que deben enfrentar y soportar los dispositivos marinos, lo que se traduce en el uso de componentes especializados y costosos en la etapa de construcción [319], ii) una baja densidad en la investigación e instalación de HRES con energías marinas [1], iii) escasas redes de medición y caracterización del recurso marino en diferentes latitudes, lo que limita la interpretación y amplia caracterización del recurso, que para el caso de la corriente mareal, por ejemplo, no solo está influenciado por la altura de marea y velocidad de flujo, sino que además influye la rugosidad del fondo marino y la indicidencia de los remolinos turbulentos, viento local, olas y diferencias de presión y, iii) aunque el potencial del océano es muy significativo, desafortunadamente el desarrollo y consolidación de prototipos comerciales (especialmente WEC) es un proceso lento [320].

Solución TT-BESS

La segunda configuración es una solución HRES marina con turbinas de corriente mareal acompañadas de un sistema de almacenamiento de energía. Aunque la caracterización del recurso mareal advierte una velocidad de corriente muy baja, el algoritmo encontró soluciones viables en dos de los tres casos de simulación (Tabla 3.3.3). En el caso de LPSP = 0 %, el algoritmo no encontró una configuración óptima para un conjunto de turbinas que contempla hasta 169 dispositivos. Una vez se reduce la condición LPSP (3 % y 5 %), los resultados son más favorables desde un punto de vista técnico y económico, aunque el sobredimensionamiento de la solución castiga el LCOE que es de los más costosos y exagerados entre las cuatro configuraciones HRES analizadas en este trabajo.

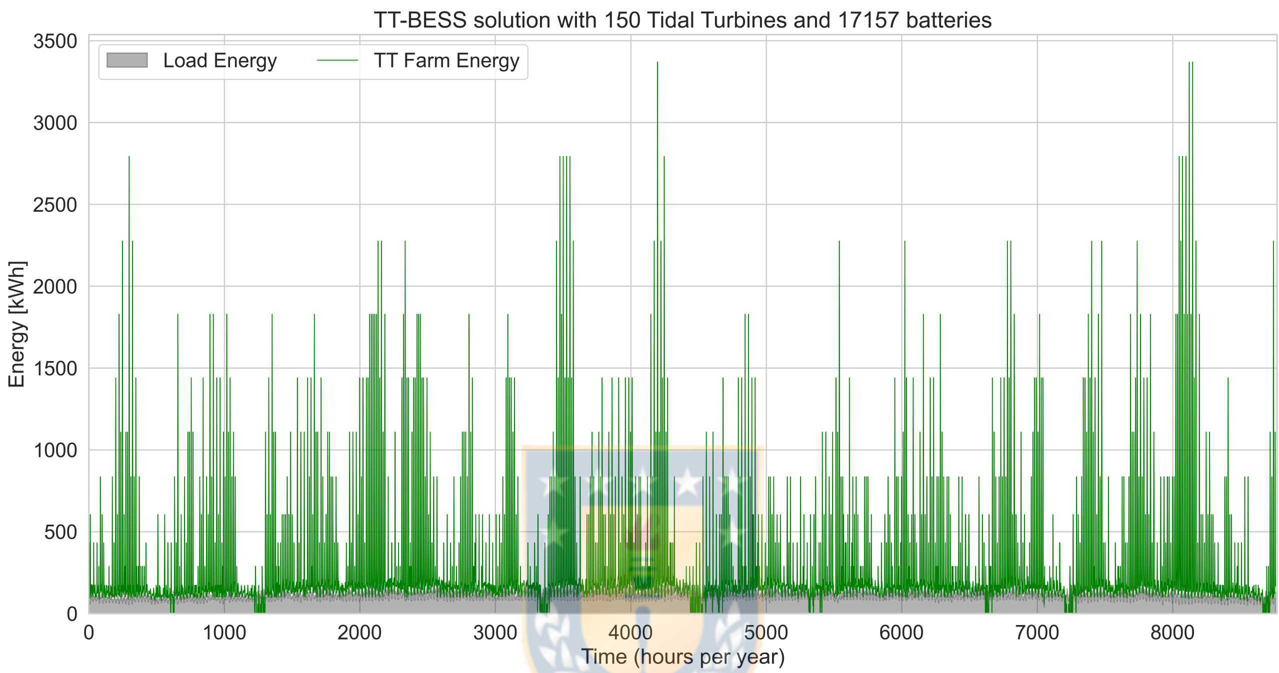

Figura 3.3.15: Simulación de la configuración TT-BESS donde se resalta la energía horaria generada (verde) versus energía consumida (gris) en la comunidad insular. La turbina marina utilizada es la Schottel Instream Turbine con potencia nominal de 70 kW. El tiempo de autonomía de la solución renovable es de 1 hora. LPSP = 3.5 %.

Como se mencionó anteriormente, los canales estrechos y condiciones geomorfológicas especiales, ayudan en el incremento del flujo mareal en ciertas zonas del planeta, por ejemplo los fiordos. La velocidad de corriente mareal en la coordenada de análisis es muy baja, comparada con zonas altamente energéticas como son los canales Chacao y Desertores, lugares donde la velocidad de marea excede los 2 m/s el 50 % del tiempo [37]. Ambos canales están al Norte de la Isla las Huichas, a más de 200 km de distancia, característica que puede sancionar el LCOE toda vez que el HRES no tiene alta capacidad de generación [321], además de imponer un problema de pérdida de energía en la transmisión, que se agudiza por la baja demanda de energía en la comunidad. Bajo este escenario, consideramos importante evaluar el potencial de la corriente mareal, en un canal estrecho cercano ubicado a 44.5 km al suroeste de la Isla Las Huichas (45.42°S 74.03°O). Con datos promedio de velocidad de corriente mareal y valor máximo horario anual de 1.55 m/s y 3.6 m/s, se simuló el HRES TT-BESS en los tres casos de LPSP. Para el caso de LPSP de 0 % la solución óptima es de 9 turbinas marinas y 4620 baterías. Esta configuración tiene un LCOE de 2.81 $/kWh. Los casos posteriores de LPSP de 3 % y 5 %, resultan en soluciones óptimas con 6 turbinas marinas y 4086 baterías, donde cada TT posee una potencia nominal de 70 kW. El LCOE se reduce en un 11 % para un LPSP del 3 % y en un 24 % para un LPSP del 5 %. La combinación de 6 TT y 4086 baterías produce un exceso de energía de aproximadamente el 108 % de la energía anual consumida en la isla, es decir, 1058 MWh/año.

