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TÉSIS

“ANÁLISIS DE LA PRODUCCIÓN Y EL CONSUMO SOSTENIBLES MEDIANTE INTELIGENCIA ARTIFICIAL PARA UNA SOCIEDAD RESILIENTE”

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RESUMEN

La adopción masiva de tecnologías avanzadas ha generado desafíos significativos. La automatización pone en riesgo fuentes de empleo, incrementa el consumo eléctrico necesario para sostener sistemas digitales y ejerce una presión creciente sobre recursos hídricos y minerales críticos. Ante esta realidad, el presente estudio plantea la necesidad de un plan estratégico que combine innovación y sostenibilidad, de modo que las nuevas tecnologías promuevan el bienestar social sin comprometer la disponibilidad de recursos para generaciones futuras, a fin de promover la migración hacia una sociedad sostenible y resiliente (Sociedad 5.0.).

Para ello se emplearon técnicas de aprendizaje automático, específicamente *k-means clustering*, con el fin de analizar datos de huella ambiental en diversas regiones de relevancia global. Para dicho análisis se tomaron en cuenta 12 indicadores medioambientales asociados tanto a la huella de consumo como a la producción nacional de cada uno de los países considerados en el estudio, tanto desde un enfoque total como per cápita.

El análisis identificó cuatro grupos (clústeres) de regiones que comparten características similares en cuanto a intensidad de consumo y niveles de producción, lo que permitió reconocer áreas con alta demanda energética que requieren mayor eficiencia y fuentes renovables, zonas con estrés hídrico crítico que limitan la expansión tecnológica, territorios con explotación mineral intensa que demandan estrategias de reciclaje y economía circular, y regiones de baja huella global con elevado potencial de crecimiento sostenible mediante prácticas responsables.

Los resultados obtenidos sirven de base para recomendaciones concretas en cada caso, tales como diversificar la matriz energética, implementar sistemas de reúso de agua, promover políticas de extracción responsable y fortalecer capacidades locales en gestión de recursos. En conclusión, el uso combinado de *clustering* y evaluación de huella ambiental ofrece una herramienta cuantitativa robusta para priorizar intervenciones regionales, apoyar la toma de decisiones informada y avanzar hacia un desarrollo resiliente, socialmente inclusivo y respetuoso del medio ambiente.

Palabras Clave: Sostenibilidad, indicadores medioambientales, *K-means clustering*, huella de consumo y producción nacional.

ANALYSIS OF SUSTAINABLE PRODUCTION AND CONSUMPTION THROUGH ARTIFICIAL INTELLIGENCE FOR A RESILIENT SOCIETY

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ABSTRACT

The widespread adoption of advanced technologies has brought significant challenges. Automation threatens sources of employment, increases the electricity consumption required to sustain digital systems, and places growing pressure on critical water and mineral resources. In view of this situation, the present study proposes the necessity of a strategic plan that integrates innovation and sustainability so that new technologies promote social welfare without compromising resource availability for future generations, thus promoting migration toward a sustainable and resilient society (Society 5.0.).

To achieve this, machine learning techniques (specifically K-means clustering) were used to analyze environmental footprint data from various regions of global relevance. For this analysis, 12 ecological indicators associated with both the consumption footprint and national production of each of the countries considered in the study were taken into account, both from a total and per capita perspective.

The analysis identified four groups (clusters) of regions with similar consumption intensities and production levels, allowing the identification of areas with high energy demand that require greater efficiency and deployment of renewable sources; zones experiencing critical water stress that constrain technological expansion; territories with intensive mineral exploitation that call for recycling strategies and a circular-economy approach; and regions with a low overall footprint but strong potential for sustainable growth through responsible practices.

The results provide a basis for concrete recommendations in each case, such as diversifying the energy mix, implementing water-recirculation systems, promoting responsible extraction policies, and strengthening local resource-management capacities. In conclusion, the combined use of clustering and environmental-footprint assessment offers a robust quantitative tool for prioritizing regional interventions, supporting informed decision-making, and advancing toward a resilient, socially inclusive, and environmentally respectful model of development.

Keywords: Sustainability, environmental indicators, K-means clustering, consumption footprint and domestic production.

CAPÍTULO 1. INTRODUCCIÓN

1.1. GENERALIDADES

Las revoluciones industriales transforman las prácticas industriales tradicionales mediante el uso de técnicas nuevas determinadas por las tecnologías disponibles de la época. A lo largo de la historia se han sufrido distintas revoluciones industriales, las cuales han marcado el rumbo de la humanidad (Raja-Santhi & Muthuswamy, 2023).

En 1760 la invención de la máquina de vapor propició la primera revolución industrial, promoviendo la transición de una sociedad basada en la agricultura, hacia la industrialización y urbanización. Durante esta etapa, el carbón fue la principal fuente de energía permitiendo la operación de grandes máquinas de vapor que fueron empleadas en la industria textil y manufacturera; por su parte, el tren fue empleado como principal medio de transporte (Xu et al., 2018).

La invención de máquinas de combustión interna propició una segunda revolución industrial en 1900. Lo cual dio comienzo a un periodo de industrialización rápida, utilizando aceite y electricidad como fuentes de energía para la producción en masa (Clark, 2010)

Por su parte, la tercera revolución industrial comenzó en 1950, cuando la invención de transistores y microprocesadores permitió la producción automatizada asistida por dispositivos electrónicos como sensores digitales y computadoras (Fields, 1999)

Actualmente se encuentra en marcha una cuarta revolución industrial, que es lo que se conoce como industria 4.0, esto es la transformación digital de las industrias manufactureras centrándose en la automatización, interconectividad, y la optimización de procesos en tiempo real utilizando tecnologías digitales como el internet de las cosas (*Internet of Things*, IoT), aprendizaje automatizado (*Machine Learning*, ML), inteligencia artificial (*Artificial Intelligence*, AI), sistemas ciberfísicos (*Cyber-Physical Systems*, CPS), computación en la nube, fabricación aditiva (AM), gemelos digitales, ciberseguridad y demás para la comunicación y control de cada una de ellas; para permitir el aumento de la eficacia productiva y la automatización en su mayor extensión posible (Da Xu, 2020).

El concepto de industria 4.0 es aplicable a todo tipo de empresa industrial, permitiendo el mantenimiento predictivo de equipos, y una mayor productividad y calidad de los productos y/o servicios, gracias a la implementación de la automatización y robots que ayuden a efectuar tareas (Raja-Santhi & Muthuswamy, 2023). Sin embargo, la implementación de la industria 4.0 conlleva una serie de retos de crucial importancia.

En el ámbito socioeconómico, el alto nivel de automatización implica la potencial pérdida de empleos por el remplazo de la labor humana, lo cual causaría desequilibrio económico y mayor desigualdad social. Atentando también contra la sustitución de la inteligencia humana, puesto que, en cierto punto, la inteligencia artificial podría remplazar incluso a profesionistas altamente calificados (Pech & Vaněček, 2022). De acuerdo con el Departamento de Asuntos Económicos y Sociales de las Naciones Unidas (*United Nations Department of Economic and Social Affairs*, DESA), el riesgo de pérdida de empleos debido a la automatización es de 80% para el caso de los grupos sociales de bajo y mediano ingreso (United Nations Department of Economic & and Social Affairs (DESA/DPAD), 2017).

En general, esta cuarta revolución industrial involucra altos costos de inversión y operativos de generadores, centrales computacionales, dispositivos virtuales y digitales, maquinas, equipos, infraestructura y conectividad; por lo tanto, se requieren profesionistas altamente capacitados para el manejo de las tecnologías anteriormente mencionadas (Ortiz et al., 2020). La **Figura 1**, resume las características de cada una de las revoluciones industriales a lo largo de la historia.

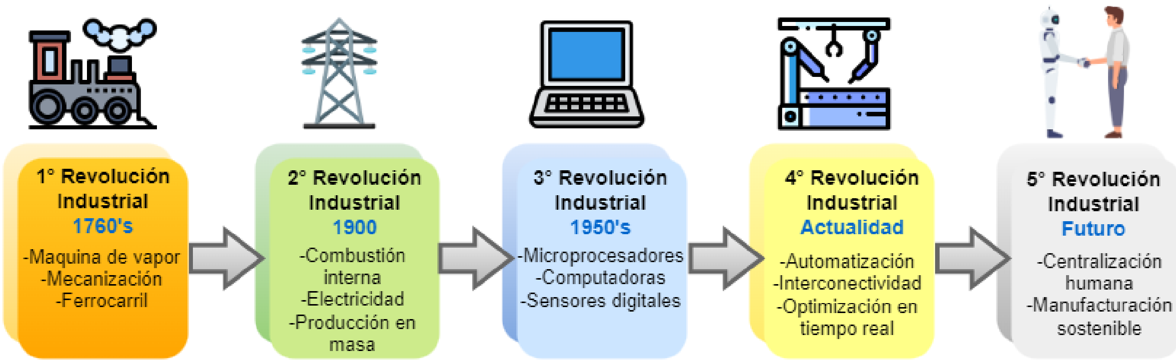

Figura 1. Revoluciones industriales a lo largo de la historia (elaboración propia).

No obstante, el incremento en la digitalización puede llevar a un aumento del consumo de recursos debido al crecimiento de los volúmenes de producción (Kosolapova et al., 2021). La fabricación de dispositivos tecnológicos es dependiente de las reservas de metales, los cuales también son altamente demandados para la manufactura de partes automotrices, estimándose para 2030 un gran riesgo de escasez de dichos materiales (Bag et al., 2021). Otros factores importantes para considerar son el consumo energético e hídrico relacionado con la operación de las tecnologías implicadas en la Industria 4.0, recordando que las industrias representan el sector mayormente demandante de agua (Kosolapova et al., 2021).

De esta forma, existe el riesgo del agotamiento de los recursos naturales, lo cual ocurre cuando estos se consumen a una velocidad mayor a la que pueden regenerarse (Raj, 2024). Además de la presión en el consumo de recursos que implican las tecnologías asociadas a la Industria 4.0., en la actualidad existen diversos factores que contribuyen al agotamiento de los recursos naturales. Como es el caso del crecimiento demográfico, ya que una mayor población requiere más recursos. A su vez que, las culturas consumistas con sus perspectivas materialistas promueven el consumo desmedido de los recursos para fines ajenos a la supervivencia y el progreso humano. Los avances tecnológicos, en sí mismos también contribuyen al agotamiento de los recursos, ya que permiten una explotación más rápida y eficiente de los mismos.

Sin embargo, algunos visionarios prevén la siguiente revolución industrial, Industria 5.0 como aquella que introducirá de nuevo el toque humano a los productos manufacturados, enfocándose de forma simultánea en la manufacturación sostenible (Raja-Santhi & Muthuswamy, 2023). Surgiendo de igual forma, el concepto de Sociedad 5.0 iniciado en Japón, basado en una sociedad centrada en el ser humano; existiendo un balance entre el desarrollo económico y la responsabilidad social. Esta sociedad se enfoca en el bienestar común de los ciudadanos y el desarrollo de una sociedad sostenible y resiliente (Kasinathan et al., 2022a).

Este impulso hacia una producción más humana e inteligente, que busca conjugar avances tecnológicos con objetivos sociales y ambientales, requiere un marco que encauce su desarrollo sin sobrepasar la capacidad de los ecosistemas; por ello, la incorporación de límites planetarios se vuelve esencial para garantizar que las prácticas de Industria 5.0 y Sociedad 5.0 permanezcan dentro de umbrales compatibles con la salud del planeta y el bienestar de las generaciones futuras.

Son nueve límites planetarios los que fueron propuestos por primera vez por Johan Rockström y un grupo de 28 científicos en 2009, dentro de los cuales las generaciones venideras de la humanidad pueden continuar desarrollándose y prosperando, dichos límites se enlistan a continuación (Richardson et al., 2023a).

1. *Cambio climático.* Asociado a la concentración de CO_2 en la atmósfera.
2. *Cambios en la integridad de la biósfera.* Se relaciona a la diversidad genética de un determinado ecosistema.
3. *Flujos biogeoquímicos.* Hace referencia a los ciclos de nitrógeno y fósforo.
4. *Agotamiento del ozono estratosférico.* Disminución de la concentración de ozono en la estratósfera.
5. *Acidificación de los océanos.* Concentración del ion carbonato en océanos.
6. *Uso de agua fresca.* Alteración del agua azul (agua almacenada en ríos, lagos, arroyos, humedales, aguas subterráneas y glaciares) y agua verde (porcentaje de precipitación que se infiltra en el suelo y está disponible para plantas).

7. *Cambios en el uso de suelo.* Considera la cantidad y patrón de cambio del sistema terrestre: bosques, pastizales, sabanas, tundra, matorrales, etc.
8. *Carga de aerosoles en la atmósfera.* Concentración de partículas de aerosol en la atmósfera.
9. *Introducción de entidades novedosas.* Se definen como sustancias nuevas, nuevas formas de sustancias existentes o formas de vida modificadas que tienen el potencial de provocar efectos geofísicos y/o biológicos indeseables.

En septiembre de 2023, un grupo de científicos cuantificó por primera vez, los nueve límites que regulan la estabilidad y resiliencia del planeta Tierra. Concluyendo que seis de los nueve límites han sido transgredidos, dichos límites son presentados en la **Figura 2** (Rockström et al., 2009)

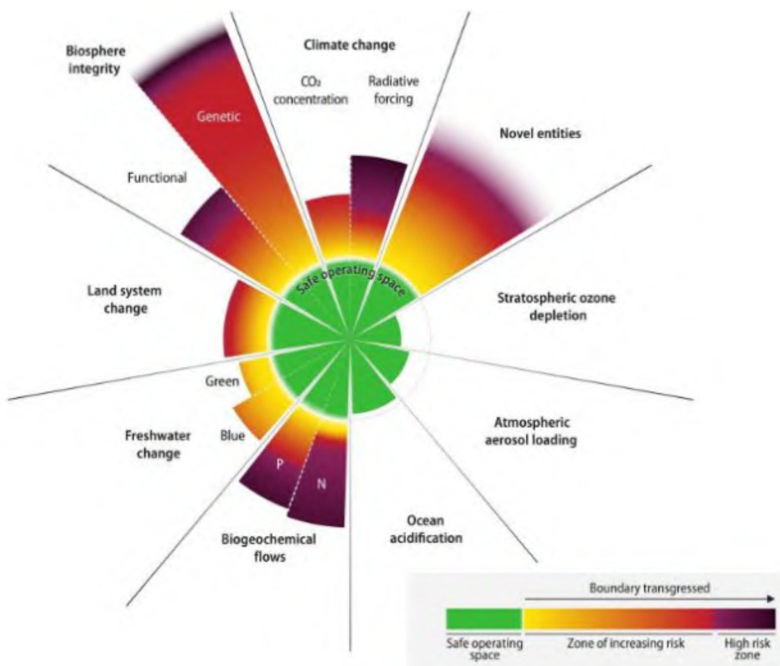

Figura 2. Estado actual de los nueve límites planetarios. Tomado de: Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. Science Advances, 9(37). https://doi.org/10.1126/SCIADV.ADH2458

Cruzar los límites planetarios aumenta el riesgo de generar cambios ambientales abruptos o irreversibles a gran escala. Los cambios drásticos no necesariamente ocurrirán de la noche a la mañana, pero en conjunto, los límites marcan un umbral crítico para aumentar los riesgos para las personas y los ecosistemas (Richardson et al., 2023b).

Los límites planetarios son procesos interrelacionados dentro del complejo sistema biofísico de la Tierra, por lo que un enfoque global en el cambio climático no es suficiente para una mayor sostenibilidad; sino que es necesario comprender la interacción de cada una de las fronteras planetarias (Biermann & Kim, 2020).

De esta forma, ante la inminente e imparable adopción masiva de tecnologías avanzadas a raíz de la cuarta revolución industrial (Industria 4.0), aunada a diversos otros factores que contribuyen al agotamiento de los recursos naturales, en la actualidad resulta de vital importancia el estudio de los patrones de uso de los recursos naturales. Lo cual constituye el primer paso en vías de la búsqueda hacia una sociedad sostenible y resiliente, como la promovida por la Sociedad 5.0. Permitiendo velar por las necesidades presentes sin poner en riesgo las de generaciones del futuro, asegurando la protección del medio ambiente, el desarrollo social y el crecimiento económico. Siendo de importancia considerar cumplir con las barreras planetarias, ya que la transgresión de estas podría resultar en consecuencias catastróficas para la humanidad (Rockström et al., 2009).

1.2. ANTECEDENTES

Los conceptos de Industria 4.0, Industria 5.0 y Sociedad 5.0 son en la actualidad ampliamente abordados en la literatura. Sin embargo, la mayoría de los estudios referentes a estos temas, se centran en investigaciones de tipo cualitativo. Los estudios de diversos autores han señalado las ventajas y problemáticas principales relacionadas con la cuarta revolución industrial.

No obstante, sobresale como principal desafío el impacto de la masiva adopción de tecnologías avanzadas, en el consumo de recursos valiosos. Kosolapova et al. (2021) fundamentan que la cuarta transformación industrial conlleva un cambio significativo en la forma de utilizar los recursos, afectando la implementación de un desarrollo sostenible, llevando a cabo un análisis para los recursos hídricos, proponiendo una metodología para evaluar la correlación entre el manejo de agua y los niveles de desarrollo industrial de ciertas regiones.

Por su parte, Bag et al. (2021) desarrollaron un modelo teórico que relaciona los recursos clave para la adopción de la Industria 4.0, y el efecto de esta en la producción sostenible y economía circular. Una búsqueda bibliográfica ha permitido identificar los recursos tangibles presentados en la **Tabla 1** como aquellos recursos principales que sufrirán consecuencias por la adopción de la cuarta revolución industrial, así como los problemas fundamentales relacionados con estos y la forma de mitigar dicho impacto.

Además de los recursos tangibles antes mencionados, se han detectado también otro tipo de recursos clave en la cuarta revolución industrial; como el capital humano, innovación tecnológica y la adaptabilidad a las tecnologías emergentes.

Sin embargo, diversos autores han identificado que las tecnologías de la cuarta revolución industrial orientadas estratégicamente hacia el desarrollo sostenible pueden permitir una transición hacia los esquemas de la Industria 5.0 y Sociedad 5.0, logrando la instauración de sociedades donde las herramientas tecnológicas sean empleadas para el bien común y no sólo para el beneficio de unos cuantos, velando a su vez por la preservación del medio ambiente.

Tabla 1. Recursos tangibles relacionados con la cuarta revolución industrial, problemáticas asociadas con el uso de los mismos y sus posibles soluciones.

Recurso	Uso	Problemática	Posible solución
Minerales: neodimio, disprosio, terbio litio, cobalto, tierras raras, cobre, aluminio y silicio.	Vital para aplicaciones de alta tecnología.	-Impacto ambiental de su creciente demanda. -Dependencias geopolíticas.	-Exploración de nuevos depósitos minerales en regiones geopolíticamente estables. -Mejorar su reciclaje y reutilización. -Innovaciones científicas de materiales.
Agua	Sistemas de enfriamiento de dispositivos, uso industrial.	Al tratarse de un recurso no renovable su uso inadecuado pone en riesgo su disponibilidad para las generaciones presentes y futuras.	-Irrigación inteligente. -Reciclado de aguas industriales. -Sistemas de captación de agua.
Energía eléctrica	Fuente de energía para sistemas tecnológicos.	En su mayoría la energía eléctrica es obtenida de combustibles fósiles, cuyo uso genera gases de efecto invernadero los cuales contribuyen al calentamiento global.	-Avances en la eficiencia y almacenamiento de fuentes de energía renovables.

Skobelev & Borovik (2017) describen las tecnologías modernas emergentes que se utilizan en las organizaciones donde trabajan los autores, identificando que la convergencia de estas tecnologías proporcionará la transición desde la Industria 4.0 hacia la Industria 5.0. De igual forma, (Pereira et al., 2020) reconocen que el uso estratégico de las tecnologías de la cuarta revolución industrial es clave para el establecimiento de una Sociedad 5.0, donde dichas tecnologías sean usadas a favor del ser humano, posicionando a este como el elemento de mayor importancia. En Japón, desde junio de 2016, se han adoptado estrategias como medida para lograr la transición a una sociedad sostenible y resiliente, los objetivos de dichas estrategias coinciden con los Objetivos de Desarrollo Sostenible (Fukuyama, 2018).

Por otro lado, Kasinathan et al. (2022a) efectuaron un estudio teórico proponiendo un escenario basado en la integración de la Industria 5.0 y la Sociedad 5.0 con la intención de constituir ciudades y pueblos inteligentes donde se permita un Desarrollo Sostenible, de acuerdo con los Objetivos de Desarrollo Sostenible (*Sustainable Development Goals*, SDGs) adoptados por la Organización de las Naciones Unidas (ONU). Llevando a cabo además un análisis FODA para evaluar el enfoque integrado propuesto para lograr la sostenibilidad.

Si bien existen diversos estudios teóricos relacionados con los procesos de transformación tecnológica y social contemporáneos, resulta evidente la necesidad de desarrollar estudios cuantitativos sobre los patrones de uso de los recursos naturales indispensables para tales transiciones, con el fin de identificar las vías más adecuadas hacia modelos de desarrollo resilientes y sostenibles.

Una de las tecnologías digitales fundamentales de la cuarta revolución industrial es el aprendizaje automático. La agrupación en clústeres (*clustering*) es una técnica de aprendizaje automático que organiza objetos similares en grupos o clústeres, con características similares; maximizando la similitud de los elementos de cada grupo, y reduciendo la similitud con otros grupos (Gratsos et al., 2023).

El algoritmo de agrupación en clústeres más utilizado y aplicado es *K*-means. Esta técnica clasifica los objetos en “k” clústeres y, mediante un proceso iterativo, los ubica en el centroide del clúster más cercano (Chong, 2021). Un método popular para determinar el número ideal de clústeres (parámetro k) es el método del codo. Este método se basa en el análisis de la suma de errores cuadrados de los elementos que conforman el clúster (*sum of squared errors*, SSE) (Sutomo et al., 2023).

Actualmente, la agrupación en clústeres se utiliza en una amplia gama de campos, como la biología, la medicina, la psicología, los negocios, la investigación de mercados, las ciencias sociales, la informática y la ingeniería. Algunas aplicaciones de la agrupación incluyen la segmentación de mercados, que se utiliza para clasificar documentos, la agrupación de genes y proteínas, el reconocimiento de patrones, el análisis de datos espaciales y muchas otras áreas (Aljarah et al., 2021).