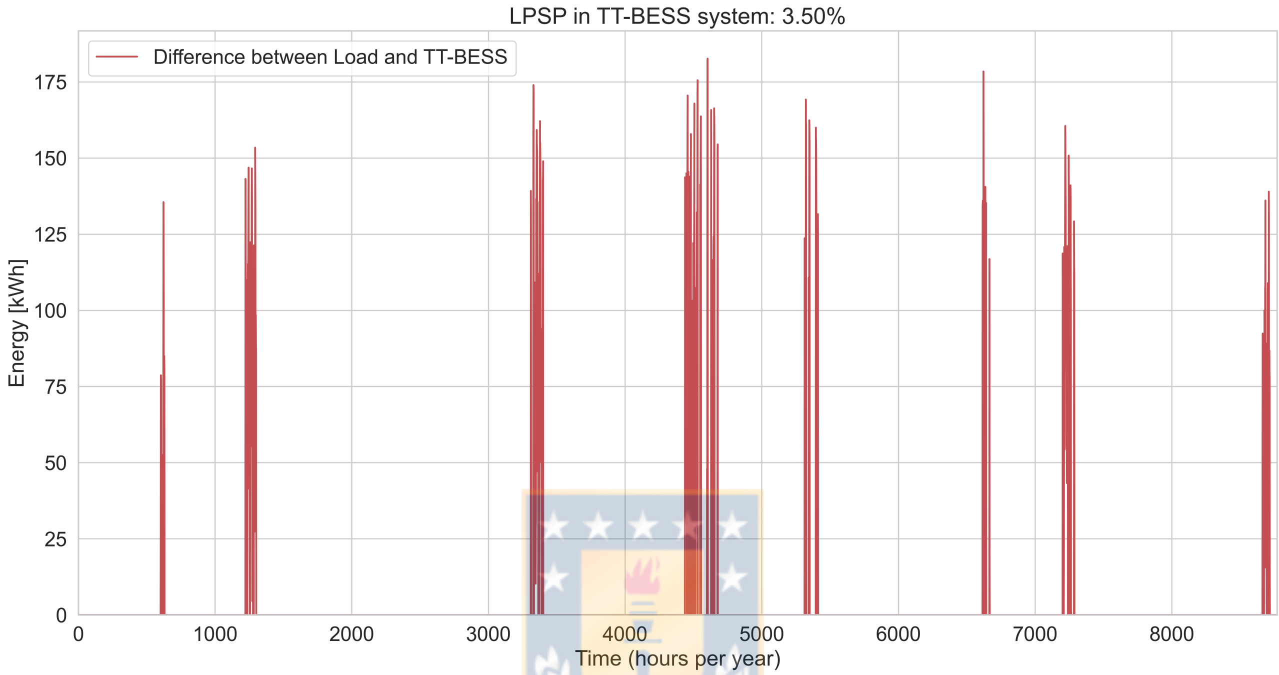

Figura 3.3.16: Carga no atendida durante el año de simulación del HRES TT-BESS, con un LPSP esperado de 3 %. El LPSP obtenido luego de la optimización del HRES fue del 3.5 %.

Una de las características de la energía mareomotriz es su alta predictibilidad en amplios períodos de tiempo (semanas, meses, años). Su comportamiento está muy bien definido a lo largo del ciclo lunar (28 días), con *mareas vivas* en luna nueva/llena y *mareas muertas* en fase creciente/menguante dentro del ciclo. Este proceder cíclico en el tiempo, puede explicar el comportamiento "sinusoidal" de la energía generada a partir de las turbinas marinas, que se puede visualizar en la figura 3.3.15.

Baja corriente mareal representa mayor número de turbinas para satisfacer un LPSP específico. La figura 3.3.15 muestra picos de generación superiores a 2000 kWh mientras la mayor demanda horaria de la carga no supera los 200 kWh. Hay una baja correlación entre generación y demanda de energía, una de las desventajas de este tipo de recurso renovable [322]. Incrementar la sincronización entre demanda y generación se logra a través de estrategias como *Demand Side Management* (DSM) donde el usuario modifica su nivel y patrón de consumo de energía, sin embargo, esto requiere una cuota alta de educación, incentivos y cambio de hábitos en la comunidad.

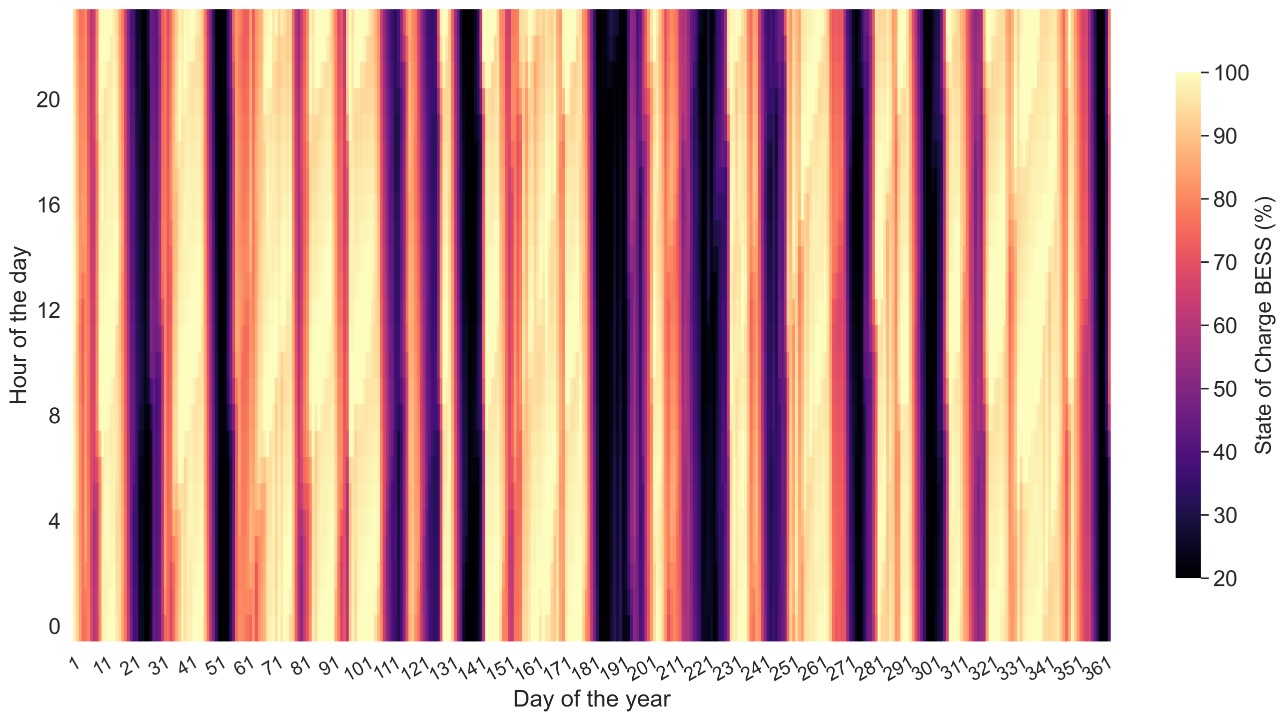

Figura 3.3.17: Surface Plot para determinar la variación del SOC durante un año de simulación. Las líneas negras indican un SOC del 20 %, límite inferior crítico que evita el deterioro acelerado del banco de baterías.

La figura 3.3.16 representa la pérdida de carga del HRES considerando un LPSP de 3 % (usando los datos de baja corriente mareal). Allí se identifica que la carga no atendida está repartida a lo largo del año, con una mayor representatividad en los meses de invierno. A su vez, el banco de baterías incide periódicamente en el suministro de energía directo a la carga. En la figura 3.3.17 se puede visualizar el ciclo de descarga regular, que en los casos más críticos de DOD (80 %), obedece a períodos de baja corriente mareal y baja correlación entre oferta y demanda.