El agrupamiento *K-means* se ha implementado para identificar patrones de uso ambiental, basándose en indicadores ambientales (Goodwin et al., 2024). Sin embargo, a lo largo de los años, ningún estudio ha implementado *K-means clustering* para la identificación de patrones de uso de recursos naturales a nivel global, a fin de servir como base hacia una sociedad sostenible y resiliente.

Por ello, la presente tesis de investigación hace uso de *K-means clustering,* permitiendo revelar las dinámicas de uso de los recursos naturales y las trayectorias de sostenibilidad. Lo cual facilita una comprensión más profunda de cómo las naciones abordan los desafíos ambientales a lo largo del tiempo y actúa como herramienta estratégica para la toma de decisiones orientadas al bienestar integral. Asimismo, permite identificar aquellas naciones que enfrentan situaciones críticas en materia de sostenibilidad, ofreciendo una perspectiva innovadora con utilidad en la formulación de políticas públicas, trascendiendo las metodologías tradicionales.

1.3. JUSTIFICACIÓN

El acelerado avance tecnológico y la creciente complejidad de los sistemas productivos han generado una profunda transformación en la forma en que las sociedades acceden, utilizan y gestionan sus recursos. Esta evolución, si bien ha traído consigo beneficios importantes en términos de eficiencia e innovación, también ha intensificado la presión sobre los recursos naturales, comprometiendo su disponibilidad y calidad para las generaciones futuras.

Frente a este escenario, se vuelve imperativo impulsar una transición estratégica hacia modelos de desarrollo sostenibles, integrales y centrados en el bienestar humano. No basta con adoptar soluciones aisladas; es necesario diseñar políticas y prácticas que consideren simultáneamente la resiliencia ambiental, la equidad social y la viabilidad económica.

Aunque esta problemática ha sido abordada en múltiples estudios desde una perspectiva teórica y cualitativa, persiste una carencia de análisis cuantitativos que permitan comprender con precisión los patrones de uso y agotamiento de los recursos naturales esenciales. Este vacío limita la capacidad de proponer rutas viables hacia un modelo de desarrollo que armonice el progreso tecnológico con los límites planetarios.

Por ello, el presente estudio busca identificar, mediante una evaluación rigurosa y basada en datos, los patrones de uso de recursos naturales clave (recursos energéticos, minerales, hídricos, etc.). Para de este modo, servir como base para el diseño de soluciones concretas que respondan a los desafíos ambientales actuales y promuevan un futuro más justo, resiliente y sustentable.

1.4. PLANTEAMIENTO DEL PROBLEMA

El problema que se aborda en esta investigación consiste en identificar la vía más adecuada hacia una sociedad resiliente y sostenible, a partir del análisis de los patrones de uso de los recursos naturales esenciales que sostienen los actuales procesos de transformación tecnológica y productiva. Si bien existe abundante literatura conceptual sobre los retos de la sostenibilidad, persiste la necesidad crítica de generar evidencia cuantitativa que permita comprender cómo las naciones utilizan estos recursos a lo largo del tiempo y cómo dichas dinámicas inciden en su capacidad para enfrentar los desafíos ambientales, económicos y sociales. En este contexto, el uso de técnicas de agrupamiento o *clustering* se propone como una herramienta analítica que, al revelar trayectorias comunes y divergentes entre países, pueda facilitar el diseño de estrategias y políticas informadas para una transición efectiva hacia modelos de desarrollo más equilibrados, equitativos y duraderos.

1.5. HIPÓTESIS

El uso de técnicas de *clustering* para el análisis de los patrones de uso de los recursos naturales esenciales permitirá identificar trayectorias diferenciadas de sostenibilidad entre naciones, constituyéndose como una herramienta estratégica para orientar la transición hacia un modelo de desarrollo resiliente y sostenible.

1.6. OBJETIVOS

1.6.1. Objetivo general

Identificar la vía más adecuada hacia un futuro resiliente y sostenible, mediante el uso de técnicas de *clustering* para el análisis de los patrones de uso de los recursos naturales esenciales en contextos de transformación tecnológica y productiva.

1.6.2. Objetivos particulares

- Analizar las principales problemáticas sociales y medioambientales vinculadas con los actuales procesos de cambio tecnológico y económico.
- Aplicar técnicas de *K-means clustering* (aprendizaje automático no supervisado) para evaluar indicadores ambientales globales relacionados con el uso de recursos naturales clave.
- Identificar patrones de consumo de recursos naturales a nivel global, así como aquellas naciones que presentan mayores desafíos en términos de sostenibilidad.
- Proponer acciones estratégicas orientadas a facilitar una transición efectiva hacia modelos de desarrollo más sostenibles y resilientes.

CAPÍTULO 2. MARCO TEÓRICO

2.1. GENERALIDADES

Los recursos naturales pueden definirse como los materiales naturales que son transformados y utilizados por los seres humanos y los ecosistemas. Esto incluye una gran cantidad de servicios ecosistémicos esenciales para la producción económica y el mantenimiento de la vida, como en el caso de la mitigación de inundaciones, el secuestro de carbono y la preservación de la biodiversidad (Dewulf et al., 2015).

Los recursos naturales pueden clasificarse según su tasa de regeneración, que distingue entre recursos de flujo (renovables) y recursos de reserva (no renovables). Los recursos de reserva son finitos y no pueden reponerse, ya que su erradicación reduce la disponibilidad futura. Existen dos tipos de recursos no renovables: los que pueden reciclarse tras su extracción del medio ambiente (p. ej., metales) y los que se producen para el consumo (p. ej., combustibles) (Schulze et al., 2020).

Los recursos de flujo, a menudo conocidos como renovables, tienen una alta capacidad regenerativa. Su clasificación se basa en su agotabilidad; el uso de recursos como la radiación solar, el viento o las olas no reduce su cantidad ni calidad, por lo que se consideran como recursos inagotables. Sin embargo, otros recursos de flujo, como la vida silvestre, las aguas subterráneas, los peces y el suelo, pueden agotarse si su consumo supera su capacidad de regeneración (Bridge & Wyeth, 2019). El agotamiento de los recursos ocurre cuando los recursos naturales se consumen a una velocidad mayor a la que pueden regenerarse (Raj, 2024).

En el último medio siglo, el volumen global de extracción de recursos naturales ha crecido a un ritmo nunca antes visto, propulsado por la expansión económica, las revoluciones industriales y las modificaciones en los patrones de consumo (Zhou & Gu, 2024). De acuerdo con el Panel Internacional de Recursos del Programa de Medioambiente de las Naciones Unidas (*United Nations Environment Programme's*

International Resource Panel), la extracción global de materiales se incrementó de 27 000 millones de toneladas en 1970 a 92 000 millones de toneladas en 2017. Las estimaciones más actualizadas señalan que la extracción llegó a cerca de 106 000 millones de toneladas en 2020 (Bruyninckx et al., 2024). Esta tendencia señala que la economía global incrementa su dependencia de los recursos naturales, pese al aumento de la sensibilización acerca de la degradación del medio ambiente y el cambio climático (Muthuswamy & K, 2023).

En 2019, se identificó que el impacto ambiental per cápita de los países de altos ingresos es más de 13 veces mayor que el de los países de bajos ingresos (Wiedmann et al., 2020). Esta distribución desigual del consumo de recursos está estrechamente vinculada a las asimetrías de poder global y a los patrones de comercio que externalizan los costos ambientales a las regiones menos industrializadas.

Simultáneamente, la evidencia científica indica que las actividades humanas están superando los umbrales ecológicos críticos. El marco de límites planetarios, desarrollado por Rockström et al. (2009), y actualizado por Steffen et al. (2015) y Richardson et al. (2023c), identifica nueve límites biofísicos dentro de los cuales la humanidad puede operar con seguridad. Según la evaluación más reciente, se han transgredido seis de estos límites, incluyendo los relacionados con el cambio climático, la integridad de la biosfera, los flujos bioquímicos de nitrógeno y fósforo, la alteración del sistema terrestre, la alteración del agua dulce y la liberación de nuevas sustancias, como productos químicos sintéticos y plásticos (Richardson et al., 2023a). Cada una de estas transgresiones está estrechamente vinculada a los patrones globales de extracción, procesamiento y consumo de recursos, lo que hace que el uso de recursos naturales sea una variable central para evitar encadenar a las sociedades a trayectorias insostenibles que ponen en peligro la integridad ecológica y el bienestar social.

Cabe destacar que, si bien la economía del siglo XX estuvo dominada por un conjunto relativamente limitado de materiales a granel, como el carbón, el hierro, el cemento y el petróleo, la economía del siglo XXI depende cada vez más de un espectro más amplio de metales y materiales compuestos, muchos de los cuales son cruciales para las tecnologías emergentes asociadas a la cuarta revolución industrial (Madhavi & Nuttall, 2019; Moskowitz, 2009). A su vez, la transición a sistemas de energía renovable e infraestructura digital ha generado un crecimiento exponencial de la demanda de materiales como el litio, el cobalto, el indio, las tierras raras y el silicio de alta pureza (Eerola et al., 2021). Estos materiales suelen tener baja sustituibilidad, son geológicamente escasos y/o están geopolíticamente concentrados, por lo que su extracción depende de circunstancias ambientales y sociales

Mientras la cuarta revolución industrial se centra en la eficiencia digital en la fabricación, la Industria 5.0 integra los aspectos humanos en estas tecnologías, buscando un diseño sostenible y resiliente. Este enfoque es crucial en la Sociedad 5.0, una sociedad sostenible y resiliente, donde el énfasis está en armonizar los avances tecnológicos con el uso sostenible de los recursos y el bienestar humano.

La meta de la Sociedad 5.0 es conciliar las tecnologías avanzadas, como la automatización y la digitalización, con las demandas humanas fundamentales, en particular para enfrentar los desafíos medioambientales y de gestión de recursos (Hall, 2019; Oztemel & Gursev, 2020; Shaddiq et al., 2023). Este modelo combina los avances tecnológicos con una perspectiva enfocada en el ser humano, con el objetivo de elevar la calidad de vida y promover un compromiso sustentable con el medio ambiente. Un elemento crucial de esta sociedad sostenible y resiliente, implica optimizar el uso de recursos y alinearse con los Objetivos de Desarrollo Sostenible (SDGs) de las Naciones Unidas, que buscan un equilibrio entre el desarrollo económico, preservación ecológica y bienestar social (Leng et al., 2022).

Se promueve la implementación de tecnologías avanzadas, no solo como herramientas para el progreso económico, sino como instrumentos para el equilibrio ecológico y el progreso social (Bibri et al., 2024). Este enfoque implica el desarrollo e implementación de tecnologías intrínsecamente sustentables, el fomento de economías circulares y el eficaz uso de los recursos.

Enfatizando la necesidad de repensar nuestra relación con los recursos naturales. Impulsa a ir más allá del modelo convencional de «tomar-hacer-desechar», impulsando una transición hacia un uso sostenible de los recursos que abarque el reciclaje, y el consumo responsable (Moraes et al., 2023; Sikder et al., 2023; Tiwari et al., 2021). Este cambio de paradigma busca minimizar los residuos, reducir el agotamiento de recursos no renovables y mitigar los impactos ambientales, alineando así los avances tecnológicos con los principios de sostenibilidad.

La implementación de estas estrategias, es de importancia para abordar algunos de los problemas más urgentes identificados en los SDGs, como la lucha contra el cambio climático, garantizar agua limpia y saneamiento, promover la industrialización sostenible y fomentar patrones de consumo y producción responsables (Kasinathan et al., 2022b; Mourtzis et al., 2022; Žižek et al., 2021). Se prevé que la integración de tecnologías avanzadas en la Sociedad 5.0 desempeñe un papel fundamental en este proceso, ofreciendo soluciones innovadoras para la gestión sostenible de los recursos. Estas soluciones abarcan desde la agricultura de precisión, que optimiza el uso del agua y los fertilizantes, hasta las redes inteligentes que mejoran la eficiencia energética, y desde las tecnologías de valorización energética de residuos hasta los materiales avanzados que reducen la huella ambiental (Abdallah & Elfeky, 2021).

2.2. MANEJO SOSTENIBLE DE RECURSOS

La gestión sostenible de los recursos naturales se vuelve crucial para el avance tecnológico y el bienestar social. La intersección de los fundamentos de una sociedad sostenible y resiliente, con la gestión de los recursos naturales, representa un área crítica de estudio y acción. La integración de tecnologías avanzadas, un enfoque centrado en el ser humano, la sostenibilidad, la resiliencia, la colaboración, la toma de decisiones basada en datos y el equilibrio entre los mundos cibernético y físico; impactan significativamente la forma de abordar la utilización y conservación de los recursos naturales (Yitmen et al., 2023). Esto implica desarrollar estrategias que no solo sean tecnológicamente eficientes, sino también sostenibles y equitativas desde una perspectiva social (Tavares et al., 2022). A continuación, se abordan algunos de los elementos claves para la migración hacia una sociedad sostenible y resiliente, así como su relación con el cuidado de los recursos naturales.

- *Uso de tecnologías avanzadas.* El uso de tecnologías avanzadas se convierte en una herramienta vital para la gestión eficiente de los recursos naturales. Estas tecnologías permiten un monitoreo más preciso y una mejor predicción del uso de recursos como el agua, la energía y los materiales, optimizando su uso y reduciendo el desperdicio (Nižetić et al., 2019). La **Tabla 2** ejemplifica aplicaciones tecnológicas para la mejora de la gestión de recursos naturales (Dou et al., 2023).
- *Sostenibilidad.* Desempeña un papel fundamental en el desarrollo de prácticas de gestión de recursos que no solo sean ambientalmente responsables, sino también económicamente viables a largo plazo. Fomentando la creación de sistemas y prácticas que equilibren la salud ecológica con la prosperidad económica.

  Incluyendo la promoción de economías circulares, un concepto transformador que aboga por la reutilización y el reciclaje de recursos, minimizando así significativamente la extracción y el consumo de recursos naturales no renovables (Marín-Beltrán et al., 2022). En estas economías circulares, los residuos se consideran no como basura, sino como recursos valiosos que pueden reintegrarse continuamente a los ciclos de producción, lo que conduce a una reducción sustancial del impacto ambiental. Este cambio hacia economías circulares, representa un paso crucial para lograr un futuro más sostenible donde la eficiencia de los recursos y la gestión ambiental sean primordiales.
- *Resiliencia y la adaptabilidad.* En un mundo donde los desafíos ambientales, como el cambio climático y la degradación de los ecosistemas, son cada vez más importantes, la capacidad de adaptarse y responder eficazmente a estos cambios es clave para garantizar la sostenibilidad de los recursos (Gann

et al., 2019). La resiliencia y la adaptabilidad no solo consisten en reaccionar a los cambios, sino también en diseñar proactivamente estrategias de gestión de recursos que puedan resistir las incertidumbres ambientales futuras.

- *Colaboración y toma de decisiones basada en análisis de datos.* La cooperación entre diferentes sectores y el uso de análisis de datos avanzados pueden conducir a soluciones más innovadoras y eficaces en la gestión de los recursos naturales (Al Nuaimi et al., 2015). Este enfoque colaborativo, que reúne a actores de diversos campos, como la tecnología, la ecología y las ciencias sociales, garantiza que las soluciones desarrolladas sean beneficiosas tanto para las comunidades como para el medio ambiente. Además, la integración del análisis de datos ayuda a evaluar con precisión las necesidades de recursos y los impactos ambientales, fomentando un paradigma de gestión de recursos más sostenible y eficiente.
- *Equilibrio entre el mundo cibernético y el mundo físico.* Permite una mayor armonización entre la tecnología y el entorno natural. Esto abre nuevas posibilidades para la gestión de recursos, donde las soluciones tecnológicas complementan y enriquecen las interacciones con el mundo natural (Buytaert et al., 2014).

Tabla 2. Uso de tecnologías avanzadas en la conservación de recursos naturales.

Área	Aplicaciones tecnológicas
Manejo energético	○ *Predicción de demanda energética*. Optimización de la producción y distribución energética, garantizando un suministro energético confiable y eficiente, minimizando el desperdicio energético. ○ *Optimización y control energético*. El control automático de sistemas de calefacción, refrigeración e iluminación, permite reducir el desperdicio de energía, promoviendo prácticas de consumo energético sostenible. ○ *Introducción de energías renovables*. El análisis de datos meteorológicos, el historial de generación de energía permite la integración eficaz de energías renovables en la red eléctrica, reduciendo la dependencia de los combustibles fósiles y promoviendo la transición hacia una infraestructura energética más ecológica y sostenible.
Sistemas de transporte inteligentes	○ *Predicción y gestión de tráfico*, pronóstico de patrones de tráfico y niveles de congestión en tiempo real. ○ *Optimización del transporte público*, planificación de rutas y horarios. Las medidas anteriormente mencionadas contribuyen a la mejora del flujo de tráfico, reduciendo el consumo de combustibles fósiles y el impacto ambiental, optimizando la eficiencia general del transporte.
Planeación y desarrollo urbano	Evaluación el impacto ambiental de los proyectos de desarrollo urbano, prediciendo el impacto mediante el análisis de los niveles de ruido, la calidad del aire, los recursos hídricos y la biodiversidad. Permitiendo la toma de decisiones informadas, garantizado prácticas de desarrollo sostenible y minimizando los efectos ambientales negativos.
Clasificación y reciclaje de residuos	Los sistemas de clasificación de residuos basados en ML mejoran las iniciativas de reciclaje, reducen los residuos en vertederos y promueven una economía circular.
Monitoreo de calidad ambiental	Análisis de datos de dispositivos de monitorización y sensores ambientales para evaluar la calidad del aire y agua, niveles de ruido y otros parámetros ambientales. A fin de detectar patrones, identificar fuentes de contaminación y predecir riesgos ambientales; facilitando la su detección temprana y permitiendo intervenciones adecuadas.

2.3. RECURSOS ESENCIALES PARA LA INSTAURACIÓN DE UNA SOCIEDAD SOSTENIBLE Y RESILIENTE

En la presente sección se presenta una visión del estado actual de recursos tangibles implicados en la instauración de una sociedad sostenible y resiliente basada en el concepto de la Sociedad 5.0.

2.2.1 RECURSOS ENERGÉTICOS

Diversas fuentes energéticas son empleadas en la actualidad para satisfacer la demanda de energía.

- **Energía solar.** Aprovechada principalmente a través de células fotovoltaicas, que dependen en gran medida del silicio purificado derivado del cuarzo común. El mercado mundial de paneles solares está ampliamente influenciado por países como China, Estados Unidos y Rusia, importantes proveedores de silicio (Mastoi et al., 2022).
- **Energía eólica.** Este tipo de energía, actor clave en el sector de las energías renovables, se basa en materiales como el acero (procedente del mineral de hierro) y el hormigón (procedente de la piedra caliza) para la construcción de turbinas y utiliza minerales raros como el neodimio para los imanes. Destacando China como un importante proveedor de estos elementos de tierras raras (Singh et al., 2022).
- **Combustibles fósiles.** Es innegable que los combustibles fósiles (carbón, petróleo y gas natural) aún tienen una influencia significativa en nuestra matriz energética global actual. Estimándose que más del 80 % del consumo energético mundial proviene de combustibles fósiles. Sin embargo, se observa una transición notable hacia energías más limpias, especialmente en los países más desarrollados (Pablo-Romero et al., 2022).
- **Energía nuclear.** Es una fuente energética importante con bajas emisiones de carbono. En 2021, se registraron alrededor de 440 reactores nucleares operando en todo el mundo, suministrando aproximadamente el 10 % de la electricidad mundial, según informó la Asociación Nuclear Mundial (Popov

et al., 2023). La energía nuclear es fundamental en las estrategias energéticas de muchos países, especialmente para aquellos que buscan reducir las emisiones de gases de efecto invernadero.

Carayannis et al. (2021) destacan la importancia de la energía de fusión nuclear en el contexto de la instauración de una sociedad sostenible y resiliente, especialmente con el avance del proyecto del Reactor Termonuclear Experimental Internacional (ITER) en 2020. Proponiendo una «Comisión Global de Acción Urgente sobre Energía de Fusión» para fomentar la colaboración internacional y acelerar la transición de los combustibles fósiles a una economía basada en la fusión, en consonancia con los objetivos de una energía sostenible.

- **Biocombustibles.** Los biocombustibles (elaborados a partir de desechos vegetales y animales) se están convirtiendo en una parte cada vez más vital del sector de las energías renovables. La Agencia Internacional de Energía (International Energy Agency, IEA) señala que la producción de biocombustibles ha experimentado un aumento constante, impulsada en gran medida por políticas que promueven combustibles sostenibles para el transporte (Allegretti et al., 2023)
- **Hidrógeno.** Un actor emergente en el panorama energético es el hidrógeno, a menudo considerado como el combustible del futuro. Con un mercado mundial del hidrógeno valorado en aproximadamente 150 000 millones de dólares en 2021 y proyectado a alcanzar los 2,5 billones de dólares para 2050, el hidrógeno tiene el potencial de revolucionar el sector energético (Pathak et al., 2023). Su capacidad para almacenar y suministrar energía de forma utilizable sin emisiones directas lo convierte en un candidato prometedor para un futuro de energía limpia. La investigación y la inversión en tecnologías de hidrógeno se están intensificando, como lo demuestra el aumento significativo de proyectos de hidrógeno verde en todo el mundo, que se espera alcancen una capacidad de producción de 50 millones de toneladas al año (Ayodele & Munda, 2019). Esta tendencia indica su posible papel fundamental para satisfacer las demandas energéticas requeridas para

nuevas tecnologías digitales, adaptándose a diversas aplicaciones, desde el transporte hasta la generación de energía industrial.

De esta forma, destaca la naturaleza multifacética de la transición energética, que, si bien protege el medio ambiente, también conlleva desafíos económicos, sociales y técnicos. Abordar estos desafíos requiere el esfuerzo colectivo de empresas, consumidores, inversores e instituciones educativas para impulsar un cambio de mentalidad y comportamiento hacia la sostenibilidad.

2.2.2. RECURSOS MINERALES

El progreso tecnológico se basa en una variedad de minerales esenciales, cada uno de ellos juega un rol singular en la creación de infraestructura de alta tecnología.

- ***Litio.*** Es un factor clave en el sector de las baterías. Su historia está intrínsecamente ligada al auge de los vehículos eléctricos y los sistemas de almacenamiento de energías renovables. Se estima que las reservas mundiales de litio rondan los 22 millones de toneladas métricas. Junto con Australia, Chile y China se convirtieron en los otros países líderes en producción de litio en el mundo, liderando colectivamente el suministro para satisfacer la creciente demanda mundial de litio (Kundu et al., 2023). Esta cifra refleja la acelerada transición mundial hacia soluciones energéticas sostenibles.
- ***Cobalto.*** Procede principalmente de la República Democrática del Congo, que produjo aproximadamente 95.000 toneladas métricas en 2021, por lo que presenta una historia de desafíos éticos (Tae, 2021). Este mineral es indispensable para la fabricación de baterías de alta densidad, pero su obtención suele generar inquietudes sobre el abastecimiento responsable y el impacto en las comunidades locales.
- ***Elementos de tierras raras.*** China domina la producción de elementos de tierras raras, produciendo alrededor de 168.000 toneladas métricas en 2021, estos elementos son indispensables en diversas tecnologías, desde teléfonos inteligentes hasta vehículos eléctricos (Van Gosen et al., 2022). La

sólida posición de China en el sector de los elementos de tierras raras no solo subraya su importancia global, sino que también pone de relieve la necesidad estratégica de diversificar las cadenas de suministro.

- ***Cobre.*** Este elemento conocido por su excelente conductividad, es esencial en una gran variedad de aplicaciones, desde el cableado eléctrico hasta los sistemas de energía renovable. Chile es el mayor productor de cobre con una producción de 5,7 millones de toneladas métricas en 2020, desempeñando un papel crucial (Cruz et al., 2022). Perú se encuentra en segundo lugar, aportando una importante contribución a la producción mundial de cobre.
- ***Aluminio****.* El aluminio, famoso por su ligereza y resistencia a la corrosión, es vital en industrias que abarcan desde el transporte hasta la construcción. En 2025, China consolidó su liderazgo en la producción mundial de aluminio, con una producción de 40 millones de toneladas métricas (Dai et al., 2019). Esta considerable cifra destaca el papel crucial de China en el mercado del aluminio.
- ***Silicio.*** Destaca como como base fundamental de la industria de los semiconductores, su producción es crucial para el mundo tecnológico. En 2022, la producción mundial de silicio industrial alcanzó los 7,783 millones de toneladas, una cifra que también indica la cantidad de residuos sólidos que contienen silicio generados en cada etapa del proceso de producción (Yu et al., 2023). Esta cifra no solo se refiere a la cantidad, sino a la importancia central del silicio en la era digital.

Cada uno de estos minerales (litio, cobalto, tierras raras, cobre, aluminio y silicio) son fundamentales en la instauración de la Sociedad 5.0, desempeñando un papel fundamental en todos los aspectos, desde el almacenamiento de energía hasta los dispositivos digitales.

2.2.3. RECURSOS HÍDRICOS

El agua, no solo es indispensable para el sustento de la vida, sino también es un recurso crucial para aplicaciones industriales. El agua dulce, proveniente principalmente de acuíferos y cuencas fluviales, se encuentra bajo una presión creciente debido a factores como el cambio climático y el consumo excesivo.

Esta situación requiere soluciones innovadoras para la gestión del agua. La desalinización, es una tecnología clave particularmente en Oriente Medio, la cual ha experimentado un aumento significativo. Actualmente, existen alrededor de 21.123 plantas de desalinización operativas a nivel mundial, que atienden las necesidades diarias de agua de más de 300 millones de personas en todo el mundo (Alawad et al., 2023)

Por su parte, el reciclaje del agua es de importancia fundamental para abordar la escasez de agua. En países como Israel, el reciclaje del agua contribuye a más del 85% del uso de agua para la agricultura, lo que demuestra su potencial en la gestión sostenible del agua (Shoushtarian & Negahban-Azar, 2020). Además, las técnicas avanzadas de riego están ganando terreno en la agricultura, un sector responsable de aproximadamente el 70% de las extracciones mundiales de agua dulce. Técnicas como el riego por goteo, que puede aumentar la eficiencia hídrica hasta en un 90 %, y la agricultura de precisión se están convirtiendo en herramientas esenciales para la agricultura sostenible (Bwambale et al., 2022).

El papel integral del agua se extiende más allá de la agricultura, adentrándose en los ámbitos de la producción de energía y los procesos industriales. El agua es un elemento clave en la generación de energía hidroeléctrica, una fuente de energía limpia y renovable. En las industrias, el agua se utiliza ampliamente para refrigeración y procesamiento, lo que destaca su carácter indispensable en diversos sectores manufactureros. Además, el concepto de ciudades inteligentes en el uso del agua se perfila como un avance crucial. Estas ciudades integran el uso eficiente del agua en su diseño e infraestructura urbana, abordando los desafíos hídricos específicos de los entornos urbanos (Ramírez-Márquez et al., 2024).

Este enfoque integral de la gestión del agua, que abarca las zonas rurales con sus necesidades agrícolas y los entornos urbanos con sus requisitos específicos, es vital para un futuro hídrico sostenible. La estrategia implica no solo conservar el agua, sino también optimizar su uso en diferentes sectores. Esto incluye la adopción de tecnologías de eficiencia hídrica en hogares e industrias, así como la promoción de políticas que fomenten la conservación y el uso sostenible del agua.

A medida que la población mundial sigue creciendo y los impactos del cambio climático se acentúan, la necesidad de estrategias eficaces de gestión del agua se vuelve cada vez más crucial. No solo es tener suficiente agua, sino garantizar que esta sea utilizada de la manera más eficiente y sostenible posible. Lo cual implica equilibrar las necesidades hídricas de las comunidades, las industrias y los ecosistemas de manera que se logre el bienestar del planeta y de sus habitantes. Se trata de crear un sistema cohesivo que gestione los recursos hídricos mundiales de forma eficaz y sostenible, satisfaciendo las necesidades actuales sin comprometer la capacidad de las generaciones futuras para satisfacer las suyas (Poláková et al., 2023).

CAPÍTULO 3. METODOLOGÍA

3.1. GENERALIDADES

Cruzar los límites planetarios aumenta el riesgo de generar cambios ambientales abruptos o irreversibles a gran escala. Los cambios drásticos no necesariamente ocurrirán de la noche a la mañana, pero en conjunto, los límites marcan un umbral crítico de los riesgos para las personas y los ecosistemas (Richardson et al., 2023b).

Los límites planetarios son procesos interrelacionados dentro del complejo sistema biofísico de la Tierra, por lo que un enfoque global en el cambio climático no es suficiente para una mayor sostenibilidad; sino que es necesario comprender la interacción de cada una de las fronteras planetarias (Biermann & Kim, 2020).

El *Sustainable Consumption and Production Hotspots Analysis Tool* (SCP-HAT) evalúa 12 indicadores medioambientales estrechamente relacionados con límites planetarios anteriormente mencionados y los recursos involucrados en la cuarta revolución industrial. Dichos indicadores son presentados en la **Tabla 3** (The International Resource Panel, 2024).

El aprendizaje automático es una subrama de la AI, la cual predice resultados con precisión a través del aprendizaje estadístico. Haciendo uso de datos históricos para entrenar el sistema y mejorar la precisión de las predicciones (Monostori et al., 1996).

A su vez, los métodos de *clustering* son técnicas de aprendizaje automático no supervisadas que dividen un conjunto de datos en clústeres (grupos), los elementos de cada grupo son similares entre sí, pero diferentes de los elementos del otro grupo (Quiñones-Grueiro et al., 2019).

Tabla 3. Indicadores medioambientales de SCP-HAT.

Indicadores medioambientales	Descripción	Unidades	
		Total	**Per cápita**
Uso de materiales	Uso de materiales renovables, p.ej. agricultura, silvicultura; y materiales no renovables, p.ej. combustibles fósiles, metales y minerales.	million tonnes	million tonnes/capita
Uso de la tierra (suelo)	Seis tipos de uso de tierra: cultivos anuales, cultivos permanentes, pastos, silvicultura extensiva, silvicultura intensiva, zonas urbanas.	million ha	million ha/capita
Consumo de agua azul	Consumo total anual de agua azul, p.ej. agua procedente de cuerpos de agua subterráneos o de fuentes de agua superficiales como ríos o lagos.	million m^3 H_2O	million m^3 H_2O/capita
Uso de energía primaria	Aprovechamiento de energía primaria procedente de diferentes portadores de energía, p.ej. carbón y energía nuclear.	PJ	PJ/capita
Agotamiento de combustibles fósiles	Compara la tasa anual de extracción de combustibles fósiles con las reservas geológicas de combustibles fósiles.	million tonnes Oil eq.	million tonnes Oil eq./capita
Potencial pérdida de especies por uso de tierra	Impacto de los procesos de producción de uso de tierra en la biodiversidad.	micro-PDF*year	micro-PDF*year/capita
Cambio climático (Corto plazo)	Tasa de cambio de la temperatura, expresada en Potencial de Calentamiento Global a un horizonte de 100 años (GWP100).	million tonnes CO^2 eq.	million tonnes CO^2 eq./capita
Cambio climático (Largo Plazo)	Aumento de temperatura a largo plazo, expresado en Potencial de Cambio de Temperatura Global para un horizonte de 100 años (GTP100).	million tonnes CO^2 eq.	million tonnes CO^2 eq./capita

Contaminación del aire (salud humana)	Daños a la salud humana por respiración de partículas, expresada en años de vida ajustados en función de la discapacidad (Disability-Adjusted Life Years, DALY).	kilo-DALY	kilo-DALY/capita
Agotamiento de minerales	Compara la tasa anual de extracción de una materia prima con las reservas geológicas de recursos minerales.	million tonnes Cu eq.	million tonnes Cu eq./capita
Escasez de agua	Agua disponible (por área) en un cuenca después de que se haya satisfecho la demanda de los seres humanos y los ecosistemas acuáticos. Cuanta menos agua, mayor es el riesgo de estrés hídrico.	million m_3 H^2O eq.	million m^3 H_2O eq./capita
Eutrofización marina	Impactos de la escorrentía de nitrógeno procedente de la contaminación del aire y la lixiviación o escorrentía de los sistemas agrícolas hacia los ríos.	kt N-eq.	kt N-eq./capita

K-means es un algoritmo que clasifica conjuntos de datos con "n" puntos de datos en "K" grupos o clústeres, agrupando los datos según el punto central del clúster (centroide) más cercano a los datos (Mohseni-Dargah et al., 2022). Este algoritmo agrupa datos minimizando la similitud de datos entre grupos y maximizando la similitud de datos dentro de los grupos. El algoritmo *K-means* consta de los siguientes pasos (Wahyu Pribadi et al., 2022):

1. Se selecciona el número de grupos a formar (valor K).
2. Se elige un valor aleatorio para el centro del grupo original de K centroides, para determinar la distancia entre cada punto de datos de entrada y cada centroide.
3. Se calcula la distancia euclidiana de cada dato a cada centroide.
4. Cada dato se asigna al centroide más cercano.

5. Se determina la posición del nuevo centroide calculando el valor medio de todas las muestras asignadas a cada centroide anterior.
6. Se repite el paso 3 si la posición del nuevo centroide y del anterior es diferente o si los datos cambian de un grupo a otro.

De esta forma, la aplicación de técnicas de análisis de datos, como *K-means clustering* resulta de vital ayuda para el análisis de los indicadores medioambientales presentados en la **Tabla 3**, a fin de identificar los patrones de consumo a través del tiempo y sirviendo como herramienta estratégica para la toma de decisiones orientadas a la instauración de una sociedad sostenible y resiliente

3.2. K-MEANS CLUSTERING

La aplicación de *K-means clustering* inicia con la recopilación de datos, 12 indicadores medioambientales diferentes (**Tabla 3**) del *Sustainable Consumption and Production Hotspots Analysis Tool* (SCP-HAT) son recopilados, para 68 países representativos a nivel global cada cinco años desde 1990 hasta 2022 (The International Resource Panel, 2024). En algunos casos, los valores faltantes del indicador se reemplazan con el promedio del indicador para el año correspondiente.

Se consideran dos enfoques diferentes para los indicadores medioambientales: producción nacional (*domestic production*) y huella de consumo (*consumption footprint*). Además, se analizan los valores totales y per cápita de cada uno de los indicadores.

En la segunda etapa, los datos se normalizan utilizando la normalización *StandardScaler* del paquete de preprocesamiento *scikit-learn*. Para una muestra x, la puntuación estándar se calcula como (scikit-learn developers, 2024):

$$z = \frac{x - u}{s}$$

Donde:

$x = muestra\ de\ entrenamiento$

$u = media\ de\ las\ muestras\ de\ entrenamiento$

$s = desviación\ estándar\ de\ las\ muestras\ de\ entrenamiento$

Para la optimización de K-clúster, el número óptimo de clústeres para cada conjunto de datos (cada año) se encuentra mediante el método del codo. El algoritmo *K-means* se utiliza para agrupar los puntos de datos una vez que se ha determinado el número ideal de grupos. Finalmente se concluye con el análisis e interpretación de los resultados del *clustering*. La **Figura 4**, presenta cada uno de los pasos de la metodología seguida para el desarrollo de la presente tesis de investigación.

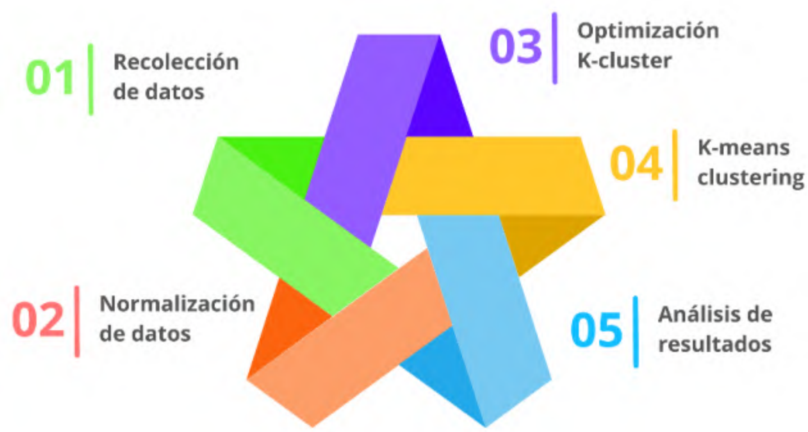

Figura 3. Metodología para la aplicación de *clustering*.

El método del "codo" ayuda a seleccionar el número óptimo de clústeres (K), ajustando el modelo a un rango de valores para "K". El punto de inflexión en la curva corresponde a la representación gráfica del grado de distorsión (*distortion score*) vs. K, el cual indica el mejor ajuste del modelo. en dicho punto (scikit-learn developers, 2024).

En este caso, los conjuntos de datos se ajustan mejor a K=4. Para efectuar un análisis comparativo, es necesario elegir el mismo número de clústeres (K) para todos los clústeres analizados.

Cada uno de los grupos de los conjuntos de datos se clasificó según cuatro colores diferentes, verde, azul, amarillo y rojo. Los valores promedio de los indicadores de cada grupo se normalizan de la siguiente manera:

$$x_i^N = \frac{x_i}{x_{imax}} \ \forall i$$

$i = indicador\ medioambiental\ i$

$x_i^N = valor\ promedio\ normalizado\ del\ indicador\ i$

$x_i = valor\ promedio\ real\ del\ indicador\ i$

$x_{imax} = valor\ máximo\ del\ indicador\ i$

Los valores normalizados se utilizan para crear mapas de radar para comparar los clústeres de cada año.

4. RESULTADOS Y DISCUSIÓN

En seguida se presentan los resultados obtenidos de la aplicación de *K-means clustering* para los 68 países considerados, en base a los indicadores medioambientales del SCP-HAT.

4.1. HUELLA DE CONSUMO

Bajo el enfoque de huella de consumo (*consumption footprint*), se consideran la presión e impacto ambientales para la nación donde se lleva a cabo el consumo final de productos y servicios. Examinando todos los aspectos de la cadena de suministro del producto, incluidas las operaciones internacionales. Por ejemplo, este enfoque considera el uso de la tierra fuera de las fronteras nacionales para la producción de alimentos de consumo interno (The International Resource Panel, 2024).

4.1.1. Huella de consumo per cápita

En las **Figuras 4** y **5,** la clasificación de clúster del enfoque de huella de consumo per cápita revela que:

a) Los clústeres clasificados como rojos tienen el impacto más alto en uso de energía primaria, agotamiento de combustibles fósiles, agotamiento de minerales, cambio climático (a largo plazo) y contaminación del aire. Para los casos de 2010 y 2015 (**Figura 5**), los conglomerados rojos presentan los valores más altos para la mayoría de los indicadores.

b) La mayoría de los clústeres amarillos se caracterizan por tener el impacto más significativo en el uso de tierra, pérdida potencial de especies por uso de la tierra y eutrofización marina.

c) Los clústeres azules tienen el mayor impacto en consumo de agua azul y escasez de agua. Sin embargo, para 2020 y 2022 se identifica una reducción en el consumo de agua azul (**Figura 5-g, h**).

d) La mayoría de los clústeres clasificados como verdes presentan los valores más bajos de los indicadores analizados. Sin embargo, algunos grupos verdes tienen un potencial significativo de pérdida de especies debido al uso de tierra.

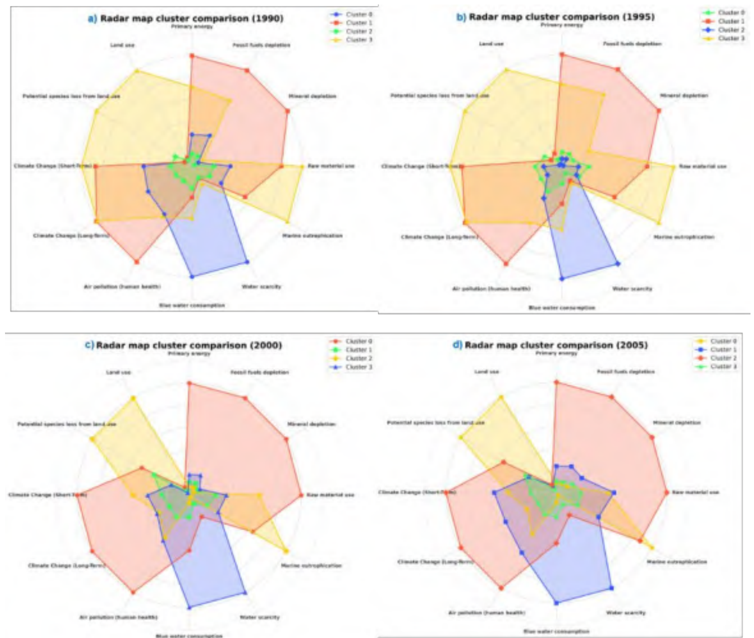

Figura 4. Gráfico de radar de la comparación de los valores promedio de los indicadores de cada clúster (1990-2005).

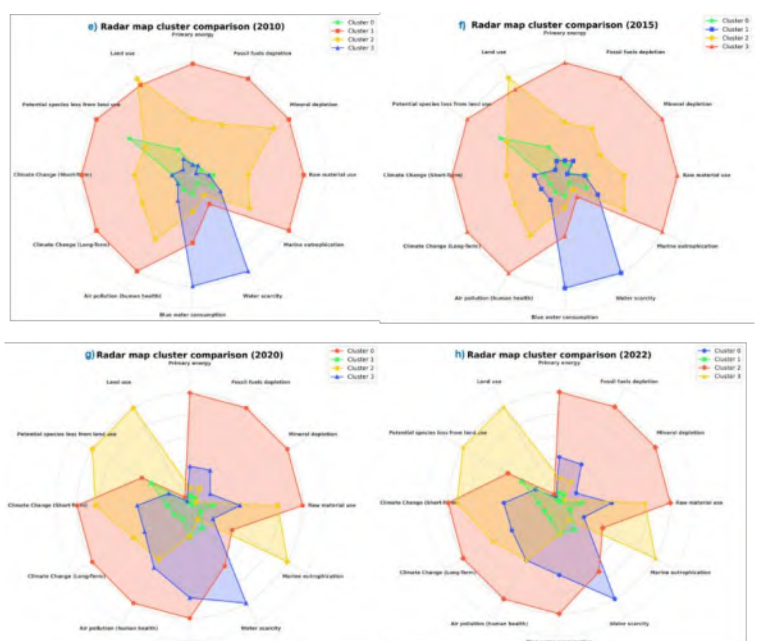

Figura 5. Gráfico de radar de la comparación de los valores promedio de los indicadores de cada clúster (2010-2022).

Desde una perspectiva per cápita, los Estados Unidos de América (USA), Canadá, Rusia, varias naciones europeas y Australia suelen estar incluidos en los clústeres rojos y amarillos, como se muestra en las **Figuras 6** y **7**. Por su parte, la mayoría de los países africanos y de América del Sur incorporan clústeres verdes.

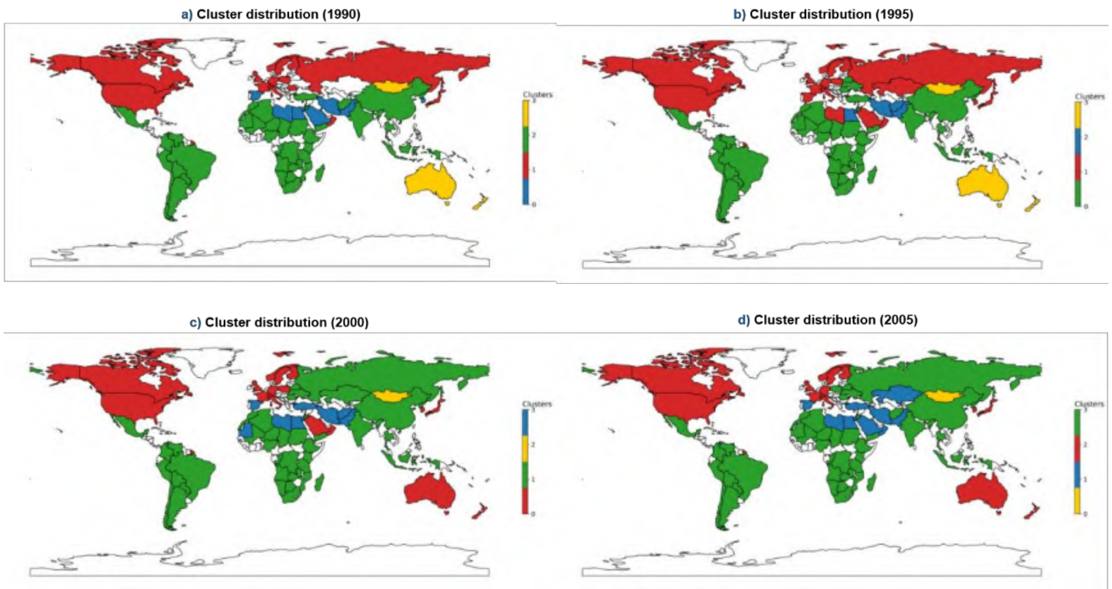

Figura 6. Distribución de clústeres (1990-2005).