Solución PV-BESS

Los HRES con recursos solares y eólicos son las soluciones energéticas con mayor atención e investigación en la literatura [1]. Vale resaltar que las olas tienen mayor potencial energético en latitudes altas y las corrientes mareales, aunque estén presentes en todas las costas, poseen mayores índices energéticos bajo ciertas particularidades en la batimetría y topología del territorio, condiciones usuales en zonas de alta latitud, como los fiordos. Ahora bien, el sentido común subraya que la radiación solar es más alta si la latitud es cercana al trópico, sin embargo, varios estudios señalan que la radiación solar incidente en latitudes altas puede ser incluso superior a la constante solar (G_{sc} = 1367 W/m^2) bajo determinadas condiciones meteorológicas [285, 286]. Por lo tanto, aunque la Isla Las Huichas esté ubicada en zonas temperadas, es indispensable estudiar si la radiación solar incidente en la comunidad insular, es suficiente para consolidar una solución energética viable.

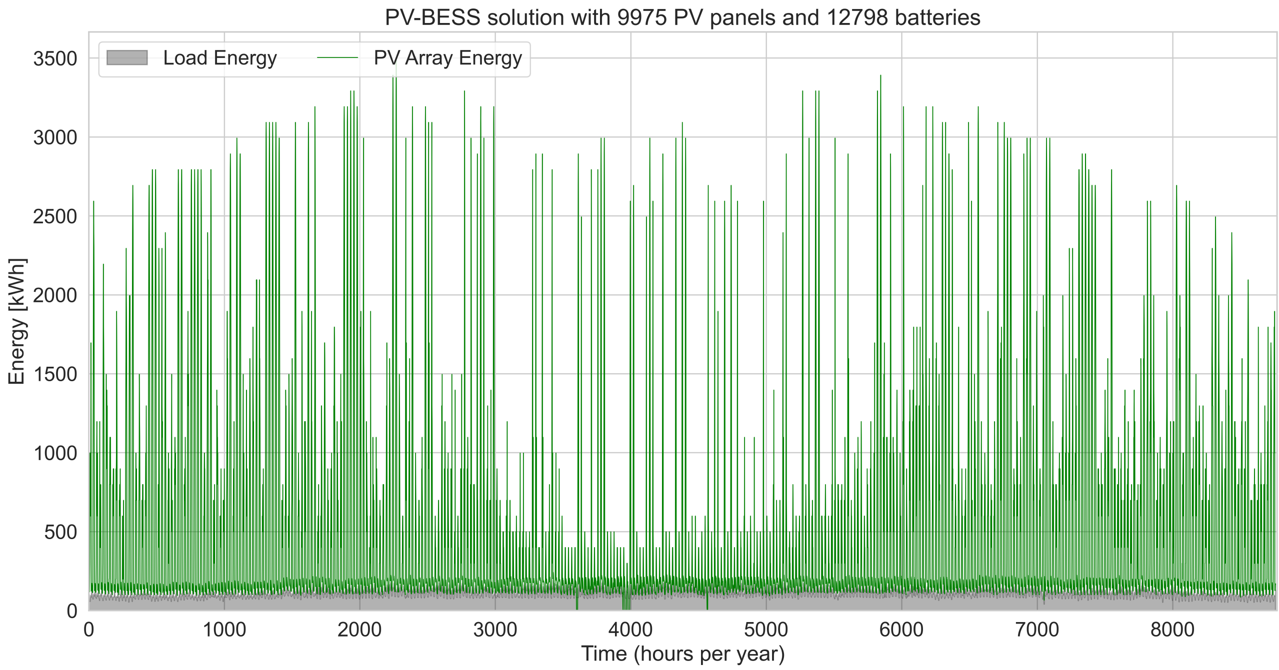

Figura 3.3.18: Simulación de la configuración PV-BESS donde se resalta la energía horaria generada (verde) versus energía consumida (gris) en la comunidad insular. Se simuló el panel fotovoltaico policristalino CanadianSolar MaxPower CS6U-330 de 335 W_p. El tiempo de autonomía de la solución renovable es de 1 hora. LPSP = 0.5 %.

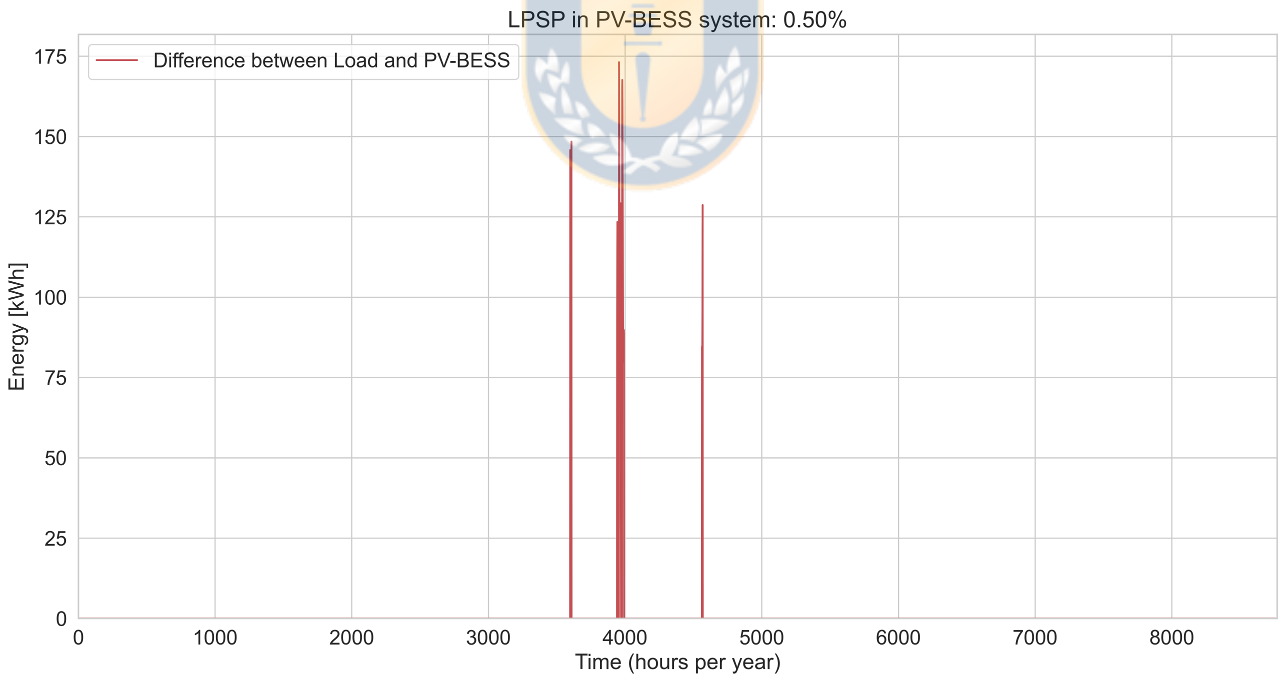

Figura 3.3.19: Carga no atendida durante el año de simulación del HRES PV-BESS, con un LPSP esperado de 0 %. El LPSP obtenido luego de la optimización del HRES fue del 0.5 %.

Los resultados del algoritmo son convergentes en diferentes configuraciones PV-BESS. La optimización de la función económica LCOE reduce el conjunto de soluciones a un mínimo global de 9975 paneles solares acompañados de 12798 baterías. Esta configuración puede satisfacer la carga de la isla con un LPSP del 0.5 % (ver Fig. 3.3.19). El LCOE es de 2.4 $/kWh y el surplus de energía alcanza 2375 MWh/año. La figura 3.3.18 ayuda a interpretar el comportamiento en la curva de producción de energía solar, mostrando una generación excesiva en esta solución. Esta dinámica obedece al alto consumo de energía en horario nocturno donde la radiación solar es cero, por lo tanto, el algoritmo tiene que sobredimensionar la planta solar para que la cosecha de energía diurna, que alimenta el BESS, sea capaz de sustentar la demanda de energía durante las 365 noches del año. Además, el promedio de radiación solar diario durante los meses de invierno se reduce al 25 % de los niveles obtenidos en verano. Dado este escenario de sobredimensionamiento, una de las estrategias propuestas en la literatura, es acompañar el panel solar con una fuente de energía complementaria, como lo es el viento, que se encargue de suplir la carga durante los períodos de baja o nula radiación solar [323].

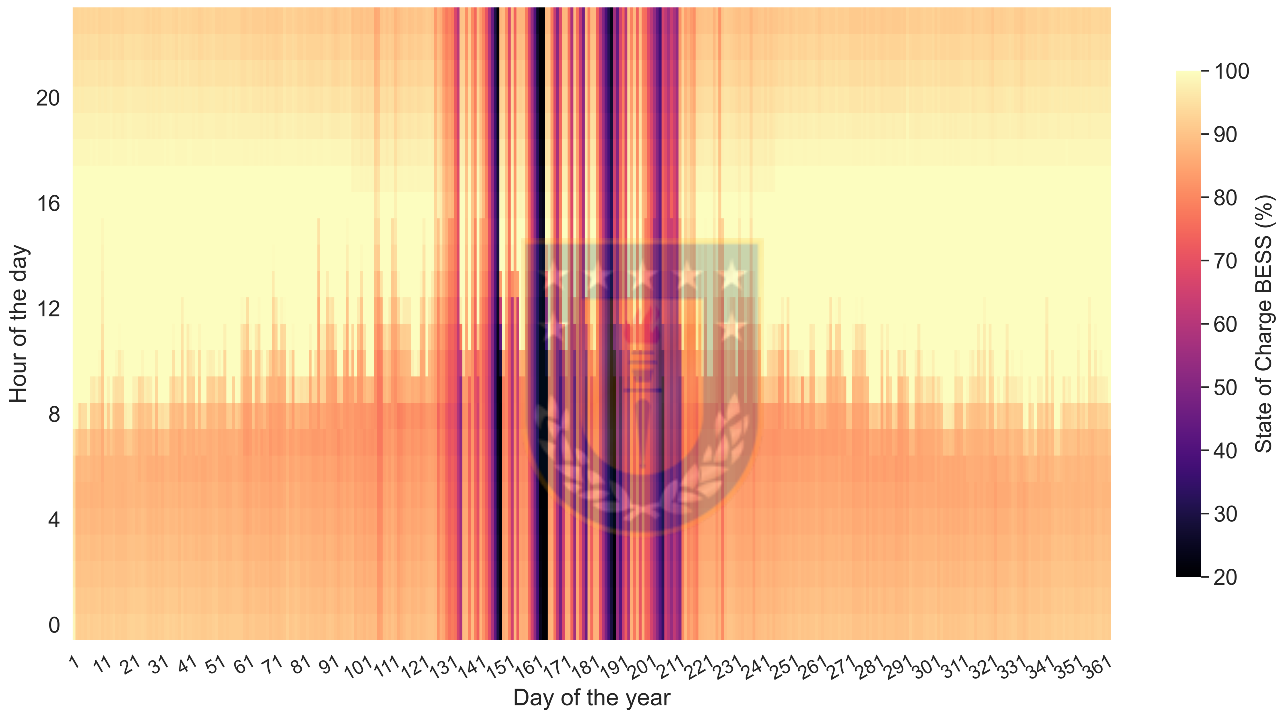

Figura 3.3.20: Surface Plot para determinar la variación del SOC durante un año de simulación. Las líneas negras indican un SOC del 20 %, límite inferior crítico que evita el deterioro acelerado del banco de baterías.

La figura 3.3.20 reproduce muy bien el comportamiento de la radiación solar, mediante el comportamiento del SOC en el BESS. De manera general, durante el ocaso y el alba, el SOC de las baterías se reduce gradualmente, en especial, cuando se acerca la temporada de invierno. En época de verano la intensidad de descarga del banco de baterías es menor. Con horas de sol efectivas, se identifica una autonomía de la planta solar en el suministro de energía a la carga y al BESS. Sin embargo, esta dinámica se interrumpe en los meses de invierno, donde la radiación solar es mucho menor, y el sistema de almacenamiento de energía debe atender la carga durante períodos nocturnos prolongados.

Solución WT-BESS

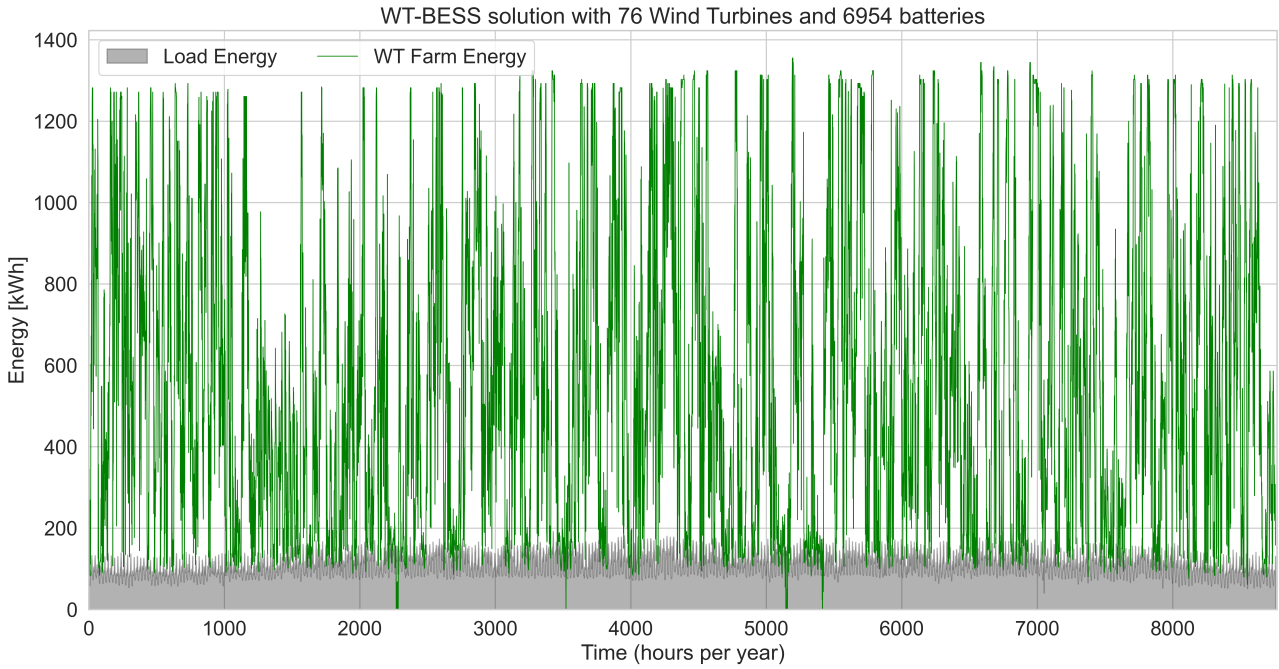

Figura 3.3.21: Simulación de la configuración WT-BESS donde se resalta la energía horaria generada (verde) versus energía consumida (gris) en la comunidad insular. Se utilizó una miniturbina ENAIR 200 de 20kW de potencia nominal. El tiempo de autonomía de la solución renovable es de 1 hora. LPSP = 0.5 %.