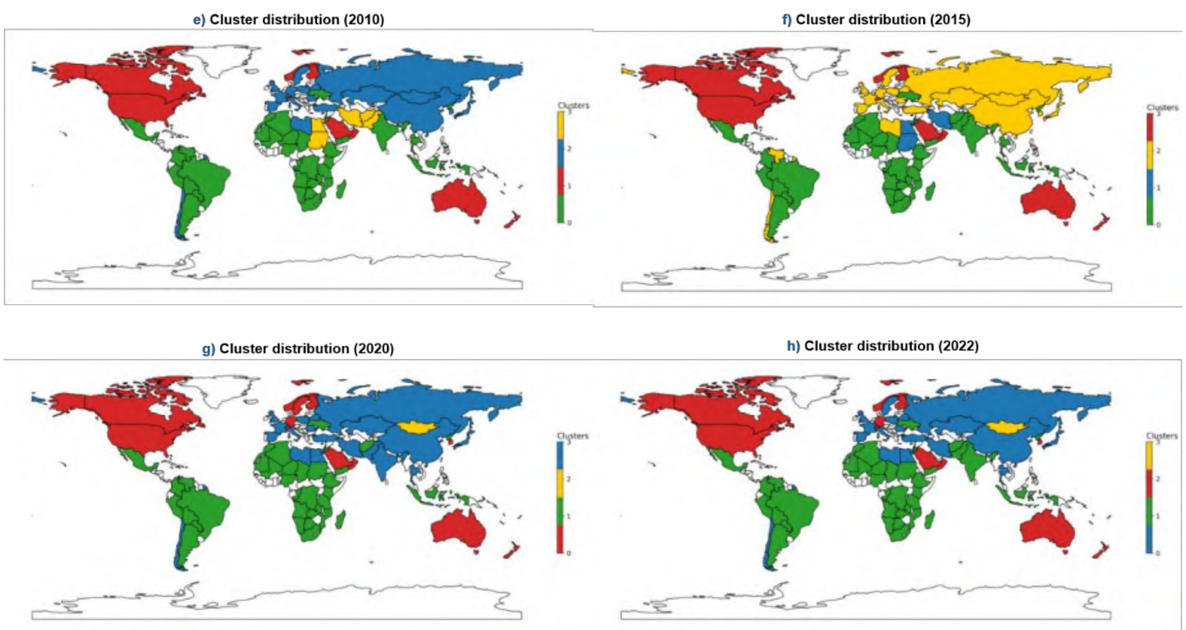

Figura 7. Distribución de clústeres (2010-2022).

4.1.2. Huella de consumo total

De acuerdo con las **Figuras 8** y **9**, la clasificación de clústeres para el enfoque de huella de consumo total muestra que:

- **a)** Los clústeres clasificados en rojo tienen el mayor impacto en el agotamiento de los combustibles fósiles y el uso de energía primaria. Excepto en el caso de 2010 (**Figura 9-g**), los clústeres rojos muestran también los valores más altos para la mayoría del resto de los indicadores.
- **b)** La mayoría de los clústeres amarillos se caracterizan por tener el impacto más significativo en la contaminación del aire, consumo de agua azul y escasez de agua.
- **c)** Los clústeres azules tienen un impacto ambiental moderado para la mayoría de los indicadores, excepto en el caso de 2010 (**Figura 9-g**).
- **d)** En todos los casos los clústeres clasificados como verdes tienen los valores más bajos para los 12 indicadores analizados.

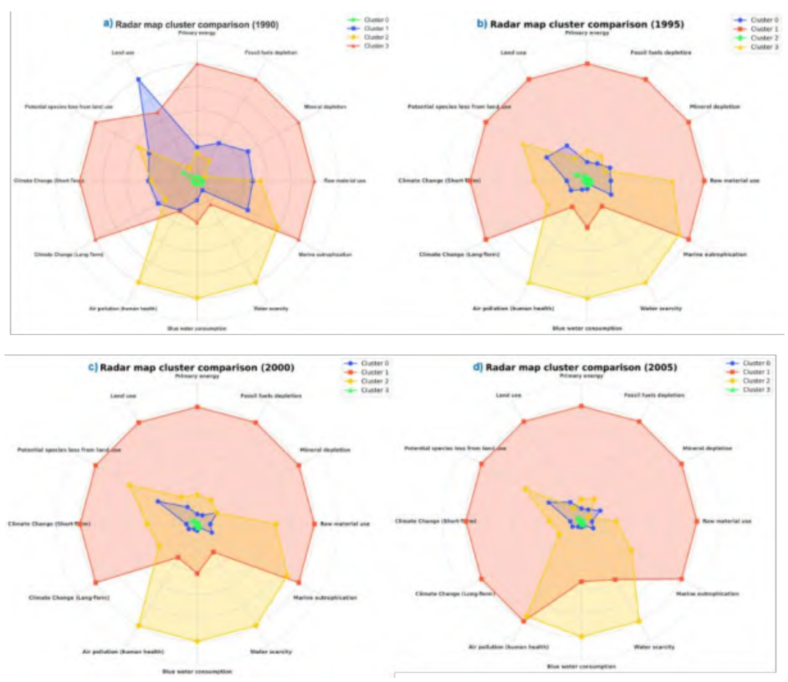

Figura 8. Gráfico de radar de la comparación de los valores promedio de los indicadores de cada clúster (1990-2005).

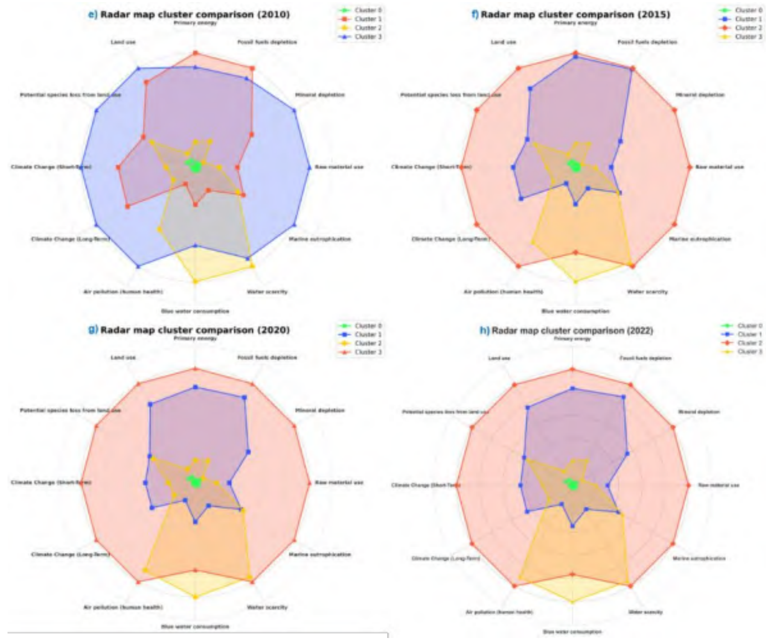

Figura 9. Gráfico de radar de la comparación de los valores promedio de los indicadores de cada clúster (2010-2022).

Con base en las **Figuras 10** y **11**, se puede identificar que, desde un enfoque total USA, China e India suelen formar parte de los clústeres rojos y amarillos. La mayoría de los países sudamericanos y africanos integran clústeres verdes, sólo unos pocos países participan en clústeres azules.

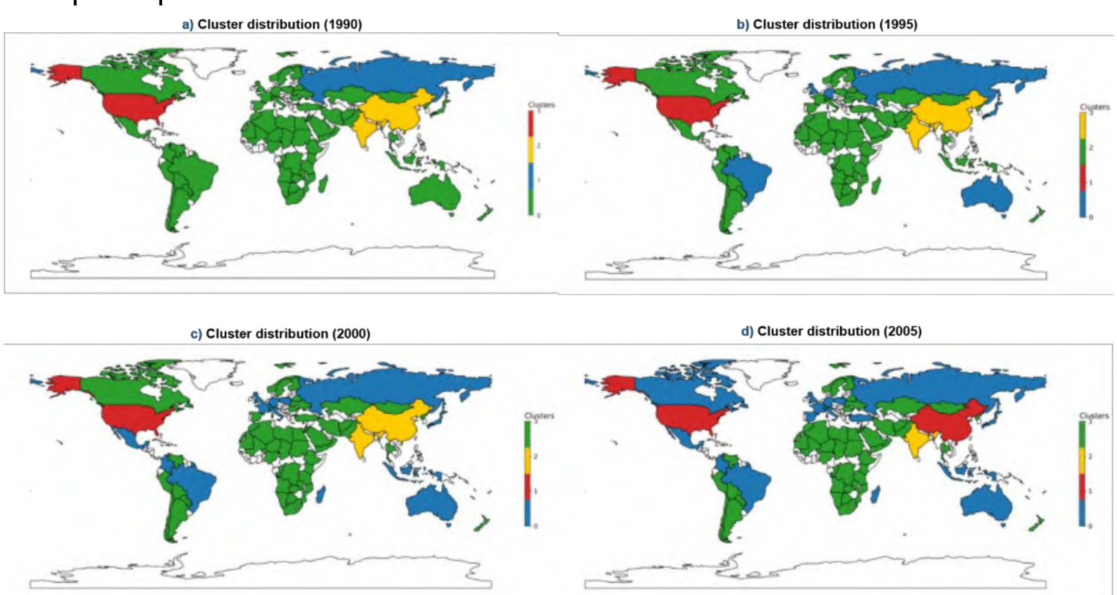

Figura 10. Distribución de clústeres (1990-2005).

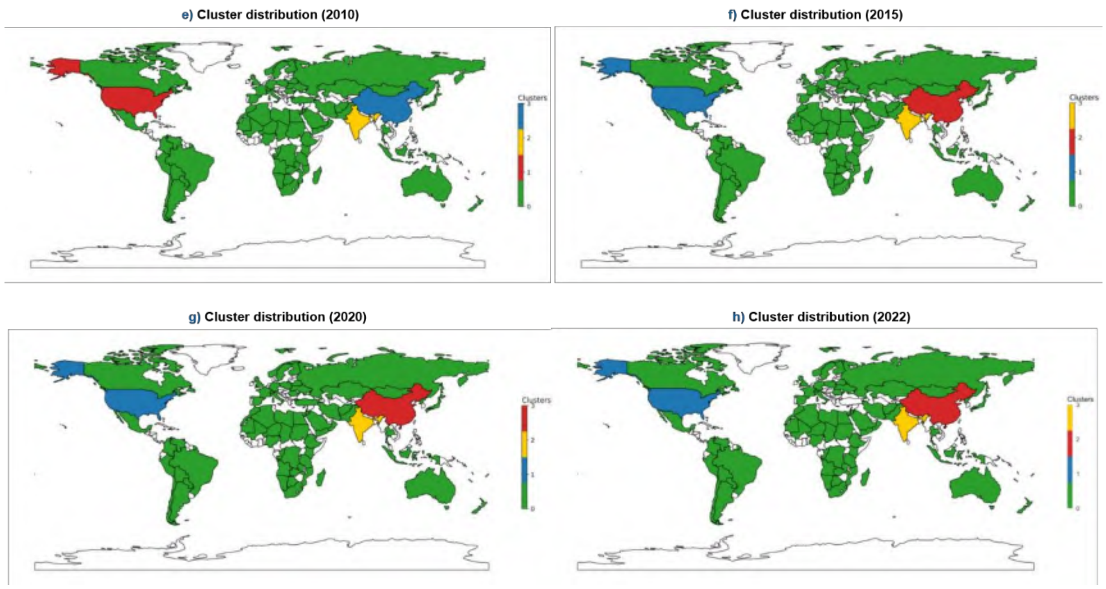

Figura 11. Distribución de clústeres (2010-2022).

4.2. PRODUCCIÓN NACIONAL

Desde la perspectiva de la producción nacional, las presiones y repercusiones medioambientales son atribuidas a la nación donde se presentan físicamente. Por ejemplo, la cantidad de materias primas cosechadas o las emisiones de gases de efecto invernadero generadas en el sector interno (The International Resource Panel, 2024).

4.2.1. Producción nacional per cápita

En las **Figuras 12** y **13**, la clasificación por clústeres desde el enfoque de producción nacional per cápita revela que:

- **a)** La mayoría de los clústeres clasificados como rojos tienen el mayor impacto en el uso de energía primaria, agotamiento de los combustibles fósiles, cambio climático (a largo plazo) y contaminación del aire.
- **b)** Los clústeres amarillos se caracterizan por tener el impacto más significativo en el uso de tierra, posible pérdida de especies por el uso de la tierra, cambio climático (a corto plazo), uso de materias primas y eutrofización marina.

c) Los clústeres azules para 1990 y 1995 (**Figura 12-a, b**) tienen un impacto significativo en la contaminación del aire; mientras que para 1995, 2000, 2015, 2020 y 2022, hay un importante agotamiento de minerales. En el caso de 2010 y 2015 (**Figura 13-e, f**), es relevante el consumo de agua azul y la escasez de agua.

d) Los clústeres verdes para 1990 y 1995 (**Figura 12-a, b**) tienen un impacto relevante en la escasez de agua.

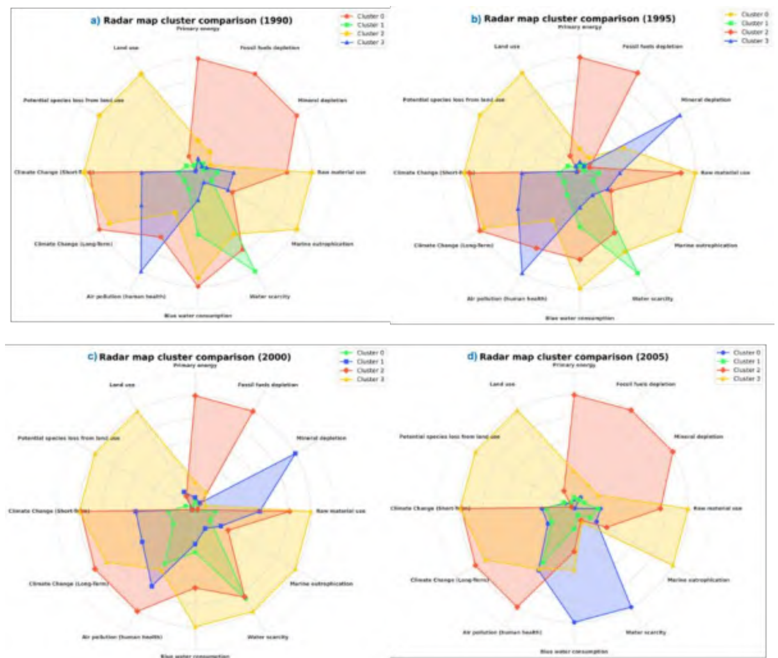

Figura 12. Gráfico de radar de la comparación de los valores promedio de los indicadores de cada clúster (1990-2005).

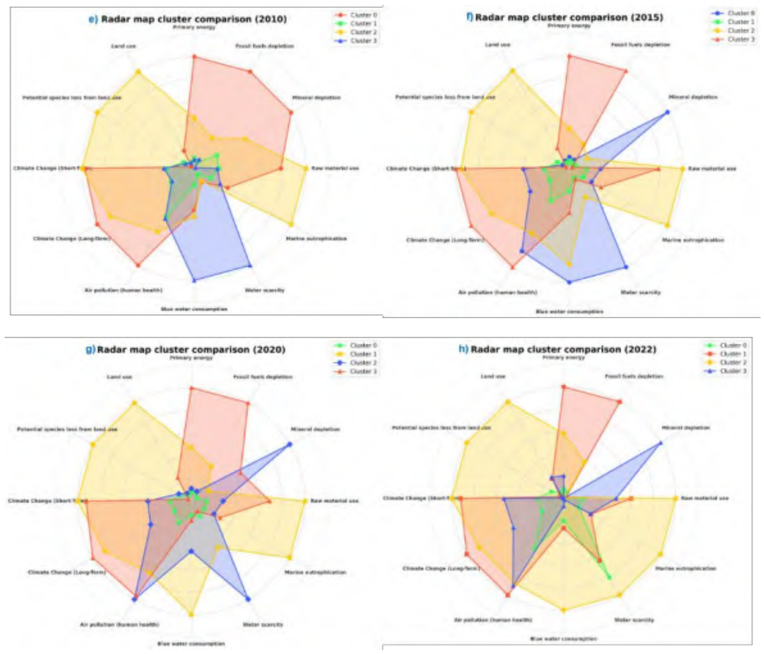

Figura 13. Gráfico de radar de la comparación de los valores promedio de los indicadores de cada clúster (2010-2022).

Las **Figuras 14** y **15** muestran que USA, Canadá, Rusia, Libia, Arabia Saudita y Omán suelen formar parte de los clústeres rojos. El clúster amarillo está integrado en todos los casos por Mongolia y Australia. Los países sudamericanos y africanos integran clústeres verdes.

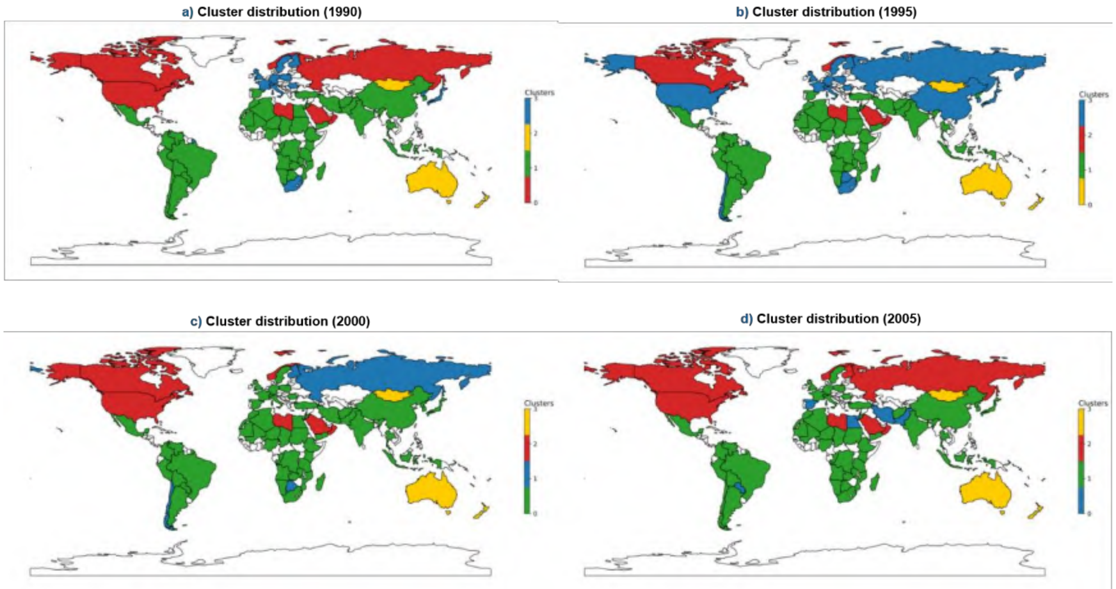

Figura 14. Distribución de clústeres (1990-2005).

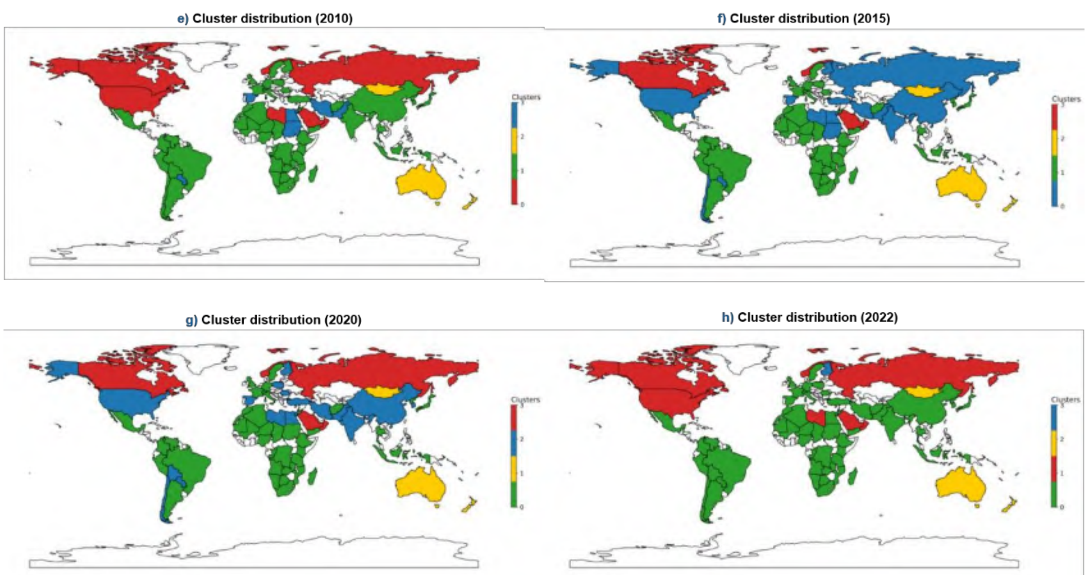

Figura 15. Distribución de clústeres (2010-2022).

4.2.2. Producción nacional total

Según las **Figuras 16** y **17**, la clasificación de clústeres para el enfoque de producción nacional total se identifica que: Los clústeres clasificados en rojo muestran un mayor impacto en la mayoría de los indicadores analizados.

a) La mayoría de los clústeres amarillos se caracterizan por tener el impacto más significativo en la contaminación del aire, consumo de agua azul y escasez de agua.

b) Los clústeres azules suelen mostrar un impacto relevante en el uso de tierra, agotamiento de combustibles fósiles y agotamiento de minerales.

c) En todos los casos, los clústeres clasificados como verdes tienen los valores más bajos para los 12 indicadores analizados.