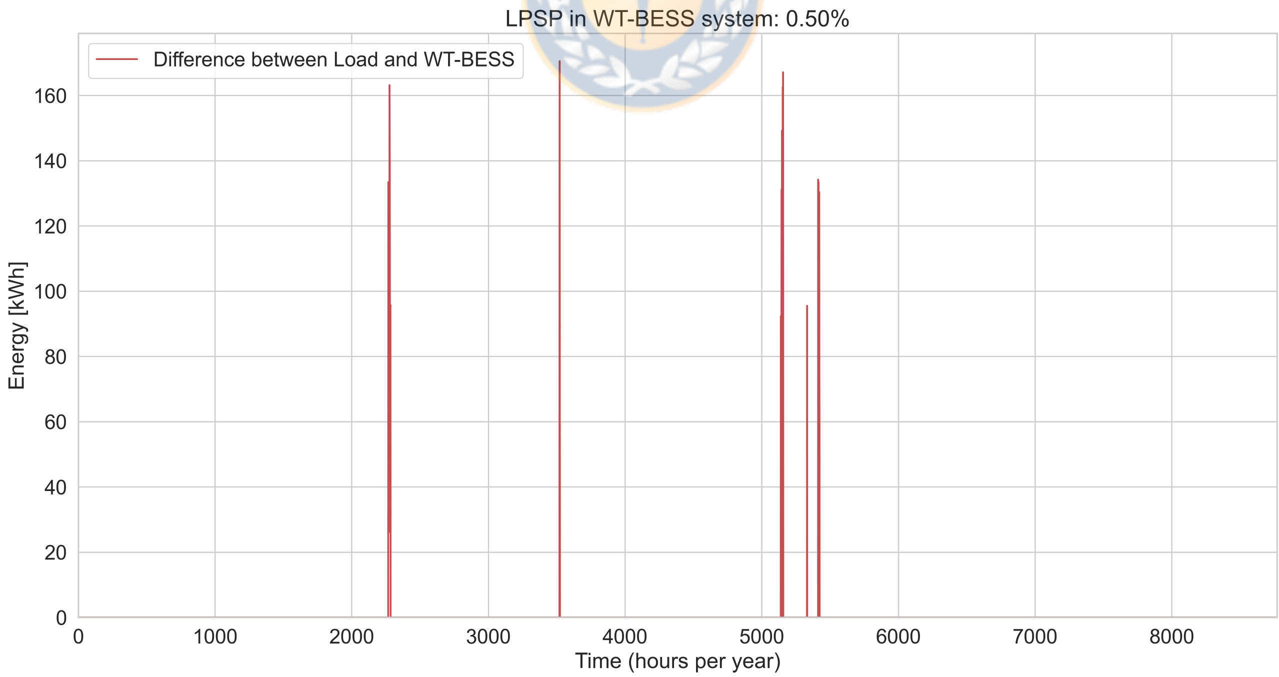

Figura 3.3.22: Carga no atendida durante el año de simulación del HRES WT-BESS, con un LPSP esperado de 0 %. El LPSP obtenido luego de la optimización del HRES fue del 0.5 %.

La figura 3.3.21 representa la curva de generación de las miniturbinas eólicas versus la demanda de energía en el año de simulación. Los picos de producción de energía diaria, aunque reportan varios órdenes de magnitud mayor a la carga, son inferiores a los obtenidos con la solución PV-BESS. El viento es un recurso con alta variablilidad espacio-temporal, lo que conlleva a una producción de energía muy variable como se representa en la figura 3.3.21. Bajo un LPSP de 0 % (caso base) el HRES WT-BESS requiere 76 miniturbinas eólicas y un banco de baterías con 6954 unidades. Hay una pequeña carga desatendida en el año de simulación que corresponde al 0.5 % de la carga total (Fig. 3.3.22). El LCOE obtenido es de 2.7 \$/kWh con un NPC de 36 millones de dólares. El surplus de energía es de 3646 MWh/año.

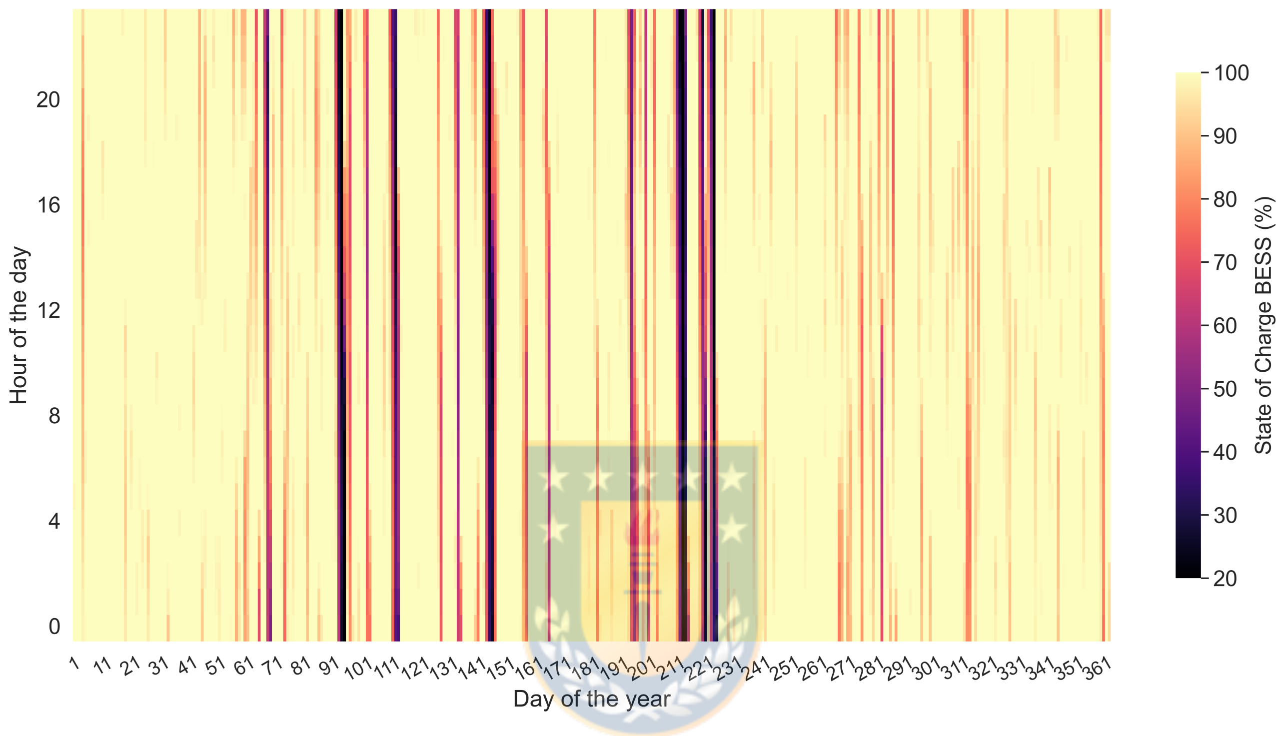

Figura 3.3.23: Surface Plot para determinar la variación del SOC durante un año de simulación. Las líneas negras indican un SOC del 20 %, límite inferior crítico que evita el deterioro acelerado del banco de baterías.

Cuando se varía el LPSP de esta configuración los resultados son:

- Con una carga desatendida del 3 %/año, el algoritmo optimizó una solución de 33 miniturbinas acompañadas con 5955 baterías, una arquitectura 36 % más económica comparada con el caso base. El LCOE se reduce a 1.77 \$/kWh y el surplus de energía desciende a 991 MWh/año., energía suficiente para atender las necesidades energéticas de la planta desalinizadora. La carga no atendida suma 32797 kWh/año., el 3.3 % de la carga total.

- Si se incrementa el porcentaje de carga no atendida en el año de simulación (LPSP = 5 %), la configuración HRES mejora algunos indicadores, a saber: LCOE se reduce a 1.68 kWh/año, el NPC se ubica en los 22 millones de dólares y el surplus de energía desciende a 575 MWh/año. La configuración que rige estos indicadores se compone de 26 miniturbinas y la misma cantidad de baterías que el caso anterior. Por último, una carga desatentida de 54 MWh/año (LPSP = 5 %) representa el consumo de veintisiete (27) casas (con tres-cuatro habitantes) y una media de consumo de electricidad de 170 kWh/mes [324].

Trabajo Futuro

La energía marina es un actor relevante en los HRES, especialmente si se emplean en latitudes altas donde su potencial es extraordinario. En este trabajo se simularon y analizaron cuatro configuraciones híbridas, dos de ellas con recursos renovables marinos. Cada configuración se simuló con 3 opciones de LPSP, logrando convergencia en los resultados para todas las configuraciones a excepción del TT-BESS con LPSP = 0 % (en el caso de velocidad de baja corriente mareal). Aunque se alcanzó viabilidad técnica y económica en los diferentes HRES, los mejores índices económicos están asociados a las olas y corrientes mareales. Sin embargo, para lograr competitividad de HRES marinos con las actuales tarifas de electricidad, es fundamental que: i) la gran variedad de prototipos WEC en etapa TRL 1-6 (modelos computacionales y pruebas de laboratorio) y TRL 7-8 (pruebas en el mar de prototipo a escala real), transiten aceleradamente a validación económica en extensas pruebas a mar abierto (TRL 9), ii) una vez consolidada la tecnología, se puede proceder a dinamizar con mayor ímpetu su comercialización (costos más competitivos para capital inicial y O&M) y iii) para reunir a todos los actores en la cadena de valor, son indispensables marcos regulatorios claros y atractivos que incrementen la integración de energías marinas en las nuevas matrices energéticas mundiales.

Si bien los HRES marinos simulados tienen viabilidad técnica y económica en el caso de estudio, hay una exagerada producción de electricidad que no está sincronizada con el perfil de consumo. Una alternativa a este inconveniente, es la integración de diferentes fuentes de energía renovable para atender una carga determinada. Esta incorporación de recursos, otorga complementariedad, suaviza la curva de generación y puede minizar el tamaño del BESS. En este sentido, la versión 2 del módulo de optimización se encargará de simular de manera simultánea las cuatro (4) fuentes renovables (Fig. 3.3.1). Conservando la función multiobjetivo, el algoritmo evaluará por cada paso de tiempo, el comportamiento eléctrico de cada dispositivo a partir de cada recurso renovable: Wave Module, Tidal Module, Solar Module, Wind Module. Con lo anterior, se busca minimizar la cantidad de dispositivos requeridos, reducir el tamaño del banco de baterías, restringir el impacto en el lado de la generación debido al comportamiento aleatorio de los recursos renovables (especialmente sol y viento), lo que va en pro de mejorar la productividad del HRES, toda vez que la capacidad instalada se optimiza, impactando positivamente los indicadores económicos de la solución.

Adicionalmente, admitir nuevas tecnologías de conversión en los módulos marinos, supone mejorar la compatibilidad de la capacidad instalada con las características del perfil de consumo, reducir los ordenes de magnitud en el exceso de energía e inevitablemente, una reducción en el dimensionamiento del HRES. Por lo tanto, y como se explicó en el HRES WEC-BESS, la versión

2 del algortimo, tendrá dispositivos WEC que se ajusten mejor al comportamiento eléctrico de la carga. En ese orden de ideas, será fundamental identificar fabricantes de turbinas marinas o dispositivos de corriente mareal, que maximicen la producción de energía eléctrica en flujos de marea de baja velocidad. Esto mejora la respuesta del algortimo al evitar sobredimensionamiento en la capacidad instalada.

La versión 2 del algoritmo debe incrementar las rutinas de comparación y comunicación entre cada módulo, lo que se traduce en una tasa de información más alta. Esto también significa actualizar todos los módulos e integrar nuevas funciones en éstos. En ese orden de ideas, y considerando el creciente interés por la producción de Hidrógeno Verde (H_2V), se precisa de una actualización y ampliación del módulo de almacenamiento de energía, que actualmente solo considera BESS. Producir H_2V es una oportunidad para impulsar economías del sector primario en sectores rurales (además de eliminar la importación de energéticos), a economías con mayor grado de desarrollo y oportunidad de exportación de energía. Transporte: rutas marítimas y vehículos, fertilizantes y electricidad son algunos de los sectores que van a requerir grandes volúmenes de H_2V en los próximos años. Por lo tanto, investigar y simular HRES con recursos marinos, además de tributar a la reducción de la pobreza energética, es una oportunidad en el crecimiento económico equitativo de las comunidades y una respuesta a la deuda vigente con el planeta.

Capítulo 4

Conclusiones

La energía undimotriz y mareomotriz (corriente mareal) es fundamental en la transición energética que vivimos. Su alta predictibilidad, su tecnología de conversión con altos factores de carga (LF) y su impresionante potencial energético en latitudes medias-altas, son propiedades notables para reducir la pobreza energética, mitigar el cambio climático y acelerar la independencia energética de los pueblos.

Mientras los inversionistas se preocupan por las decisiones de la OPEP de incrementar o reducir la producción mensual de petróleo, en el planeta conviven más de 700 millones de personas que carecen de una solución energética sustentable, que les de una oportunidad de vivir dignamente. El enfoque de grandes y complejos sistemas eléctricos centralizados, consumidores de combustibles fósiles, debe evolucionar a sistemas eléctricos compactos cercanos a la zona de consumo. Este tránsito tecnológico impacta positivamente la relación generación-carga, reduce las pérdidas por transporte de energía y, lo más importante, se cimienta en recursos renovables locales. En la generalidad de los sistemas eléctricos descentralizados, los HRES off-grid son propuestas robustas que combinan recursos renovables locales con sistemas de almacenamiento de energía. Este tipo de soluciones, en un momento posterior a su implementación, exhortan a la comunidad a sincronizar su consumo con la oferta, optimizar el uso de la energía y, por consiguiente, dar sustentabilidad y eficiencia energética al HRES. Esta investigación abordó de manera sistemática la simulación y optimización de HRES off-grid, con el interés particular de incorporar las energías marinas en su configuración, validar su factibilidad, y por consiguiente, tributar al acceso universal de la energía eléctrica. Durante el trabajo de investigación, se pueden destacar los siguientes hallazgos:

- ✓ Las comunidades que viven en zonas rurales y aisladas comparten una cualidad natural: baja densidad poblacional y alta diseminación en el territorio. Este escenario se articula apropiadamente con la implementación de HRES off-grid (sistema eléctrico descentralizado), que bajo los criterios de un modelo energético sustentable, debe utilizar los recursos renovables locales con mejores índices energéticos dependiendo de la latitud donde se ubique. Sin embargo, la literatura científica converge hacia HRES off-grid: i) que proponen recursos solares y eólicos como sus principales fuentes de energía en cualquier latitud, ii) con tasas muy bajas de inserción de energías marinas, incluso en comunidades insulares o costeras, iii) donde más del 50 % de las soluciones analizadas, sigue confiando en generadores diesel para satisfacer, de manera individual o combinada, la demanda de energía en pequeños centros de consumo.