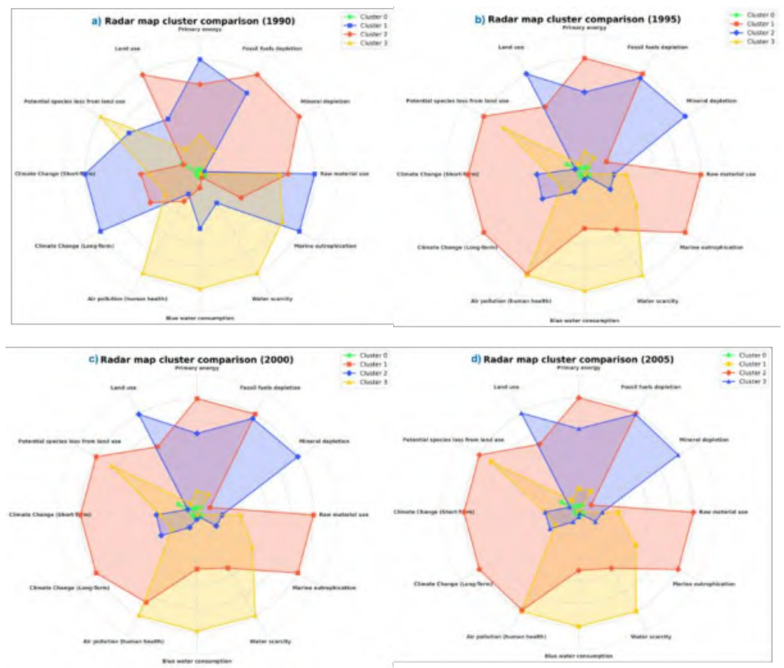

Figura 16. Gráfico de radar de la comparación de los valores promedio de los indicadores de cada clúster (1990-2005).

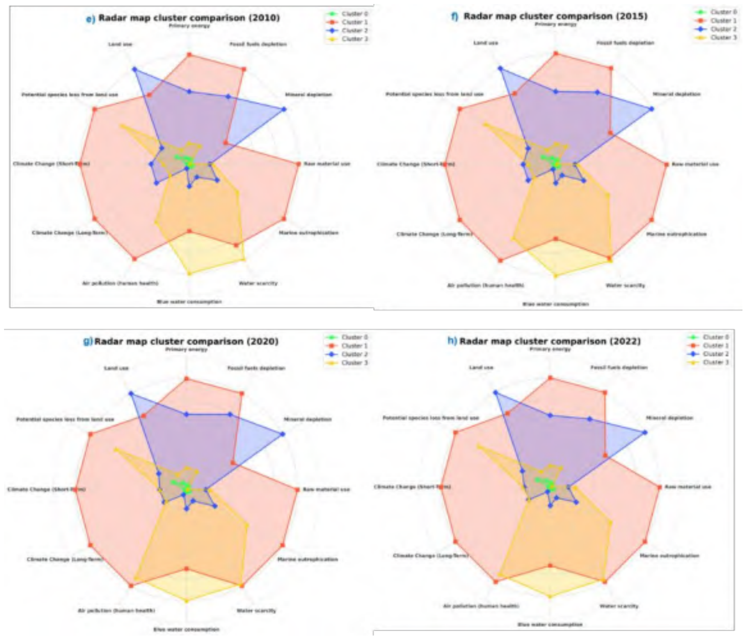

Figura 17. Gráfico de radar de la comparación de los valores promedio de los indicadores de cada clúster (2010-2022).

China y USA suelen pertenecer a los clústeres rojos, como se ve en las **Figuras 18** y **19**. India integra consistentemente los clústeres amarillos, mientras que las naciones sudamericanas y africanas integran los clústeres verdes. No hay diferencias en la distribución de clústeres entre 1995 y 2005, o entre 2010 y 2022.

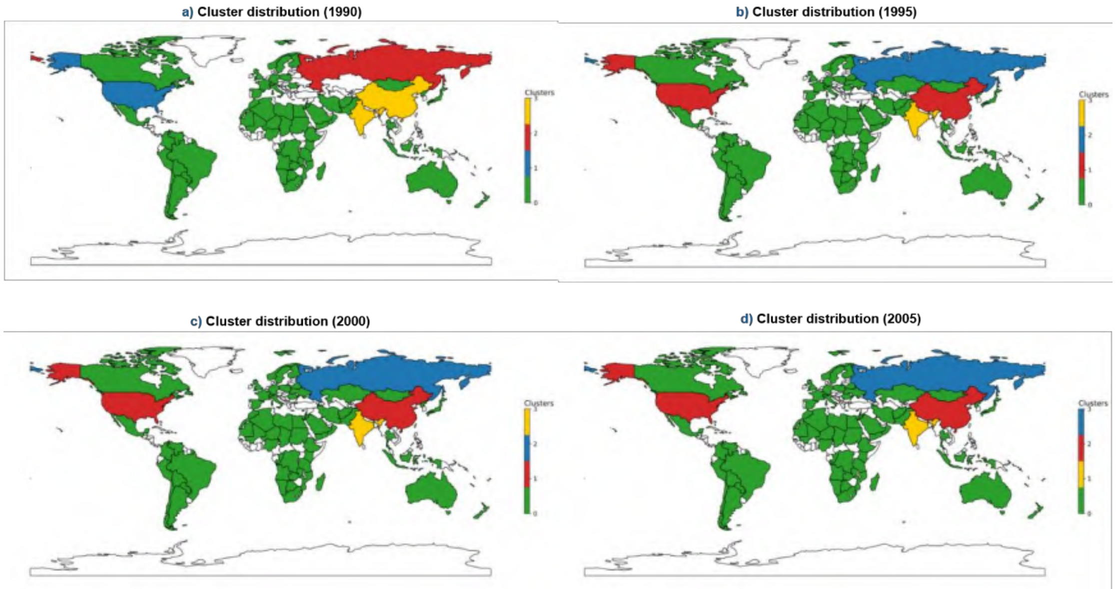

Figura 18. Distribución de clústeres (1990-2005).

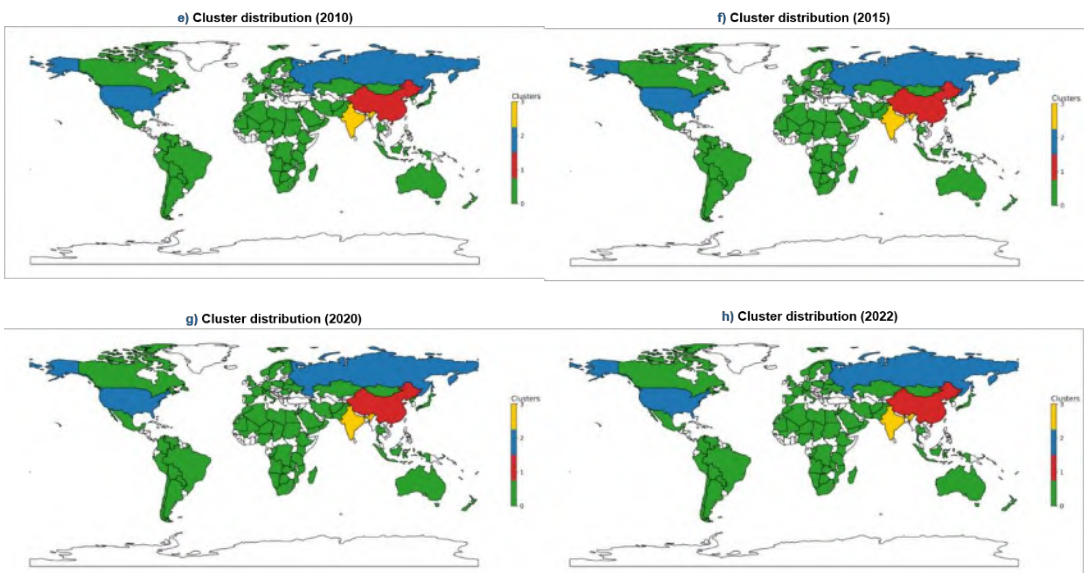

Figura 19. Distribución de clústeres (2010-2022).

4. 3. ANÁLISIS DE RESULTADOS

A continuación, se analizan a profundidad los resultados obtenidos. La sección 4.3.1. incluye los resultados obtenidos al considerar los valores per cápita de los índices medioambientales; por su parte, la sección 4.3.2 presenta el análisis de los resultados obtenidos al considerar los valores totales de los mismos índices.

4.3.1. Análisis de resultados per cápita

4.3.1.1. América del Norte

Para el enfoque de producción nacional, América del Norte no muestra variaciones a lo largo de los años para la distribución de los clústeres, excepto para USA. El análisis muestra que Canadá y Estados Unidos tienen los valores más altos de los indicadores relacionados con el agotamiento de los combustibles fósiles, uso energía primaria, cambio climático y contaminación del aire (clústeres rojos); mientras que México muestra los valores de indicadores más bajos (clústeres verdes).

Según las **Figuras 14** y **15** en 1995, 2015 y 2020, USA cambió su color de clasificación de rojo a azul, lo que puede asociarse con la Gran Recesión que afectó al mundo entre 2008 y 2015, y la recesión tras el COVID-19 (Yagan, 2016). Identificando un aumento en el agotamiento de minerales, consumo de agua azul y escasez de agua (**Figura 13-f, g**). Para obtener más información, la **Tabla 3A** presenta los valores promedio de los indicadores para cada grupo a lo largo de los años según el enfoque de producción nacional per cápita.

Los resultados para el enfoque de la huella de consumo concuerdan con lo mencionado anteriormente, donde Canadá y USA siempre se clasifican como parte de los clústeres rojos con mayor impacto en el uso de energía primaria, agotamiento de combustibles fósiles, agotamiento de minerales, cambio climático (a largo plazo) y contaminación del aire. Mientras que México tiene un bajo impacto ambiental, integrando clústeres verdes.

4.3.1.2. ***América del Sur***

En el caso de América del Sur, casi todos los países muestran los valores más bajos de los indicadores a lo largo de los años, perteneciendo a clústeres verdes. Sin embargo, para el enfoque de producción nacional, en base a la **Tabla 3A** destacan los casos de Chile, Bolivia y Paraguay con un aumento en los indicadores de consumo de agua azul y escasez de agua (clúster azul).

En el caso del análisis de la huella de consumo (**Tabla 1A**), Chile muestra un aumento en el consumo de agua azul y la escasez de agua (clúster azul) en 2010, mientras que en 2015 se identifica un impacto significativo en el uso de tierra, pérdida potencial de especies por uso de tierra, y eutrofización marina (clúster amarillo, **Figura 7-e, f**). Es importante mencionar que Chile, es considerado el tercer país más desarrollado de América, después de Canadá y Estados Unidos. La minería es una de las actividades más importantes de dicho país, contribuyendo sustancialmente a su Producto Interno Bruto (PIB) y a sus ganancias en divisas (Ghorbani & Kuan, 2017). Chile es considerado el mayor productor mundial de cobre, otros recursos explotados son hierro, molibdeno, oro y plata. Sin embargo, la industria minera es la causante de la escasez de agua y de los demás desafíos detectados, especialmente en las regiones áridas del norte donde se concentran las operaciones mineras (Acosta, 2018).

El análisis de la huella de consumo también revela que Venezuela muestra un aumento en el impacto ambiental en 2015, pasando de una clasificación de clúster verde a uno amarillo (**Figura 7-f**), identificándose un aumento en los indicadores de impacto en el uso de tierra, pérdida potencial de especies por uso de tierra y eutrofización marina. Esto coincide con que en 2015 hubo un aumento de la economía venezolana, sin embargo, antes de este año la recesión continuó clasificando a Venezuela como parte de clústeres verdes (Schincariol, 2020).

4.3.1.3. Europa

Para el enfoque de producción nacional, se puede identificar que de 1990 a 1995, Rusia cambió su clasificación de color de clúster, de rojo a azul (**Figura 14-a, b**). Esto puede ser consecuencia de la disolución de la Unión Soviética en 1991, cuando se fundó la Federación Rusa, lo que llevó a una larga y profunda depresión económica que redujo la producción (Alexeev & Weber, 2013). No fue hasta 2005 que la economía rusa se expandió como resultado de las exportaciones de energía, clasificando nuevamente a Rusia como parte de los clústeres rojos (**Figura 14-d**), advirtiendo de un aumento en los índices de agotamiento de combustibles fósiles, uso de energía primaria, cambio climático, y contaminación del aire (Ahluwalia et al., 2014)

Sin embargo, la economía rusa depende principalmente de la exportación de gas natural, petróleo y minerales. Rusia es considerada uno de los tres principales productores y exportadores de petróleo del mundo. Con la caída de los precios del petróleo, la economía rusa sufrió altibajos que afectaron la producción hasta su recuperación en 2018 (Bikar & Sedliacikova, 2018)

En el caso del enfoque de la huella de consumo, durante los primeros años Rusia se clasifica como parte de los clústeres rojos, mostrando un alto impacto en el uso de energía primaria, agotamiento de combustibles fósiles, agotamiento de minerales, cambio climático (a largo plazo) y contaminación del aire (**Figura 5-a, b**). No obstante, depresión previa a la disolución de la Unión Soviética redujo el impacto ambiental y convirtió a Rusia en parte de clústeres verdes, con valores bajos para la mayoría de los indicadores analizados, pero con un potencial significativo de pérdida de especies por el uso de tierra. En 2010, como resultado de la recuperación económica, Rusia muestra un aumento en el consumo de agua azul y en la escasez de agua (grupo azul, **Figura 5-e**). Sin embargo, para 2020 y 2022 se identifica una reducción en el consumo de agua azul (**Figura 5-g, h**). En 2015, Rusia presenta un impacto significativo en el uso de tierra, posible pérdida de especies por el uso de tierra y eutrofización marina (grupo amarillo, **Figura 5-f**).

Para el caso de España según el enfoque de producción nacional, los indicadores muestran valores bajos al formar parte de clústeres verdes. Sin embargo, desde 2005 España expandió su economía, principalmente como resultado del sector de la construcción, aumentando su impacto ambiental (**Figura 14-d**), pasando a clasificarse como parte de clústeres azules (López-Laborda et al., 2006). En la **Figura 15-g**, se observa que España cambia de clasificación de clústeres de color azul a verde, lo que supone una reducción del impacto ambiental como consecuencia de la pandemia de COVID-19. Para el análisis de la huella de consumo se identifica que la mayor parte del tiempo España integra los clústeres azules, alertando de problemas relacionados con el consumo de agua azul y escasez de agua. Para el año 1995 España estaba saliendo de una profunda recesión, formando parte del clúster rojo con alto impacto en el uso de energía primaria, agotamiento de los combustibles fósiles, agotamiento de minerales, cambio climático (a largo plazo) y contaminación del aire (**Figura 6-b**). En 2015, España forma parte del clúster amarillo, mostrando impacto significativo en el uso de tierra, pérdida potencial de especies por el uso de la tierra y eutrofización marina (**Figura 7-f**).

4.3.1.4. Asia

Para el enfoque de producción nacional, China, Japón, India e Indonesia muestran valores bajos para la mayoría de los indicadores evaluados (clústeres verdes), debido a que su enorme cantidad de población implica que en un análisis per cápita el impacto ambiental es menos significativo. Además, la población de los países mencionados continúa aumentando, a excepción del caso de Japón donde se ha implementado el control reproductivo de la población japonesa (Takeuchi-Demirci, 2021). Lo que explica que desde el año 2000 (**Figura 14** y **Figura 15**), Japón reduce su impacto ambiental pasando de clústeres azules a verdes, identificando un impacto bajo para la mayoría de los indicadores analizados pero un impacto relevante en la escasez de agua.

El enfoque de la huella de consumo muestra que de 1990 a 2005 Japón presenta un alto impacto en el uso de energía primaria, agotamiento de combustibles fósiles, agotamiento de minerales, cambio climático (a largo plazo) y contaminación del aire (grupo rojo, **Figura 6**). Después de 2010 (**Figura 7**), se identifica una reducción de la mayoría de los indicadores medioambientales analizados, pero un alto impacto en el consumo de agua azul y la escasez de agua (clúster azul). En 2015, Japón muestra un impacto significativo en el uso de tierra, posible pérdida de especies por uso de tierra y eutrofización marina (grupo amarillo, **Figura 7-f**).

Con base en el análisis de la producción nacional, la mayor parte del tiempo China tiene valores de indicadores bajos perteneciendo a clústeres verdes; en el primer lustro antes de 1990 la economía de China tuvo un aumento, siendo clasificada en

1995 como parte del clúster azul (**Figura 14-a,b**). Para 2010, China se posicionó como la segunda economía más grande y la mayor nación comercial del mundo (Kroeber, 2020). Este crecimiento ha sido impulsado por el cambio agrícola, la manufactura y la inversión extranjera, identificando al mismo tiempo un aumento en el impacto medioambiental, formando parte de los clústeres azules. Se identifica que los clústeres azules en 1990 y 1995 (**Figura 12-a, b**) tienen un impacto significativo en la contaminación del aire, mientras que, en 1995, 2000, 2015, 2020 y 2022 se muestra un agotamiento importante de minerales. En el caso de 2010 y 2015 (**Figura 13-e, f**), es relevante el consumo de agua azul y la escasez de agua. Según la **Figura 15-g,h**, como la mayoría de los países analizados, se muestra una disminución en los indicadores analizados como resultado del COVID-19, clasificando a China en 2022 como parte del clúster verde (Wang et al., 2019).

En el caso del enfoque de consumo para China, desde 2010 se puede identificar un aumento en el impacto ambiental, como resultado de la expansión de la economía. Cambiando su clasificación de clústeres de color verde a azul, identificándose un alto impacto en el consumo de agua azul y escasez de agua (**Figura 6-d** y **Figura 7-g**). En 2015, China pasa al clúster amarillo, con un impacto significativo en el uso de tierra, posible pérdida de especies por uso de tierra y eutrofización marina (**Figura 7-f**).

India forma parte de clústeres verdes con valores bajos para los indicadores analizados. Exceptuando a los años 2015 y 2020 del enfoque de producción nacional; cambiando a clústeres azules, alertando sobre un importante agotamiento de minerales, consumo de agua azul y escasez de agua (**Figura 15-f, g**). En 2020, según el enfoque de huella de consumo, India también se clasifica como parte del clúster azul, destacando una importante reducción en el consumo de agua azul posiblemente como resultado de la pandemia de COVID-19 (**Figura 7-g**).

Tanto para el enfoque de producción como para el de consumo, Indonesia siempre muestra un impacto bajo para los indicadores analizados, formando parte de clústeres verdes. Sin embargo, para el enfoque de producción nacional, para los años de 1990 y 1995 (**Figura 12-a, b**) tiene un impacto relevante la escasez de agua. Mientras que el enfoque de consumo muestra un potencial significativo de pérdida de especies debido al uso de tierra (**Figura 4** y **Figura 5**). Indonesia es reconocida como un país megadiverso, con alta biodiversidad y endemismo (Von Rintelen et al., 2017). Sin embargo, la destrucción de hábitats naturales como resultado de la sobreexplotación amenaza la supervivencia de varias especies. La sobrepesca y la conversión de hábitat, incluida la deforestación ilícita para plantaciones de palma aceitera, son desafíos importantes (Sutarno & Setyawan, 2015).

4.3.1.5. África

La mayoría de los países africanos tienen un bajo impacto ambiental formando parte de clústeres verdes. En el caso de Libia, según el enfoque de producción nacional, se clasifica como parte de los clústeres rojos durante la mayor parte de los años, identificándose un gran impacto en el uso de energía primaria, agotamiento de combustibles fósiles, cambio climático (a largo plazo) y contaminación del aire. Para los años 2015 y 2020 existe un importante agotamiento de minerales (**Figura 12-a, b**), consumo de agua azul y escasez de agua (**Figura 13-e, f**). Según el enfoque de la huella de consumo, para Libia en casi todos los años se tienen un impacto ambiental moderado para la mayoría de los indicadores (clústeres azules); excepto 1995 (clúster rojo) y 2015 (clúster amarillo) (**Figura 6-b** y **Figura 7-f**). Para 1995, Libia muestra un alto impacto en el uso de energía primaria, agotamiento de combustibles fósiles, agotamiento de minerales, cambio climático (a largo plazo) y contaminación del aire. Mientras que en 2015 se identifica impacto significativo en el uso de tierra, pérdida potencial de especies por uso de tierra y eutrofización marina.

Sudáfrica, Botswana y Egipto presentan valores bajos para los indicadores analizados desde el enfoque de producción nacional (clústeres verdes), excepto para 1990 y 1995 en el caso de Sudáfrica (clústeres azules); 1995 y 2000 para Botswana (clústeres azules); y 2005 a 2020 para el caso de Egipto. Se identifica que los clústeres azules para 1990 y 1995 (**Figura 12-a, b**) tienen un impacto significativo en la contaminación del aire, mientras que para 1995 y 2000 hay un importante agotamiento de minerales. En el caso de 2010 y 2015 (**Figura 13-e, f**), es relevante el consumo de agua azul y la escasez de agua.

4.3.2. Análisis de resultados totales

De acuerdo con los resultados obtenidos desde el enfoque de producción nacional, en base a los valores totales de los índices analizados; se identifica que China y USA comúnmente pertenecen a los clústeres rojos, como se ve observa en las **Figuras 18** y **19**. Mientras que India integra clústeres amarillos, y por su parte, las naciones sudamericanas y africanas integran los clústeres verdes. No se observa diferencias en la distribución de clústeres de 1995 a 2005, ni de 2010 a 2022.

Para el caso del análisis de huella de consumo total, con base en las **Figuras 10** y **11**, se puede identificar que, desde un enfoque total USA, China e India suelen formar parte de los clústeres rojos y amarillos. Mientas, la mayoría de los países sudamericanos y africanos integran clústeres verdes, y sólo unos pocos países participan en clústeres azules.

Desde ambos enfoques, los resultados advierten una distribución de clústeres poco proporcional. Donde los clústeres rojo, amarillo y azul; están integrados por aquellos países que en términos totales contribuyen en mayor medida al impacto medio Ambiental, como es el caso de USA, China, India y Rusia. Mientras que el resto de los países analizados constituyen los clústeres verdes.

5. CONCLUSIONES Y RECOMENDACIONES

5.1. CONCLUSIONES

La tesis de investigación desarrollada ha permitido el análisis de distintos indicadores medioambientales asociados al consumo y producción de gran variedad de países a nivel global, a través de técnicas de *clustering*. Lo cual permite la identificación de los distintos patrones de consumo de recursos naturales a lo largo del tiempo, constituyendo el fundamento básico para la migración hacia una sociedad sostenible y resiliente inspirada en el concepto de Sociedad 5.0.