- ✓ Casi el 50 % de los estudios que evaluaron HRES en comunidades insulares, caracterizaron los recursos renovables con mediciones en sitio. Aunque es una técnica costosa los datos obtenidos son precisos. Sin embargo, se proponen otro tipo de registros que emplean sensores remotos y resultados de modelos numéricos computacionales. Lo anterior habilita una diversidad de fuentes de información para evaluar un HRES específico. Por ello, al utilizar tres fuentes de información para optimizar un HRES, el conjunto de soluciones es disímil. La cuantificación de esta variabilidad demostró, en un caso de estudio con una solución PV-Wind-Diesel-Battery, que el dimensionamiento de la planta fotovoltaica puede variar en un 40 %, es decir, seleccionar una fuente de información sobre otra, implica para una comunidad insular, 1500 m^2 de terreno adicional para la instalación de paneles solares. Por lo tanto, la viabilidad de una HRES comienza con la elección de la fuente de información de los recursos renovables.

- ✓ La simulación y optimización de sistemas híbridos con energías marinas entregó soluciones convergentes en el caso de estudio. A partir de un estado de mar gobernado por $H_{m0} \leqslant$ 2.93 m y $T_e \leqslant$ 8.98 s (percentil 90), la configuración WEC-BESS con dispositivo Pelamis (***attenuator***) y Wave Dragon (***overtopping***) arrojó un LCOE de 1.35-1.82 $/kWh y 1.94 $/KWh, respectivamente, indicadores que compiten con la configuración PV-BESS que obtuvo un LCOE que oscila entre 1.59 - 2.4 $/kWh, para diferentes LPSP. Si la simulación del WEC-BESS se realiza con un dispositivo ***point absorber*** el LCOE puede llegar hasta 4.18 $/kWh cuando el LPSP no permite pérdida de carga (0 %).

- ✓ La configuración compuesta por turbinas marinas y banco de baterías (TT-BESS), se simuló considerando series de corrientes mareales en dos puntos geográficos diferentes: un punto al sur de la isla con corrientes mareales bajas y un punto al suroeste de la isla (44.5 km) con corrientes mareales altas. Los resultados indican que un escenario con corrientes mareales bajas no satisface la carga para un LPSP = 0. Sin embargo, el algoritmo encuentra soluciones para los casos de LPSP igual a 3 % y 5 %. Ahora bien, el segundo punto evaluado satisface la demanda de energía de la isla Las Huichas (caso de estudio), sin pérdida de carga, con la instalación de 9 turbinas marinas y 4620 baterías. El indicador económico de esta configuración se ubica en 2.81 $/kWh. El flujo de corriente mareal posee un promedio anual de 1.55 m/s.

- ✓ Aunque la simulación de un HRES PV-Wind-Battery tiene un LCOE de 0.199 $/kWh (usando resultados de modelos climatológicos), el consumo de diésel es de 198000 l/año (reducción del 32 % comparado con una solución 100 % Diesel) y la fracción de energía renovable de la solución es de apenas 28.8 %. De lo contrario, configuraciones HRES con energías marinas, si bien poseen un LCOE alrededor de 1.59 \$/kWh, son sistemas 100 % renovables, que garantizan independencia energética en la comunidad insular y suministro eléctrico constante a la central desalinizadora de la isla. Además, el exceso de energía puede ser empleado para producir H_2 verde, un energético que puede transformar la economía local (exportación de energía), alimentando el sector marítimo de la zona e incluso la sólida industria salmonera de la Región.

✓ El desarrollo de un nuevo algoritmo de simulación y optimización de HRES con energías marinas, contribuye de manera novedosa y original al conocimiento científico y habilita la evaluación técnica y económica de dispositivos marinos en soluciones energéticas off-grid. Dada su importancia, es relevante seguir mejorando el algoritmo, integrando mayor número de fuentes de energía renovable, ampliando las tecnologías soporte para almacenamiento de energía, especialmente, pensando en producción de H_2V, su uso como vector energético y posible exportación.

✓ Los resultados de esta investigación destacan la relevancia de las energías marinas en la independencia energética de comunidades aisladas y costeras. Se demostró que estas energías pueden garantizar la confiabilidad de sistemas energéticos off-grid, al cubrir el 100 % de la demanda de energía de la isla (LPSP = 0) de manera continua (durante un año de simulación). Adicionalmente, soluciones WEC-BESS y TT-BESS producen un importante exceso de energía que podría ser canalizado a sistemas de calefacción, los cuales actualmente son atendidos con biomasa.

Por último, esta investigación abordó de manera sistemática la simulación y optimización de HRES off-grid, incorporando las energías marinas como recursos esenciales en microrredes descentralizadas para comunidades insulares remotas. La combinación de una energía marina con un sistema de almacenamiento de energía, fue suficiente para demostrar la capacidad técnica de los HRES marinos y su alta correlación (recurso y demanda) durante un año de simulación, lo que se traduce en soluciones energéticas descentralizadas confiables. La integración de recursos solares y eólicos a soluciones WEC-BESS y TT-BESS será evaluada en la versión 2 del algoritmo, donde se busca dinamizar no solo el número de fuentes renovables disponibles, sino también el conjunto de sistemas de almacenamiento.

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Apéndice A

Modelo analítico del sistema fotovoltaico

A1. Radiación solar global horaria en una superficie inclinada

La radiación solar, específicamente la componente directa y difusa, se mide comúnmente en superficies horizontales. La medición en superficies inclinadas es escaza. Esta condición obliga a utilizar modelos matemáticos para estimar la radiación solar incidente en superficie inclinada, a partir de mediciones de radiación horizontal [310]. Sin embargo, para determinar la radiación solar global horaria en una superficie inclinada (I_β), es fundamental aplicar de manera previa dos correcciones geométricas muy importantes: i) la ecuación del tiempo (ET), que considera la excentricidad de la órbita terrestre y su inclinación axial y, ii) la variación longitudinal (V_{long}). La ecuación del tiempo expresada en minutos [325], se puede determinar usando la ecuación A1.1.

$$ET = 229{,}2 \times (0{,}000075 + 0{,}00186 \cos\Gamma - 0{,}032077 \sin\Gamma - 0{,}014615 \cos 2\Gamma - 0{,}04089 \sin 2\Gamma) \tag{A1.1}$$

$$V_{long} = \frac{4}{60}\left[L_{std} - L_{loc}\right] \tag{A1.2}$$

Donde Γ es el day angle expresado en grados y es equivalente a $\Gamma = 360(d_n - 1)/365$, para d_n que representa el número del día en el año. Por otro lado V_{long}, expresado en grados, se calcula mediante la ecuación A1.2, donde L_{std} es el meridiano en el que se basa la hora local (*Local Standard Time* - *LST*), y L_{loc} que corresponde al meridiano exacto donde está ubicado el observador.

A medida que la tierra se mueve alrededor del sol, la hora solar cambia ligeramente con respecto a LST. Esta diferencia de tiempo se establece con la ET, la cual tiene incidencia directa en los modelos matemáticos que a continuación se describen. La relación entre la hora solar (*Local Apparent Time - LAT*) y *LST* se define como:

$$LAT = LST + V_{long} + \frac{ET}{60} \tag{A1.3}$$

Una vez calculadas las dos correcciones geométricas, el siguiente paso es determinar las relaciones geométricas de algunos ángulos solares en relación con una superficie inclinada. En ese sentido, el primer ángulo a calcular es el ángulo horario (ω) definido en la ecuación A1.4.

$$\omega = 15 \times (LAT - 12) \tag{A1.4}$$

El ángulo formado entre el plano ecuatorial de la tierra y la línea que une los centros del Sol y la tierra, es llamado declinación solar (δ). Este ángulo expresado en grados sexagesimales, puede ser calculado de una manera muy precisa con la expresión de la ecuación A1.5 ([326]).

$$\begin{aligned}\delta = (&0{,}006918 - 0{,}399912\cos\Gamma + 0{,}070257\sin\Gamma - 0{,}006758\cos 2\Gamma + 0{,}000907\sin 2\Gamma \\ &-0{,}002697\cos 3\Gamma + 0{,}00148\sin 3\Gamma) \times \left(\frac{180}{\pi}\right)\end{aligned} \tag{A1.5}$$

Considerando que el panel solar está inclinado y apuntando hacia el ecuador (surface azimuth angle $\gamma = 180°$ hemisferio sur; $\gamma = 0°$ hemisferio norte), es fundamental obtener el sunrise angle (ω_{sr}). Este ángulo indica la incidencia de la primera radiación solar directa en una superficie inclinada. El sunset angle (ω_{ss}) es igual al sunrise angle con signo cambiado.

$$\omega_{ss} = \min \left\{ \begin{matrix} \cos^{-1}(-\tan\phi\tan\delta) \\ \cos^{-1}(-\tan(\phi+\beta)\tan\delta) \end{matrix} \right\} = -\omega_{sr}\,, \quad \text{South Hemisphere} \tag{A1.6}$$

$$\omega_{ss} = \min \left\{ \begin{matrix} \cos^{-1}(-\tan\phi\tan\delta) \\ \cos^{-1}(-\tan(\phi-\beta)\tan\delta) \end{matrix} \right\} = -\omega_{sr}\,, \quad \text{North Hemisphere} \tag{A1.7}$$

Donde ϕ es la latitud del lugar, β es el ángulo de inclinación del panel solar.

El ángulo de incidencia θ, corresponde al ángulo entre la radiación solar directa en una superficie y la normal a dicha superficie (ver Eq. A1.8). A su vez, el ángulo cenital θ_z es el ángulo de incidencia de la radiación solar directa sobre una superficie horizontal. Se calcula mediante la expresión matemática de la Eq. A1.9.

$$\begin{aligned}\cos\theta =& \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega + \\ & \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \tag{A1.8}$$

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \tag{A1.9}$$

Donde γ es el surface azimuth angle.

Usando $\cos\theta$ y $\cos\theta_z$ se determina el factor geométrico R_b, factor que relaciona la radiación solar directa incidente en superficie inclinada y una superficie horizontal (esta última conocida con las mediciones on site). Este factor es fundamental para determinar las componentes: beam radiation ($I_{b\beta}$), reflected radiation (I_r) and diffuse radiation ($I_{d\beta}$), que definen la radiación solar global horaria en una superficie inclinada. La expresión matemática del R_b está dada por:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \approx \begin{cases} \dfrac{\cos(\phi+\beta)\cos\delta\sin\omega_{ss} + \omega_{ss}\sin(\phi+\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_{ss} + \omega_{ss}\sin\phi\sin\delta}, & \text{South Hemisphere and } \gamma = 180^\circ \\ \dfrac{\cos(\phi-\beta)\cos\delta\sin\omega_{ss} + \omega_{ss}\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_{ss} + \omega_{ss}\sin\phi\sin\delta}, & \text{North Hemisphere and } \gamma = 0^\circ \end{cases} \tag{A1.10}$$

En la literatura se describen diferentes modelos para calcular la radiación difusa sobre una superficie inclinada. Estos modelos se clasifican en dos grandes grupos: isotrópicos y anisotrópicos. Los primeros establecen que todas las regiones del cielo son uniformes en la intesidad de $I_{d\beta}$ [327]. Sin embargo, los modelos anisotrópicos consideran un cielo no uniforme. El modelo Hay and Davies, Klucher and Reindl (HDKR) es uno de los modelos anisotrópicos más validados [328], por lo tanto, es el modelo usado en esta investigación. Las ecuaciones del modelo HDKR se describen a continuación:

$$I_{b\beta} = R_b I_b, \tag{A1.11}$$

$$I_{d\beta} = I_d\left[\left(\frac{1+\cos\beta}{2}\right)(1-f_{Hay})\left(1+f_R\sin^3\left(\frac{\beta}{2}\right)\right)\right], \tag{A1.12}$$

$$I_r = I_H\zeta\left(\frac{1-\cos\beta}{2}\right) \tag{A1.13}$$

Donde I_b es la radiación solar directa horaria sobre una superficie horizontal, I_d es la radiación solar difusa horaria sobre una superficie horizontal, ambas obtenidas de las mediciones on site, f_R una función del Modelo de Klucher que determina el grado de nubosidad (ver Eq. A1.14),

f_{Hay} es el índice anisotrópico del Modelo de Hay (ver Eq. A1.15), I_H es la radiación solar global horaria sobre una superficie horizontal y ζ es el albedo del suelo.

$$f_R = 1 - \left(\frac{Id}{I_H}\right)^2 \tag{A1.14}$$

$$f_{Hay} = \frac{I_b}{I_0} \tag{A1.15}$$

De la Eq. A1.15 I_0 representa la radiación solar extraterrestre horaria para una superficie horizontal en cualquier momento entre la salida y la puesta del sol [329]. Esta variable puede determinarse a partir de la siguiente ecuación:

$$I_0 = I_{sc}E_0 \left[\sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega\right] \tag{A1.16}$$

Donde I_{sc} es la constate solar que equivale a 1367 W/m^2 y E_0 es el factor de corrección de la excentricidad de la órbita terrestre (es decir, determina la variación de la radiación solar extraterrestre con la época del año). La ecuación para calcular E_0 esta dada por:

$$E_0 = 1{,}000110 + 0{,}034221\cos\Gamma + 0{,}001280\sin\Gamma + 0{,}000719\cos 2\Gamma + 0{,}000077\sin 2\Gamma \tag{A1.17}$$

Finalmente, la radiación solar global horaria sobre una superficie inclinada viene dada por:

$$I_\beta = I_{d\beta} + I_{b\beta} + I_r \tag{A1.18}$$