En base a los resultados obtenidos, destacan los siguientes hallazgos generales de relevancia:

- Los patrones de consumo de recursos naturales se ven afectados por factores económicos, políticos, geográficos y sociales; influyendo a su vez en la sostenibilidad a lo largo del tiempo. Tal es el caso de recesiones y auges económicos, crecimiento industrial, cambios de políticas conflictos bélicos, crisis globales como la pandemia de COVID-19, control de natalidad, crecimiento poblacional, conflictos geopolíticos, disponibilidad de recursos en las regiones, entre muchos otros.
- Se confirma que la gestión de los recursos no es uniforme en todos los países y que un pequeño número de países es responsable de la mayoría de los impactos ambientales, destacando los casos de USA, China, India y Rusia.
- El análisis de los resultados en unidades totales confirma que China e India enfrentan los desafíos más significativos en la gestión de recursos desde una perspectiva productiva. Mientras que China, India y Estados Unidos destacan por su significativa huella de consumo de recursos.
- A nivel per cápita, el estudio revela distintos desafíos de sostenibilidad para los distintos continentes y países específicos, lo que pone de relieve la necesidad de equilibrar el desarrollo económico con el uso responsable de los recursos.

A su vez, los hallazgos de este estudio refuerzan la premisa introducida por la Sociedad 5.0.; en base a la cual, las nuevas herramientas tecnológicas asociadas la cuarta revolución industrial, son claves para la transición hacia una sociedad sostenible y resiliente. En este caso se identificó que el *clustering,* técnica de aprendizaje automático, aplicada a los desafíos de sostenibilidad, puede ofrecer más que una simple clasificación de datos: sirviendo como herramienta poderosa para la generación de bases para el diseño de políticas ambientales. El novedoso enfoque de agrupamiento (*clustering*) introducido en esta tesis de investigación proporciona una hoja de ruta estratégica para guiar a los países hacia una gestión más responsable de los recursos. Al identificar patrones de uso insostenible de recursos y vincularlos con contextos económicos y políticos, este estudio acorta la distancia entre la ciencia ambiental y la implementación de políticas, garantizando que las estrategias de sostenibilidad se basen en información basada en datos, en lugar de medidas reactivas.

En definitiva, este estudio establece un marco para la evaluación de la sostenibilidad a largo plazo, demostrando que la gestión global de los recursos requiere cooperación tanto local como internacional. La clasificación continua de ciertas naciones en los clústeres de alto impacto durante varias décadas pone de relieve la naturaleza estructural de las desigualdades ambientales, lo que refuerza la necesidad de políticas globales de sostenibilidad diferenciadas pero coordinadas. Al aprovechar el aprendizaje automático para descubrir información práctica, esta investigación proporciona una base valiosa para futuras iniciativas de sostenibilidad, garantizando que las decisiones que se toman hoy contribuyan a la migración hacia un futuro más equilibrado y sostenible para las generaciones venideras.

5.2. RECOMENDACIONES

A continuación, se presentan algunos puntos clave y acciones estratégicas recomendadas, orientadas a facilitar una transición efectiva hacia modelos de desarrollo más sostenibles y resilientes.

- La utilización global desigual de los recursos naturales está estrechamente vinculada a profundas desigualdades geopolíticas y socioambientales, externalizando los costos ambientales a las regiones menos favorecidas
- Ante volatilidad de los precios por parte de las naciones que concentran los recursos energéticos y los minerales estratégicos; resulta de importancia la seguridad material, siendo necesarios los esfuerzos políticos en favor del nacionalismo de los recursos, las estrategias de acaparamiento y la deslocalización de industrias críticas.
- La gestión global de los recursos requiere políticas ambientales sólidas y la cooperación tanto local como internacional. Por lo que es importante, diseñar políticas que aborden no sólo la cantidad de uso de los recursos, sino también su función estratégica en la economía y su alineación con objetivos de sostenibilidad más amplios.
- Dado que los patrones de uso de recursos son particulares para cada nación, es necesario desarrollar estrategias y políticas de sostenibilidad específicas y basadas en análisis de datos que consideren las responsabilidades ambientales tanto nacionales como globales.
- Fortalecer la normativa ambiental para proteger los ecosistemas y la salud pública en las zonas de extracción de recurso naturales.
- Promover la transparencia y la rendición de cuentas en las cadenas de suministro para prevenir abusos laborales y daños ambientales.
- Implementación de la economía circular a fin de que los materiales que pueden ser percibidos como residuos sean aprovechados al máximo, reduciendo la generación de residuos y la demanda de recursos.
- La diversificación estratégica de fuentes de suministro, innovación en ciencia de materiales, reciclaje eficiente y exploración de nuevos yacimientos políticamente estables, es esencial para mitigar los riesgos de abastecimiento de minerales de importancia.
- Para la gestión eficiente de recursos hídricos es posible la implementación del riego inteligente, el reciclaje industrial y sistemas de captación, ayudando a reducir considerablemente el desperdicio de agua y optimizando su uso.

- En el sector energético, la transición a fuentes renovables como la solar y la eólica, si bien es una opción prometedora, requiere avances en su almacenamiento y la eficiencia.
- Las soluciones inteligentes centradas en las nuevas tecnologías, desempeñan un papel fundamental para mejorar la eficiencia energética, gestionar eficazmente los recursos y promover la sostenibilidad. Las ciudades inteligentes son parte integral de este enfoque, utilizando tecnologías innovadoras para la gestión eficiente de recursos, como el agua y la energía, a la vez que reducen los residuos y la contaminación.

5.3. CONTRIBUCIONES ADICIONALES

El trabajo realizado durante la estancia en el programa de la Maestría en Ciencias en Ingeniería Química dio lugar a las siguientes contribuciones.

5.3.1. CONTRIBUCIONES PUBLICADAS

5.3.1.1. Artículo científico-Apéndice B

Analyzing Mexico's Planting Life Program: Forest plantations for carbon reduction and energy optimization

Thelma Posadas-Paredes, Edgar Geovanni Mora-Jacobo, César Ramírez-Márquez, José María Ponce-Ortega

Chemical Engineering and Processing - Process Intensification

https://doi.org/10.1016/j.cep.2024.109694

5.3.1.2. Artículo de opinión-Apéndice C

Natural Resource Optimization and Sustainability in Society 5.0: A Comprehensive Review

César Ramírez-Márquez, Thelma Posadas-Paredes, Alma Yunuen Raya-Tapia and José María Ponce-Ortega

Resources Editorial

https://doi.org/10.3390/resources13020019

5.3.2. CONTRIBUCIONES EN REVISIÓN

5.3.2.1. Artículo científico-Apéndice D

Incorporating Machine Learning in Clustering of Spatiotemporal Patterns of Dam Filling

Alma Yunuen Raya-Tapia, Thelma Posadas-Paredes, César Ramírez-Márquez, José María Ponce-Ortega

Environment, Development and Sustainability

5.3.2.2. Artículo científico-Apéndice E

Clustering-Based Classification of Global Natural Resource Utilization Patterns for Sustainable Development

Thelma Posadas-Paredes, Francisco Javier López-Flores, César Ramírez-Márquez, José María Ponce-Ortega

Chemical Engineering Research and Design

5.3.2.3. Artículo de opinión-Apéndice F

From Resource Abundance to Responsible Scarcity: Rethinking Natural Resource Utilization in the Age of Hyper-Consumption

César Ramírez-Márquez, Thelma Posadas-Paredes, José María Ponce-Ortega

Resources Editorial

5.3.3. CONTRIBUCIONES ACEPTADAS PARA PUBLICACIÓN

5.3.3.1. Artículo de divulgación-Apéndice G

Consumismo Desmedido, Peligro Latente

Thelma Posadas-Paredes, César Ramírez-Márquez, José María Ponce-Ortega

Naturaleza y tecnología, Universidad de Guanajuato

5.3.3.2. Libro-Apéndice H

Integrated Strategies for Developing Sustainable Energy Systems From Carbon Capture to Energy System Optimization

1st Edition - October 1, 2025

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Authors: Esbeydi Villicaña-García, Edgar Geovanni Mora-Jacobo, Thelma Posadas-Paredes, Aurora de Fátima Sánchez-Bautista, César Ramírez-Márquez, José Maria Ponce-Ortega

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5.3.4. PARTICIPACIÓN EN CONGRESOS

XLVI Encuentro Nacional de la AMIDIQ, La Ingeniería Química ante los desafíos ambientales y energéticos

San José del Cabo, Baja California Sur, México, del 13 al 16 de mayo de 2025.

Trabajo presentado:

ANALIZANDO EL PROGRAMA MEXICANO SEMBRANDO VIDA: PLANTACIONES FORESTALES PARA LA REDUCCIÓN DE CARBONO Y OPTIMIZACIÓN ENERGÉTICA

Modalidad: ORAL

6. REFERENCIAS

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7. ÁPENDICES

7.1. ÁPENDICE A

HUELLA DE CONSUMO PER CAPITA

Tabla 1A. Valores promedio de los indicadores medioambientales para cada clúster, desde el enfoque de huella de consumo per cápita.

Cluster	Raw material use	Mineral depletion	Fossil fuels depletion	Primary energy	Land use	Potential species loss from land use	Climate Change (Short-Term)	Climate Change (Long-Term)	Air pollution (human health)	Blue water consumption	Water scarcity	Marine eutrophication
1990												
0	9.9929	11.7538	1.4092	66.1781	1.8897	11.1613	6.7676	4.9710	9.2259	567.9185	23436.5703	46.6896
1	23.2636	178.5047	4.3975	231.2673	2.3977	10.4468	13.5018	10.8352	18.4295	160.9021	2943.8938	84.8029
2	5.6605	4.0981	0.4625	25.8179	1.8115	24.3961	2.9967	1.8004	2.8479	114.7819	2849.3567	27.9610
3	28.7757	20.1076	3.0246	166.1376	27.9371	139.9784	15.4454	10.7337	9.7423	266.6501	4228.4264	152.8576
1995												
0	6.3198	1.7972	0.4585	26.4674	1.6515	21.2322	3.3513	2.1348	3.8328	85.3389	1986.1968	25.4857
1	19.7729	15.9537	3.5275	199.6691	3.0703	13.5434	12.4628	9.8705	14.9981	185.2702	4238.6831	76.8965
2	3.8024	0.2444	0.2775	14.0888	0.5550	3.3465	2.2730	1.4823	4.8778	559.2530	29152.4023	21.3938
3	25.9574	4.4567	2.6369	147.2988	23.0765	118.8738	13.9361	9.7508	8.6430	313.1686	4958.4636	141.7821
2000												
0	25.0947	34.7946	4.0531	230.9216	3.4388	26.7132	13.8285	10.9872	14.6438	206.8489	4364.1620	86.7917
1	6.0252	3.0566	0.4911	27.3948	1.8494	19.8689	3.3948	2.2389	3.3196	82.7938	1709.9921	24.4846
2	15.6797	1.6144	0.3113	17.1583	43.8381	54.7363	6.9618	3.4442	6.3953	28.5888	446.1541	132.5025
3	8.3471	3.8001	0.8271	42.5936	1.0309	10.1396	5.1293	3.6408	6.8250	419.5968	19739.6646	39.6728

2005												
0	13.7976	3.7944	0.4564	25.1137	38.3377	47.7927	6.6420	3.7564	7.3206	38.9801	554.6587	110.1015
1	15.3293	9.2247	1.3558	68.2287	2.7798	13.6196	8.5555	6.5123	10.5103	433.1788	18445.4283	48.5684
2	29.4767	34.7123	4.9820	284.5547	3.1602	26.4124	15.1620	12.2674	16.7177	198.3160	4354.2767	96.2697
3	6.5702	5.8036	0.5672	31.2192	1.2073	15.6876	3.5265	2.3791	3.6891	95.6674	2209.9316	24.7437
2010												
0	6.6128	1.8124	0.4528	26.1087	1.0679	17.0201	3.2004	2.0865	2.9168	84.8724	1881.2677	21.6126
1	35.1409	20.6534	5.0135	281.7216	3.7617	25.9103	17.8262	14.2672	18.7979	299.5501	6822.1573	102.5670
2	17.6480	17.4176	2.6338	142.4806	4.0277	12.9008	9.3317	7.4652	12.6422	160.9471	4673.9897	60.9470
3	5.2179	0.7493	0.4959	25.9745	0.6794	2.5670	3.3069	2.1804	4.9940	489.7686	22509.0755	29.6850
2015												
0	6.7962	1.7074	0.4997	28.2762	1.0437	15.1811	3.1378	2.0365	3.1283	85.5352	1922.1425	21.7557
1	6.0373	0.9580	0.7362	36.7539	0.5352	2.2334	4.6021	3.2633	4.6658	465.6121	24770.1063	33.3812
2	17.8966	15.0968	2.3953	130.3439	3.6252	13.5504	8.8566	6.9545	11.4032	132.0607	3655.1012	60.0720
3	34.0163	41.5960	4.9680	277.1062	3.1972	22.8874	17.0197	13.5151	18.4382	251.3683	5403.9970	98.5668
2020												
0	30.5398	55.1974	4.8273	281.4297	2.6137	18.8104	14.3170	11.2598	15.9763	232.6817	4208.4694	80.6826
1	6.3714	1.3408	0.3948	25.0722	0.9907	15.2122	2.8708	1.7812	2.1530	65.6096	1560.4334	20.5456
2	23.8647	3.5662	0.8556	45.2796	30.5910	38.3015	11.9738	6.4604	8.8435	63.9680	937.1588	186.2500
3	13.5711	11.5077	1.7467	98.1382	1.4409	8.2659	6.6715	5.2206	10.1600	190.4533	6782.8667	44.0208
2022												
0	15.4595	12.9260	1.9115	116.6378	1.5538	8.7128	7.6475	5.9945	9.9420	175.8031	6568.6687	46.5100
1	6.5589	1.2623	0.3988	25.9263	0.8543	13.8198	2.8963	1.8399	2.7603	76.8760	1833.0444	20.0910
2	32.6565	73.4831	4.7810	281.7502	2.5276	18.8604	15.3164	12.1326	16.6597	270.4966	4696.8299	81.9236
3	25.1731	4.0288	1.0736	64.2228	28.1585	35.3161	14.1120	8.3832	9.8719	75.5830	1153.6905	181.4470

HUELLA DE CONSUMO TOTAL

Tabla 2A. Valores promedio de los indicadores medioambientales para cada clúster, desde el enfoque de huella de consumo total.

Cluster	Raw material use	Mineral depletion	Fossil fuels depletion	Primary energy	Land use	Potential species loss from land use	Climate Change (Short-Term)	Climate Change (Long-Term)	Air pollution (human health)	Blue water consumption	Water scarcity	Marine eutrophication
1990												
0	385.8820	535.4808	52.1871	2761.9104	53.4944	631.1407	206.1831	154.7630	261.9552	6616.3349	199013.3403	1457.2044
1	3830.8809	7974.8419	601.1445	25477.0176	1355.6074	2110.6562	2183.4697	1747.7085	3305.0292	35686.7424	608955.9514	12925.6179
2	4368.1870	1191.9139	327.6776	21109.0623	178.5478	2547.2924	2065.8844	1414.3362	11395.4204	216208.8109	6601563.3065	20586.0903
3	8062.5752	15890.9182	1617.9950	88146.3533	913.2048	4471.3664	5265.1666	4538.9930	3397.0090	76642.4405	1519570.7300	25925.5915
1995												
0	1725.8708	1061.8733	291.8648	15443.6380	326.8618	1807.7017	1002.9561	791.4507	1162.3844	12071.6039	195096.8000	6355.8691
1	8570.0913	4744.1691	1710.2468	96208.8470	941.6366	4515.3134	5711.2094	4906.6791	3474.2011	68179.4575	1347275.0000	27031.7084
2	246.5677	105.3047	28.8127	1599.0888	41.0187	482.0698	139.2159	100.7573	178.2389	5381.8583	190033.4000	1037.3816
3	6234.1523	826.6939	414.5270	25451.6497	210.0344	2863.2048	2593.6185	1936.4189	13496.1461	171353.6482	5373916.0000	24617.4802
2000												
0	1176.3630	1301.0299	179.8971	9731.6649	167.9700	1938.8678	632.6824	491.4182	664.1520	9991.3202	196113.9000	4244.2684
1	10602.2106	6648.0841	2056.9917	114840.1722	995.8051	5002.6617	6845.0927	5901.4801	4363.9794	76785.3324	1562472.0000	29501.1374
2	7107.7785	1289.2436	483.2864	28525.2500	268.5085	3333.4622	2928.6630	2207.6872	13319.5477	181758.2899	5678625.0000	26125.9389
3	201.1800	119.3686	22.4065	1220.2613	39.6939	283.3720	115.5159	83.4799	142.1859	5572.3653	203553.5000	807.6168
2005												
0	1220.7652	1151.9758	189.4820	10236.0217	154.1016	1671.0074	649.4698	509.3625	680.8703	11009.1724	275561.3000	4088.4424
1	13336.9938	6139.5798	1610.7339	91503.4087	799.8601	5103.0842	6661.3976	5637.8832	12533.6519	115713.0799	3598057.0000	34773.6996
2	4014.1600	445.5475	357.6718	17573.0702	107.8690	2865.0409	1843.4000	1255.3804	11906.3624	221282.9655	6188866.0000	17304.4593

3	202.2578	127.0583	20.5597	1120.9246	34.3415	239.8327	116.5961	83.4619	139.9397	6230.7749	223894.8000	766.4640
2010												
0	489.5469	323.1451	65.5383	3537.4441	61.2449	570.2668	260.5779	198.6561	293.8942	7817.6571	246093.2000	1629.4078
1	9010.5999	4423.7012	1900.6316	109162.6069	768.3668	3767.9669	6340.2426	5482.7625	4513.7569	87272.5067	1727883.0000	23931.0109
2	5166.1490	642.1246	496.1938	24195.4795	123.7710	3160.5371	2412.6678	1774.1330	16685.5878	266886.4018	7460074.0000	21189.4346
3	24382.7546	7776.6335	1709.3448	95736.7155	894.0488	7175.1602	9386.4826	8006.7373	26568.0397	182142.6221	6847037.0000	49094.4816
2015												
0	526.4517	329.7092	65.7455	3506.5254	59.6384	554.9665	263.5775	199.1125	293.5404	6791.1610	208779.4000	1651.2812
1	9968.9216	4691.9596	2119.3249	117817.6656	779.3035	3955.7498	6122.3715	5261.6681	4489.7587	86809.9060	1646007.0000	23781.9652
2	31893.9316	10325.1352	2143.7766	121731.2007	980.2384	8097.4243	11191.6791	9563.4110	27545.4589	201309.0080	7718360.0000	53677.9540
3	5671.8513	690.9488	518.9718	25796.2872	129.5919	3337.4005	2810.9573	2174.1906	20724.3889	269932.4453	7430556.0000	22981.2513
2020												
0	537.2894	360.6068	64.8016	3653.0829	57.2910	566.9612	258.1202	190.6400	286.7192	6716.1450	204751.1000	1637.5376
1	10066.3795	4911.9415	2093.5091	120270.0098	803.6561	3835.6223	5509.4880	4684.9045	4455.1244	98719.9259	1919399.0000	24333.6901
2	6295.1495	732.4117	538.2085	28398.8162	140.3156	3537.0817	2975.2904	2283.1452	22301.0638	288114.3469	7880588.0000	25464.0309
3	33751.2570	9147.2984	2432.9713	143739.1688	1015.7771	8318.2668	12594.0731	10707.9210	25271.8592	219624.6628	8268941.0000	52504.6491
2022												
0	555.1878	346.8543	61.7888	3643.4561	55.3779	555.8324	268.5730	199.0733	291.7635	6866.4666	210022.5000	1625.2021
1	10709.0005	4788.9785	2154.9445	123823.7500	820.0769	3988.6919	5849.3626	5037.7443	4639.9231	102050.4450	1986858.0000	24298.2738
2	35295.6514	8776.4442	2450.1377	148354.2279	1058.4852	8282.6459	13042.4498	11150.1489	24997.5463	223652.7488	8428372.0000	53155.3143
3	7151.8208	871.5272	619.0723	31879.6805	152.8149	3730.3159	3345.0676	2619.9407	22745.2118	292320.6182	8022568.0000	26388.4898

PRODUCCIÓN NACIONAL PER CAPITA

Tabla 3A. Valores promedio de los indicadores medioambientales para cada clúster, desde el enfoque de producción nacional per cápita.

Cluster	Raw material use	Mineral depletion	Fossil fuels depletion	Primary energy	Land use	Potential species loss from land use	Climate Change (Short-Term)	Climate Change (Long-Term)	Air pollution (human health)	Blue water consumption	Water scarcity	Marine eutrophication
1990												
0	34.1856	105.3464	15.4381	687.2123	5.3809	5.3844	16.8397	12.5291	10.4132	278.3470	4209.1856	68.1424
1	7.5734	5.5658	1.3975	63.1987	2.3434	26.1301	3.0804	1.7501	2.7074	151.3044	5388.5010	27.2080
2	43.8710	13.4478	3.2217	194.1070	32.9157	219.3152	17.7350	11.2234	6.5016	258.0808	3369.1232	196.1870
3	13.8002	9.2061	1.0075	85.9696	1.1457	5.8954	8.7776	7.1845	15.9297	66.9833	535.6358	59.8009
1995												
0	43.3755	10.4001	3.3777	205.6329	29.5184	197.6766	17.0335	10.8426	5.5188	304.0832	4167.1885	190.9609
1	7.1003	0.9971	1.7429	63.9543	1.8070	24.0024	3.1059	1.7773	2.5814	141.7072	5311.8243	25.4086
2	37.9938	2.3401	21.7848	985.3619	4.9890	4.5108	16.3063	11.3287	8.7730	228.1746	3177.4534	59.2851
3	15.0024	23.9760	1.5102	95.8811	2.1249	6.1143	8.5720	7.0040	11.6682	90.9328	1167.0467	53.1150
2000												
0	8.4919	1.6006	1.5443	70.8248	1.3755	18.0560	4.1676	2.8457	4.6320	121.2555	4203.4205	30.4818
1	26.7027	168.8026	1.6599	109.0533	5.7190	5.9005	9.1658	6.9132	6.6142	96.6289	830.9962	51.6213
2	39.0603	4.2916	19.9984	916.1671	4.4889	5.3016	17.6295	13.0897	8.8413	226.3936	4119.8472	66.2469
3	47.8125	16.4239	3.8506	233.2028	29.5078	192.0122	17.8476	11.5756	5.1810	341.3211	4811.5312	201.6560
2005												
0	11.2761	0.3918	1.8105	62.0375	1.2886	14.1275	4.9693	3.4487	5.2906	522.0051	28160.7964	41.8114
1	10.2830	7.7193	1.4497	71.0887	1.4710	16.3522	4.2603	2.9577	4.6124	92.9230	1847.0386	30.2034
2	36.9509	76.2399	16.0542	741.4724	4.4508	4.0754	17.3531	12.9205	8.4301	197.3924	3326.5120	60.8654

3	48.7828	18.3229	3.9002	246.8296	24.7985	153.7298	17.5381	11.6428	5.1759	280.3800	3839.0515	184.9368
2010												
0	38.6470	28.1618	16.7437	751.8013	4.1328	3.9859	17.3100	13.3308	8.6709	196.6149	3482.8907	58.9069
K 1	11.0205	6.6419	1.1792	70.2382	1.3194	15.0379	4.4758	3.1754	4.3613	79.5833	1617.3632	29.6208
2	49.9325	14.8354	5.3108	338.3890	22.6505	136.6232	17.7694	11.5135	5.6713	228.6227	3214.7548	170.7664
3	10.3543	0.3323	1.5753	58.9470	1.3479	11.8032	4.8044	3.0289	4.4833	527.2997	25221.7633	45.9328
2015												
0	17.4147	78.0533	2.0077	102.2354	1.6800	8.0943	7.4106	5.5944	8.2083	280.4904	10738.3321	43.8152
1	9.5338	4.6866	1.2020	66.6550	1.1852	14.6539	4.0493	2.8214	3.1845	54.8710	1017.6103	27.8422
2	63.1305	14.3448	5.4000	341.4783	20.3157	120.6592	17.4976	11.1797	6.4580	236.1462	3103.3837	193.9934
3	49.6475	2.1206	21.4350	956.5300	4.3113	3.6995	18.3363	14.0728	9.8103	108.5412	1148.6287	62.8047
2020												
0	8.4858	3.8603	1.4317	67.0318	0.9915	12.3255	3.3705	2.1579	2.0570	62.0630	1288.8996	25.7544
1	61.7255	12.0758	6.3452	399.0627	18.4062	108.0260	17.7141	11.0432	6.7894	490.4259	3901.2703	190.1102
2	17.2995	69.3103	1.7770	94.8546	1.4433	13.7392	6.7871	5.1714	9.2567	216.8717	8253.6362	43.7212
3	42.5617	34.7186	17.9759	848.7344	4.4186	3.1666	16.4172	12.5343	8.9759	83.2270	849.9525	55.7964
2022												
0	10.7954	5.6856	0.9795	60.6888	1.0098	12.9554	4.0614	2.8133	3.9935	101.9491	3221.4276	29.5077
1	37.7034	23.4699	14.5818	710.1461	3.6133	3.4826	16.2220	12.4884	7.6446	136.6671	2528.0965	53.4107
2	62.5922	12.2936	5.4998	412.5695	17.7105	103.1366	17.6283	10.9294	6.7056	512.1499	3934.2833	190.2597
3	29.2366	1044.9000	0.0389	145.1031	3.8782	1.0363	9.4311	6.4832	6.9221	35.8733	54.8598	52.3579

PRODUCCIÓN NACIONAL TOTAL

Tabla 4A. Valores promedio de los indicadores medioambientales para cada clúster, desde el enfoque de producción nacional total.

Cluster	Raw material use	Mineral depletion	Fossil fuels depletion	Primary energy	Land use	Potential species loss from land use	Climate Change (Short-Term)	Climate Change (Long-Term)	Air pollution (human health)	Blue water consumption	Water scarcity	Marine eutrophication
1990												
0	338.4766	63.0324	60.0133	3016.8815	55.3183	653.7054	172.8575	126.3831	195.8882	5350.3168	173189.6000	1274.3939
1	7147.9447	4377.4543	1164.1159	68906.2696	711.4485	2571.9990	5168.5575	4484.4249	2568.0122	81382.2333	1592498.0000	27413.4449
2	5487.3898	104444.4631	1426.7153	53849.7717	1283.2811	594.0944	2662.3752	2233.9666	3532.4077	20662.6248	187522.0000	11387.8835
3	4976.0979	548.0356	345.4277	23422.4116	319.8031	3596.3674	2302.4241	1560.3415	12808.0708	171109.9073	5461587.0000	22747.4951
1995												
0	365.1061	68.4604	66.6200	3284.1767	56.5143	620.3422	190.0482	139.3093	200.7092	5543.7288	184184.6000	1320.0089
1	9192.7302	2569.6493	920.3983	56863.9288	633.2359	3541.5290	4936.8099	4072.5681	11191.8342	105657.3007	3360635.0000	33664.4999
2	2337.9639	11915.5013	881.7610	40279.3252	940.7049	326.0217	2018.2789	1703.1158	1969.7797	9869.5303	75297.1900	8640.0273
3	3335.2377	39.7122	154.8904	11190.0793	101.1298	2846.1889	1474.0595	932.5596	11346.7132	227413.0094	6119041.0000	17325.1681
2000												
0	398.9980	101.4406	71.0372	3498.1030	56.6409	645.4843	198.9950	146.2673	187.1644	5898.3281	194059.0000	1360.6534
1	10185.6917	3209.6909	923.8804	58151.9879	631.2994	3522.8661	5456.6101	4573.3030	10855.0061	115456.6285	3577299.0000	34618.4889
2	2207.9437	25074.2395	884.0677	40730.3318	933.3435	324.5088	1902.9557	1622.2361	1565.3387	9054.7401	72398.5600	6612.7943
3	3789.7985	44.9397	188.8536	12095.9567	106.5251	2991.9732	1721.2818	1136.1618	12490.7911	248122.3753	6765170.0000	18989.9605
2005												
0	449.2855	134.0711	77.3206	4024.3509	54.9804	622.0548	217.4539	160.1900	177.3754	6682.4020	227099.4000	1432.6336
1	4378.9516	54.2580	232.5505	14105.3375	111.1261	3123.6456	1989.8722	1365.1691	14451.7791	252513.8915	7022618.0000	21143.4760
2	12729.6955	3429.3516	1107.0962	68788.3894	634.6963	3537.2625	6825.0735	5862.4168	14297.4808	128593.1365	3977235.0000	36874.1577
3	2614.4887	27200.0449	1094.6118	50187.0953	926.6082	322.1300	2006.3504	1693.5519	1408.4035	10317.5299	76792.0200	6179.8971

2010												
0	498.5321	95.5748	75.9533	4092.3842	54.2986	624.3417	228.1891	168.1783	186.6990	7146.7503	240202.1000	1522.1900
1	25264.2075	5400.1617	1609.4983	93564.3942	586.6747	4687.6304	10830.4080	9437.8843	33208.9757	185834.5314	7162963.0000	50659.1630
2	4765.3966	14037.8473	1146.1964	61941.1414	803.3162	1361.7824	3788.2286	3268.9336	1567.0631	61606.5937	1153348.0000	14958.0895
3	5527.6687	71.9730	314.9231	18055.0890	117.6114	3305.4665	2580.4113	1896.1864	20251.2250	303205.6051	8359779.0000	25766.4756
2015												
0	559.9486	176.3499	80.1051	4179.2598	53.2137	623.8928	236.2765	173.2453	191.9105	6132.8853	198277.0000	1592.4558
1	30756.8211	7121.3178	1761.1602	105086.9065	592.3120	4713.2873	12332.6028	10760.5125	32761.3269	210868.5880	8229885.0000	50840.9276
2	5326.9272	12538.3845	1322.5043	69045.3523	802.3441	1357.7100	3624.1959	3090.6311	1608.8080	52844.4911	958072.8000	14821.1146
3	6198.2084	116.3996	341.8847	19883.8860	122.2889	3447.8635	3087.2154	2388.0129	25142.6544	315228.4521	8456263.0000	27646.4267
2020												
0	587.8408	191.6423	79.7109	4485.9552	53.5089	649.7322	232.3173	164.2989	191.2699	6234.2422	197931.4000	1664.4468
1	31454.0483	6358.8463	1877.0596	112740.6819	598.4897	4741.8139	13693.4717	12002.9508	29713.9764	230865.1226	8887152.0000	47170.8178
2	5423.8302	13176.4074	1469.8980	76489.4875	776.8982	1369.2692	3296.4625	2757.7664	1562.7088	55599.0036	1042273.0000	13938.0475
3	6827.2475	119.3276	359.8801	22926.8660	123.7396	3485.1170	3273.2189	2535.0999	27211.1297	324429.7992	8712075.0000	29695.4856
2022												
0	620.7073	204.2992	79.2709	4605.6963	53.2375	646.6588	242.0582	171.3551	191.6437	6334.1819	200300.7000	1681.8192
1	33242.5508	7018.6957	1994.1375	118488.3808	601.6181	4685.6983	14532.7248	12798.7898	30212.2031	239106.8352	9186865.0000	48353.1973
2	5548.6659	12090.9508	1436.9007	77768.8377	771.6533	1379.1152	3458.7824	2929.3312	1493.4246	56273.3824	1049823.0000	13245.9677
3	7671.7421	137.6882	408.6515	23882.6469	125.6853	3537.5703	3619.2244	2859.0650	27875.5137	332986.1731	8940879.0000	30741.8383

7.2. ÁPENDICE B

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Analyzing Mexico's Planting Life Program: Forest plantations for carbon reduction and energy optimization

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Keywords:
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Transmission line expansion

A B S T R A C T

This study addresses the pressing challenge of optimizing the Mexican electricity system in the context of growing energy demand and the imperative to reduce carbon emissions. It adopts an innovative process intensification approach, entailing a comprehensive analysis that interweaves incentives for expanding forest plantations, carbon emissions mitigation, and efficient energy demand fulfillment. Leveraging a sophisticated mathematical model, the underlying methodology systematically explores a range of scenarios, each encompassing a unique combination of parameters and constraints, including the strategic placement of new transmission lines and forest plantation sites. Importantly, the results of this modeling application consistently demonstrate a positive correlation between reduced total annual costs and increased social profits across the various scenarios. This suggests that by strategically aligning energy infrastructure development with reforestation incentives, the Mexican electricity sector can not only work towards meeting its growing energy needs but also make significant strides in environmental conservation. In conclusion, this study offers valuable insights for achieving a sustainable balance between economic and ecological goals within the complex framework of the Mexican electricity landscape, all within the framework of the process intensification approach.

1. Introduction

In today's modern lifestyle, the electricity demand is at an all-time high [1]. While there has been a significant increase in the utilization of renewable energy sources, the electricity and heat generation sector witnessed a substantial rise in Carbon Dioxide (CO_2) emissions in 2022 [1]. The Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) revealed that cities are responsible for two-thirds of global energy consumption and 70 % of carbon emissions [2]. CO_2, a well-known heat-trapping gas, has led to adverse consequences such as global warming, rising sea levels, ocean warming, and melting ice sheets [3]. Since the 18th century, atmospheric CO_2 levels have increased by 50 %, with the current content being 150 % higher than in 1750 [4].

The significant CO_2 emissions in the electricity sector can be attributed to the reliance on fossil fuels [5]. During the COVID-19 pandemic, there was a temporary increase in renewable energy use, resulting in a 5.8 % reduction in CO_2 emissions from electricity production [6]. In this way, 2020 showed the biggest history decrement in CO_2 emissions [7]. However, in 2022, CO_2 emissions rebounded, with 57.84 % of global electricity production being derived from coal and gas (see Fig. 1) [8]. Fossil fuels present two critical challenges: their finite availability and the substantial greenhouse gas emissions they produce when burned [9].

In addressing this issue, Process Intensification (PI) emerges as a vital strategy, particularly in the context of forest plantations. PI, as defined by Ramshaw, aims to reduce the land area required to meet specific production objectives, achieved through more efficient resource management and operational enhancements [10]. While a significant portion of the research emphasizes facility size reduction, any approach that attains commensurate reductions in carbon emissions and energy demand with a diminished land footprint in forest plantations can be deemed a form of process intensification [11–15]. In the study, this approach is crucial for developing a more sustainable electricity system, as it not only focuses on reducing the physical scale of energy facilities but also enhances the overall efficiency and effectiveness of energy production and carbon capture processes. By applying PI, the goal is to improve the balance between energy generation and environmental

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Nomenclature

CENACE National Center of Energy Control
CO_2 Carbon Dioxide
GAMS General Algebraic Modeling System
GW Gigawatt
GWh Gigawatt per hour
hm^2 Square hectometer
hm^3 Cubic hectometer
IEA International Energy Agency
IPCC Intergovernmental Panel on Climate Change
kV Kilovolt
kW Kilowatt
MAXSP Maximization of the Social Profit
MIT Massachusetts Institute of Technology
MMUSD Thousands of millions of dollars
PI Process Intensification
Ton Tonne
WECC Western Electricity Coordinating Council

Sets

i control region
$i1$ control region
J total generation facilities
$j1(j)$ existing generation facilities
$j2(j)$ new generation facilities
t time period (months)

Parameters

ac^{pl} area required to obtain an economic compensation according to the "Planting Life Program", hm^2/economic compensation
$\alpha^{f}_{i,j,t}$ conversion or efficiency factor for energy sources used by electrical generation facilities according to their type of technology, GWh/hm^3, GWh/hm^2, GWh/ton
$\beta^{em}_{i,j}$ emissions factor from the combustion of resources, ton/GWh
$CINV^{n}_{i,j2}$ investment cost, MMUSD/GWh
$CINVF^{n}_{i,j2}$ investment cost for new facilities, MMUSD/GWh
$DE_{i,t}$ energy demand in region i during time period t, GWh
$Dland^{max}_{i}$ maximum land area available for reforestation, hm^2
$Dland^{min}_{i}$ minimum land area available for reforestation, hm^2
$ee^{cap}_{i,t}$ capacity of energy export lines, GWh
EI adult literacy
fa^{pl} unit economic aid, MMUSD
$F^{costforestp}_{i}$ fixed costs associated with forest plantations, MMUSD
$\varphi^{lp}_{i,j}$ coefficients for the losses of energy in power generation facilities according to their type of technology
$\gamma^{Ecap-tree}_{i}$ emissions captured by each tree, ton/tree
$\gamma^{forestp}_{i}$ exponent of capacity related to forest plantations
$\gamma^{water}_{i,j}$ water consumption factor for electricity-generating technologies, hm^3/GWh
GDPI or II decent standard of living
$GEj^{max}_{i,j,t}$ maximum energy generated in power generating facilities according to their type of technology, GWh
$GEj^{min}_{i,j,t}$ minimum energy generated in power generating facilities according to their type of technology, GWh
$ges^{cap}_{i,i1,t}$ capacity of the transmission lines for the energy sent from region i to i1 in period t, GW
$gesn^{cap}_{i,i1}$ capacity of the new transmission lines for the energy sent from region i to i1 in period t, GW
HDI_i Human Development Index
IC_i average annual cost by energy import control region, MMUSD/GWh
$ie^{cap}_{i,t}$ capacity of energy export lines, GW
k_F factor used to annualize capital costs
$L^{nl}_{i,i1}$ length of power transmission lines, km
LEI life expectancy
$M^{nl}_{i,i1}$ factor that considers the cost per km of power transmission line, MMUSD/km
$POW^{e}_{i,j1}$ power of existing energy facilities, GW
$\tau^{let}_{i,i1}$ coefficient of loss due to energy transmission
TC average annual cost of energy transportation, MMUSD/GWh
$UFC_{i,j1}$ unit fixed cost of existing generation facilities, MMUSD/GWh
$UFC_{i,j2}$ unit fixed cost for new energy installations, MMUSD/GWh
$Uland_i$ land area needed for each tree hm^2/tree
$UVC^{e}_{i,j1}$ variable unit cost of existing generation facilities, MMUSD/GWh
$UVC_{i,j2}$ variable unit cost for new energy installations, MMUSD/GWh
$V^{costforestp}_{i}$ variable costs associated with forest plantations
$Zs_{i,i1}$ binary parameter for interconnection of regions where there is energy delivery
Z^{exp}_{i} binary parameter for the exported energy
Z^{imp}_{i} binary parameter for imported energy

Variables

$CapCost^{n}_{i,j2}$ capital cost for new facilities, MMUSD/year
$CapCost^{e}_{i,j1}$ capital cost for existing facilities, MMUSD/year
$C^{capforestp}_{i}$ cost of forest plantations associated with any eco-industry, MMUSD
$Cnl_{i,j1}$ costs for the installation of new transmission lines, MMUSD
$comp^{pl}_{i}$ economic compensation given to any forest plantation through the "Planting Life Program", MMUSD
$ee_{i,t}$ energy exported from region i during period t, to an external agent, GWh
$EmPlant_{i,j}$ emissions from plant *j* in region *i*, ton/year
$Em^{forestp}_{i}$ emissions captured by a forest plantation in a given control region *i*, ton
$f^{f}_{i,j,t}$ available resources used in power generating facilities according to their type of technology, ton, hm^3, hm^2
$gec_{i,t}$ energy consumed in zone i, in period t, GWh
$GEi^{p}_{i,t}$ energy generated in region i, in period t, GWh
$GEj^{p}_{i,j,t}$ energy generated in region i, in new and existing facilities j, in period t, GWh
$GEj^{p}_{i,j1,t}$ energy generated in region *i*, in existing facilities *j1*, in period *t*
$GEj^{p}_{i,j2,t}$ energy generated in region *i*, in new facilities *j2*, in period *t*, GWh
$ges_{i,i1,t}$ energy sent from region i to i1 at period t, GWh
$gesn_{i,i1,t}$ energy sent for new transmission lines from region i to i1 at period t, GWh
$ICost_i$ costs for energy imported to a region *i*, MMUSD/year
$ie_{i,t}$ energy imported to region i in period t, from an external agent, GWh
$loste^{prod}_{i,j,t}$ loss of energy due to production in each region i, in the energy-generating facilities according to their type of technology, in the period t, GWh
$loste^{trans}_{i,t}$ loss of energy by transmission in each region i, in the period t, GWh
MAXSP maximum social profit, MMUSD/year
NA_i number of economic compensations related to the "Planting Life Program"

NT_i	total number of trees of each forest plantation
$OptCost_{i,j2}$	operating cost for new power generation facilities, MMUSD/year
$OptCost^e_{i,j1}$	operating cost for existing generation facilities, MMUSD/year
$POW^n_{i,j2}$	power of new energy facilities, GW
TAC	total annual cost, MMUSD/year
$TCost_{i,i1}$	costs for the energy transported from a region i to $i1$, MMUSD/year
$TEM1$	total annual emissions, Mtons/year
$TWater$	total annual water consumption, hm^3/year
$WaterPlant_{i,j}$	water consumption of power generation facilities, hm^3/year

Binary variables

$y^{forestp}_e$	binary variable that identifies whether a forest plantation should or not be established
$y^{nl}_{i,i1}$	binary variable that identifies whether a new power transmission line will be used
$y_{i,j}$	binary variable that indicates that a facility (j) should be used or not
$y_{i,j1}$	binary variable that indicates that an existing facility ($j1$) should or not be used in the future
$y_{i,j2}$	binary variable that indicates that a new facility ($j2$) should or not be used in the future

impact, particularly in terms of land use and carbon emissions, contributing significantly to a comprehensive and sustainable approach in the analysis and optimization of the Mexican electricity system [10–15].

In the context of forest plantations, PI takes on added significance. Forests act as natural carbon sinks, absorbing CO_2 and storing carbon in biomass and soil, contributing to reducing greenhouse gas emissions. Sustainable forest management provides a renewable biomass source for energy production. Biomass from forests, including wood and residues, can be converted into various bioenergy forms, reducing dependence on fossil fuels and decreasing carbon emissions.

The Emissions Database for Global Atmospheric Research reveals China and the United States as the largest contributors to greenhouse gas emissions, responsible for 29.16 % and 11.19 % of global emissions in 2022, respectively [16]. In the case of Mexico, 1.52 % of the 2022 global greenhouse emissions correspond to this country [16]. Without mitigation efforts, CO_2 emissions from coal burning are projected to increase from 9 Gton/year in 2000 to 32 Gton/year in 2050 [17]. The United Nations Sustainable Development Goal #7 aims to provide sustainable, affordable, reliable, and modern energy for all [18]. Transitioning to sustainable, renewable energy sources is essential, with solar energy standing out as the most abundant and readily available source [19].

Renewable energy sources have gained prominence due to their abundant and cost-competitive nature, with solar energy being a standout example. Solar energy, which reaches the planet at a rate 10,000 times faster than human electricity consumption, has experienced significant growth [20]. Solar technologies have become cost-competitive, leading to a substantial increase in installed solar capacity from 0.81 GW in 2000 to 843 GW in 2021 [21,22]. Alongside solar energy, wind energy has also emerged as a powerful and affordable renewable source [23]. Wind turbines harness kinetic energy from the wind, with offshore wind being particularly potent. Geothermal energy, hydropower, and ocean energy are other significant renewable sources, each with its unique advantages and limitations [24–26].

Despite the promise of renewable energy, certain limitations must be addressed. Solar power generation is influenced by location and weather conditions, demanding significant land areas for effective utilization [21]. While cost-competitive, the initial investment in solar technologies remains a considerable adoption challenge [22]. Wind energy faces challenges associated with the remote location of high wind speeds and potential noise pollution, which can affect wildlife. Geothermal energy, though renewable, has constraints related to heat source sustainability, potential microearthquakes from water reinjection, and the risk of water pollution [27,28]. Low-carbon electricity generation technologies are crucial, but they confront barriers such as cost and availability [29]. In contrast, coal remains an affordable energy source with established electricity generation technologies [30]. These considerations underscore the complexity and multifaceted nature of the transition to renewable energy sources while addressing associated limitations and challenges.

Global temperatures are rising at an alarming rate, with devastating consequences if unchecked [31]. The Paris Agreement aims to stabilize global temperatures to about 1.5 °C above preindustrial levels, requiring a reduction of approximately 30 gigatons of greenhouse emissions per year by 2030 [32–34]. Forest plantations, or ecoindustries, play a vital role in reducing greenhouse emissions. Afforestation and reforestation

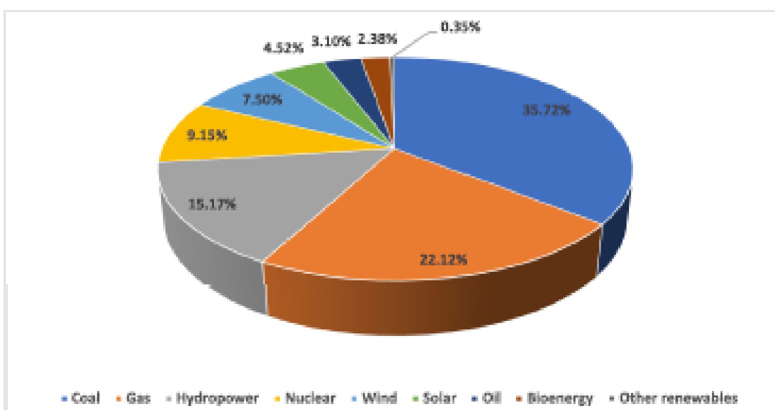

Fig. 1. World electricity production by source.

capture carbon through photosynthesis, acting as carbon sinks [34]. According to the Massachusetts Institute of Technology (MIT), ecoindustries capture 2 billion metric tons of CO_2 annually [35–38].

A study by Mora-Jacobo et al. introduces an optimization model for a sustainable electric system that substitutes non-renewable power plants with renewable energy sources and minimizes greenhouse gas emissions, cost, and water consumption [36]. The implementation of forest plantations as a strategy to reduce CO_2 emissions is a significant focus. The Mexican government's "Planting Life" program offers economic incentives for reforestation efforts, allowing for a multi-stakeholder analysis that considers social profit, carbon emissions, costs, and water consumption [26].

In addressing the main challenge within the Mexican electricity system, the study focuses on the complex management of regional power control zones, emphasizing the balancing of energy import, export, generation, and demand in these interconnected areas. Central to this is the strategic development and expansion of energy generation facilities, incorporating both renewable and nonrenewable sources, and accounting for transmission losses and technology types. The study extends to a global perspective, assessing the environmental impacts of carbon emissions, operational costs, and water consumption in power generation. A notable novelty of this research is the in-depth examination of the role of forest plantations in carbon capture, especially within the economic context of the "Planting Life" program introduced by the Mexican government. This multifaceted approach integrates environmental, economic, and technological considerations, presenting a comprehensive and novel perspective on managing the Mexican electricity system for sustainable development. This sets the foundation for the detailed exploration of these interlinked aspects in the subsequent sections of the article [26].

2. Problem statement

The division of an electric system into different control regions or zones is the problem to be studied in this work. As some of these regions are interconnected, the importing, exporting, generation, and demand of electric energy are analyzed in every single region.

To satisfy the enormous energy demand, energy generation facilities can be found in every zone; nevertheless, the creation of new power generation facilities and new transmission lines is always a possibility. These generation facilities can work with renewable or nonrenewable sources of energy (production technologies), and they also take into account the loss of energy by transmission and production according to the type of technology used.

Considering the electric system at a global scale, it is possible to analyze the carbon emissions, cost, and water consumption involved in the operation of all generation facilities. Although some carbon emissions can be captured by forest plantations, the fact is that the land available for trees is limited. Forest plantations imply a cost, but thanks to the "Planting Life" program there is an economic compensation according to the amount of area destined for forest plantations, which allows for measuring the social profit [39].

With the mathematical model described below: carbon emissions, costs, water consumption, and social profits from different scenarios can be studied in order to fulfill the energy demand while also including all the different stakeholders.

The research emphasizes the possibility of attaining both economic advancement and ecological goals concurrently. Combining infrastructure investments with eco-friendly strategies like forestation reveals substantial socio-economic and environmental advantages, resonating with global sustainability targets and setting a precedent for similar global initiatives.

Moreover, this study incorporates PI principles, promoting efficiency and ecological responsibility in energy planning. This method accentuates achieving optimal outcomes with a minimal environmental footprint, providing critical insights for sustainable energy research and shaping future policy formulations. This balanced approach to energy and environmental needs could steer future research and policymaking toward sustainable energy solutions.

3. Methodology

To optimize the Mexican electricity system in the context of increasing energy demand and the need for reduced carbon emissions, the study proposes a comprehensive energy balancing model. This model is rooted in the principle that the electrical energy generated in any control zone during a given period must equal the sum of various energy components. These components include the electricity consumed within the zone, energy transferred to and from other interconnected regions, energy transmitted *via* new lines, losses incurred during production and transmission, and energy exported externally. Furthermore, the study incorporates PI principles, which are instrumental in achieving this balance. PI, particularly relevant in the context of forest plantations, focuses on reducing the land area required for specific production goals, thereby interconnecting sustainability aspects within the energy sector. This approach aligns well with the new "Planting Life" program, which aims to create an interconnected framework that enhances both the sustainability and efficiency of the Mexican electricity system.

In the analysis of various scenarios, the study considers key parameters and constraints, particularly for the strategic placement of new transmission lines and forest plantation sites. Key factors include the capacities and costs of new transmission lines, energy loss metrics related to production technologies and transmission, land use and carbon sequestration potential of forest plantations, and adherence to environmental and sustainability standards. Additionally, the study integrates an assessment of water consumption for each proposed infra-

usage in construction, maintenance, and operational processes. The impact on local water resources is also a critical consideration, factoring in regional water scarcity and potential effects on ecosystems and communities. This approach helps in balancing infrastructure development with ecological impacts, including those related to water usage, shaping the strategic growth of Mexico's electricity system in a sustainable and environmentally responsible manner.

According to the balance of the electrical energy generated in any region i, during any period t, establishes that the electrical energy generated in the control zone i during the period t ($GEi^P_{i,t}$ in GWh), must be equal to the sum of the electricity consumed in zone i during the period t ($gec_{i,t}$); the sum of the energy sent from region i to each of the other regions ($i1$) in the period t ($ges_{i,i1,t}$), as long as there is an interconnection for the distribution of energy between each of the regions involved ($Zs_{i,i1} = 1$); the sum of the energy sent through new transmission lines from region i to each of the other regions $i1$ ($gesn_{i,i1,t}$); the loss of energy due to its production in region i, at production facilities according to the type of production technology, in period t ($loste^{prod}_{i,t}$); the loss of energy by transmission in region i, in period t ($loste^{trans}_{i,t}$); and the energy exported to an external agent from region i during period t ($ee_{i,t}$), in the case that energy is exported (Z^{exp}_i=1). This is established in the next equation:

$$GEi^P_{i,t} = gec_{i,t} + \sum_{i1} ges_{i,i1,t}\, Zs_{i,i1} + \sum_{i1} gesn_{i,i1,t} + loste^{prod}_{i,t} + loste^{trans}_{i,t} + ee_{i,t}\, Z^{exp}_i, \ \forall i, t, \quad (1)$$

The energy generated in any region i, during any period t, is equal to the sum of the energy produced by each generation facility j within the control region i:

$$GEi^P_{i,t} = \sum_j GEj^P_{i,j,t} \ \forall i, t \quad (2)$$

The loss of energy due to its production in any region i during any period t ($loste^{prod}_{i,t}$) is equal to the sum of the product of the energy produced by each generation facility j within the control region i ($GEj^{P}_{i,j,t}$), and the corresponding coefficient of energy loss by production according to the technology used in the production facility j within the control region i ($\varphi^{lp}_{i,j}$).

$$loste^{prod}_{i,t} = \sum_{j} GEj^{P}_{i,j,t}\varphi^{lp}_{i,j} \ \forall i, t \tag{3}$$

In the same way, the energy exported to an external agent from region i during period t ($ee_{i,t}$) must be less than or equal to the capacity of the energy export lines ($ee^{cap}_{i,t}$).

$$ee_{i,t} \leq ee^{cap}_{i,t} \ \forall i, t \tag{4}$$

The balance of energy demand in any region i, during any period t, establishes that the demand for electrical energy in the control region i during the period t ($DE_{i,t}$) is equal to the sum of the electricity consumed in the region i in the period t ($gec_{i,t}$), the sum of the energy sent from region i to each of the other regions $i1$ ($ges_{i1,i,t}$) minus the corresponding energy lost by transmission from i to $i1$ ($ges_{i1,i,t}$ $\tau^{let}_{i,i1}$), as long as there is an interconnection between the regions i and $i1$ ($Zs_{i,i1} = 1$) implied, the sum of the energy sent to new transmission lines from region i to each of the other regions $i1$ in period t ($gesn_{i,i1,t}$) minus the corresponding energy lost by transmission from i to $i1$ ($gesn_{i,i1}$ $\tau^{let}_{i,i1}$), the energy imported for an external agent to region i in period t, as long as there is energy import (Z^{imp}_{i}=1).

$$DE_{i,t} = gec_{i,t} + \sum_{i1} ges_{i,i1,t}\left(1-\tau^{let}_{i,i1}\right) Zs_{i1,i} + \sum_{i1} gesn_{i,i1}\left(1-\tau^{let}_{i,i1}\right) + ie_{i,t} \ Z^{imp}_{i} \ \forall i, t \tag{5}$$

The energy imported from an external source to any region i in any period t ($ie_{i,t}$) must be less than or equal to the capacity of the energy export lines ($ie^{cap}_{i,t}$).

$$ie_{i,t} \leq ie^{cap}_{i,t} \ \forall i, t \tag{6}$$

In the same way, the energy sent from any region i to $i1$ in any period t ($ges_{i,i1,t}$) must be less than or equal to the capacity of the transmission lines to send energy from region i to $i1$ in period t ($gescap_{i,i1,t}$).

$$ges_{i1,i,t} \leq ges^{cap}_{i1,i,t} \forall i, i1, t \tag{7}$$

The energy that is sent from any region i to $i1$ through new transmission lines ($gesn_{i,i1}$) must be less than or equal to their transmission capacity ($gesn^{cap}_{i,i1}$).

$$gesn_{i,i1} \leq gesn^{cap}_{i,i1} y^{nl}_{i,i1} \ \forall i, i1 \tag{8}$$

The energy lost by transmission in region i during period t ($loste^{trans}_{i,t}$) is equal to the sum of the product of the energy sent from region i to each of the other regions $i1$ in period t ($ges_{i,i1,t}$), and the coefficient of loss due to the transmission of energy ($\tau^{let}_{i,i1}$). Electricity loss coefficients are a function of voltage, distance and the material used in the transmission lines [40].

$$loste^{trans}_{i,t} = \sum_{i1} ges_{i,i1,t}\tau^{let}_{i,i1} \ \forall i, t \tag{9}$$

The energy generated in any region i, by new and existing facilities j, in any period t ($GEj^{P}_{i,j,t}$) is equal to the product of the resource available in power generation facilities according to the type of technology ($f^{f}_{i,j,t}$) and the corresponding conversion or efficiency factor for the energy sources used in power generation facilities according to the type of technology ($\alpha^{f}_{i,j,t}$).

$$GEj^{P}_{i,j,t} = f^{f}_{i,j,t}\alpha^{f}_{i,j,t} \ \forall i, j, t \tag{10}$$

The energy generated in any region i, in the new and existing facilities j, during any period t ($GEj^{P}_{i,j,t}$), |must be greater than or equal to the minimum energy generated in the said facility ($Gej^{min}_{i,j,t}$) and less than or equal to the maximum energy produced in it ($Gej^{max}_{i,j,t}$). When this facility is used, the binary variable $y_{i,j}$ is activated as follows:

$$Gej^{min}_{i,j,t} \ y_{i,j} \leq GEj^{P}_{i,j,t} \ \forall i, j, t \tag{11}$$

$$GEj^{P}_{i,j,t} \leq Gej^{max}_{i,j,t} \ y_{i,j} \ \forall i, j, t \tag{12}$$

The power of a new energy facility $j2$ in region i ($POW^{n}_{i,j2}$) must be greater than or equal to the energy generated in region i, by the new facility $j2$, in period t ($GEj^{P}_{i,j2,t}$). In this model, the number of new energy facilities considers nine technology types: biomass, combined cycle, hydroelectric, wind, geothermal, photovoltaic, internal combustion, nuclear, and turbogas. There are no restrictions on the number of facilities per technology type. However, the installation of these facilities is strategically planned, taking into account the potential of the resources or renewable energies involved.

$$POW^{n}_{i,j2} \geq \sum GEj^{P}_{i,j2,t} \quad \forall i, j2, t \tag{13}$$

The operating cost of any existing generation facility $j1$, in any control region i ($OptCost^{e}_{i,j1}$) is equal to the sum of the multiplication of the unit fixed cost of the existing energy facility $j1$ in the control region i ($UFC_{i,j1}$) and its corresponding power ($POW^{e}_{i,j1}$), as long as the use of the existing facility is necessary for the future ($y_{i,j1}$=1), and the sum of the multiplication of the unit variable cost of the existing facility $j1$ in control region i ($UVC_{i,j2}$) and the energy generated in region i by the existing facility $j1$ during period t ($GEj^{P}_{i,j2,t}$).

$$OptCost^{e}_{i,j1} = UFC^{e}_{i,j1}POW^{e}_{i,j1}y_{i,j1} + \sum UVC^{e}_{i,j1}GEj^{P}_{i,j1,t} \ \forall i, j1 \tag{14}$$

The operating cost of any new generation facility $j2$, in any control region i ($CapCost^{n}_{i,j2}$), is equal to the sum of the product of the unit fixed cost of the new energy facility $j2$ in the control region i ($UFC_{i,j2}$) and its corresponding power ($POW^{n}_{i,j2}$), and the sum of the product of the unit variable cost of the new facility $j2$ in the control region i ($UVC_{i,j2}$), and the energy generated in region i by the new facility $j2$ during period t ($GEj^{P}_{i,j2,t}$).

$$OptCost^{n}_{i,j2} = UFC^{n}_{i,j2}POW^{n}_{i,j2} + \sum_{t} UVC^{n}_{i,j2} \ GEj^{P}_{i,j2,t} \ \forall i, j2 \tag{15}$$

The capital cost of any new facility $j2$ in any control region i ($CapCost^{n}_{i,j2}$) is equal to the sum of the investment cost of the new facility $j2$ in the control region i ($CINVF^{n}_{i,j2}$), multiplied by a binary variable ($y_{i,j2}$=1) indicating that the new facility $j2$ will be used, and the product of the investment cost of the new facility $j2$ in the control region i ($CINV^{n}_{i,j2}$) and its power ($POW^{n}_{i,j2}$).

$$CapCost^{n}_{i,j2} = CINVF^{n}_{i,j2}y_{i,j2} + CINV^{n}_{i,j2}POW^{n}_{i,j2} \ \forall i, j2 \tag{16}$$

The capital cost for any existing facility is equal to zero.

$$CapCost^{e}_{i,j1} = 0 \ \forall i, j1 \tag{17}$$

The cost of energy transported from any region i to $i1$ ($TCost_{i,i1}$), is equal to the product of the average annual cost of energy transport (TC), and the sum of the energy sent from region i to $i1$ in each of the periods t ($ges_{i,i1,t}$).

$$TCost_{i,i1} = TC\sum_{t} ges_{i,i1,t} \ \forall i, i1 \tag{18}$$

The cost of importing energy to any region i ($ICost_{i}$) is equal to the product of the average annual cost of importing energy to control region i (IC_{i}), and the sum of energy imported from a region outside the region i in each of the periods t ($ie_{i,t}$).

$$ICost_i = \mathrm{IC}_i \sum_t ie_{i,t} \ \forall \mathrm{i} \tag{19}$$

The facility cost of a new transmission line in an existing generation facility in any region *i* ($Cnl_{i,i1}$) is equal to the product of the factor that considers the cost per km of the transmission line from *i* to *i1* ($\mathrm{M}^{\mathrm{nl}}_{\mathrm{i,i1}}$), and the length of the power transmission line from *i* to *i1* ($\mathrm{L}^{\mathrm{nl}}_{\mathrm{i,i1}}$). This new line is used for power transmission from *i* to *i1* ($y^{nl}_{i,i1}$=1).

$$Cnl_{i,i1} = \mathrm{M}^{\mathrm{nl}}_{\mathrm{i,i1}} \mathrm{L}^{\mathrm{nl}}_{\mathrm{i,i1}} y^{nl}_{i,i1} \ \forall i, i1 \tag{20}$$

When there is an eco-industry ($y^{forestp}_{e} = 1$), the area required for any eco-industry, which is equal to the product of the total number of trees of each eco-industry (NT_i) and the land area needed for each tree ($\mathrm{Uland_i}$), must be within the minimum ($\mathrm{Dland^{min}_i}$) and maximum limits of land ($\mathrm{Dland^{max}_i}$) available for reforestation.

$$\mathrm{Dland^{min}_i} \ y^{forestp}_i \le NT_i \ \mathrm{Uland_i} \le \mathrm{Dland^{max}_i} \ y^{forestp}_i, \ \forall \mathrm{i} \tag{21}$$

When an eco-industry exists ($y^{forestp}_i = 1$), the cost of forest plantations associated with any eco-industry ($C^{capforestp}_i$) is equal to the product of the annualization factor ($\mathrm{K_F}$) and the sum of the fixed costs associated with forest plantations ($\mathrm{F^{costforestp}_i}$) and, the product of variable costs ($\mathrm{V^{costforestp}_i}$) and the total number of trees in the eco-industry (NT_i) raised to an exponent of capacity ($\gamma^{\mathrm{forestp}}_{\mathrm{i}}$).

$$C^{capforestp}_i = \mathrm{K_F}\left(\mathrm{F^{costforestp}_i} \ y^{forestp}_i + \mathrm{V^{costforestp}_i} (NT_i)^{\gamma^{\mathrm{forestp}}_{\mathrm{i}}}\right), \ \forall \mathrm{i} \tag{22}$$

The factor used to annualize capital costs ($\mathrm{K_F}$) has a value of 0.333.

For any eco-industry, the number of economic compensations related to the "Planting Life Program" (NA_i) is equal to the area required for the eco-industry (NT_i $\mathrm{Uland_i}$) divided by the area required to obtain compensation ($\mathrm{ac^{pl}}$).

$$NA_i = \frac{NT_i \ \mathrm{Uland_i}}{\mathrm{ac^{pl}}}, \ \forall \mathrm{i} \tag{23}$$

It establishes that the economic compensation given to any forest plantation through the Planting Life Program ($comp^{pl}_i$) is equivalent to the product of the number of economic compensations (NA_i) and the unit economic aid ($\mathrm{fa^{pl}}$).

$$comp^{pl}_i = NA_i \ \mathrm{fa^{pl}}, \ \forall i \tag{24}$$

The emissions captured by a forest plantation in a given control region *i* ($Em^{forestp}_i$) are equivalent to the product of the total number of trees in the forest plantation (NT_i) multiplied by the emissions captured by each tree ($\gamma^{\mathrm{Ecap-tree}}_{\mathrm{i}}$).

$$Em^{forestp}_i = NT_i \ \gamma^{\mathrm{Ecap-tree}}_{\mathrm{i}}, \ \forall i \tag{25}$$

The total annual cost (*TAC*) is equal to the sum of the operating cost of each of the existing operating facilities *j1* in each of the regions *i* ($OptCost^{e}_{i,j1}$), the sum of the operating costs of each of the new operating facilities *j2* in each of the regions *i* ($OptCost^{n}_{i,j2}$), the product of the anualization factor of capital costs ($\mathrm{k_F}$) and the sum of the operating cost of each of the new operating facilities *j2* in each of the regions *i* ($CapCost^{n}_{i,j2}$), the sum of the cost of transporting energy from each of the regions *i* to *i1* ($TCost_{i,i1}$), the sum of the energy import costs to each one of the regions *i* ($ICost_i$), the sum of the costs in the installation of new transmission lines from each of the control regions *i* to *i1* ($Cnl_{i,i1}$), and the economic compensation given to each forest plantation ($comp^{pl}_i$).

$$\begin{aligned} TAC = & \sum_i \sum_{j1} OptCost^{e}_{i,j1} + \sum_i \sum_{j2} OptCost^{n}_{i,j2} + \mathrm{k_F} \sum_i \sum_{j2} CapCost^{n}_{i,j2} \\ & + \sum_i \sum_{i1} TCost_{i,i1} + \sum_i ICost_i + \sum_i \sum_{i1} Cnl_{i,i1} + \sum_i comp^{pl}_i \end{aligned} \tag{26}$$

The emissions generated by any plant *j* in any region *i* ($Emplant_{i,j}$), are equivalent to the sum of the product of the available resources used in the power generation facility according to its type of technology ($f^{f}_{i,j,t}$), and the resource combustion emissions factor ($\beta^{\mathrm{em}}_{\mathrm{i,j}}$).

$$Emplant_{i,j} = \sum_t f^{f}_{i,j,t} \beta^{\mathrm{em}}_{\mathrm{i,j}} \ \forall \mathrm{i, j} \tag{27}$$

The total annual emissions (*TEm*) are the sum of the emissions generated by each one of the plants *j* in each one of the regions *i* ($Emplant_{i,j}$) minus the emissions captured by the forest plantation in region *i*.

$$TEM1 = \sum_i \sum_j Emplant_{i,j} - \sum_i Em^{forestp}_i \tag{28}$$

The water consumption of any generation facility *j* in any region *i* ($WaterPlant_{i,j}$) is equivalent to the sum of the product of the energy generated in region *i* at facility *j* in period *t* ($GEj^{p}_{i,j,t}$) and its corresponding water consumption factor according to the energy generation technology for each of the periods *t* ($\gamma^{\mathrm{water}}_{\mathrm{i,j}}$).

$$WaterPlant_{i,j} = \sum_t GEj^{p}_{i,j,t} \gamma^{\mathrm{water}}_{\mathrm{i,j}} \ \forall \mathrm{i, j} \tag{29}$$

The total annual water consumption ($WaterPlant_{i,j}$) is equivalent to the sum of the water consumption of each of the generation facilities *j* present in each of the control regions *i* ($WaterPlant_{i,j}$).

$$TWater = \sum_i \sum_j WaterPlant_{i,j} \tag{30}$$

The Human Development Index (HDI_i) of each area is considered as the average life expectancy, adult literacy rate and decent standard of living. The differences in adult literacy rate between each control region (zone) are of the order of decimals of 100 %. Although these variations may appear minimal, they are quite significant. This is especially true considering that, in recent years, there has been a notable increase in adult literacy rates in several countries. These increases, interestingly,

differences to be of considerable importance. The slight variations in literacy rates across different zones can provide valuable insights into the effectiveness of educational policies and initiatives. Therefore, even marginal changes are worthy of attention and analysis [41].

$$HDI_i = \frac{1}{3}(LEI) + \frac{1}{3}(EI) + \frac{1}{3}(GDPI \ or \ II) \tag{31}$$

The maximum social profit (*MaxSP*) is defined by the following equation:

$$MAXSP = \sum_i ((1 - HDI_i) \ / \ 100) \ comp^{pl}_i \tag{32}$$

The objective function involves the simultaneous minimization of the total annual cost, total annual emissions, and total annual water consumption.

$$\mathrm{minmof}[\Phi_{TAC} + \Phi_{TEM1} + \Phi_{TWATER} + \Phi_{MAXSP}] \tag{33}$$

The normalization of each of the terms of the objective function is presented in the next equations, where $\phi^{\mathrm{min}}_{\mathrm{tac}}$, $\phi^{\mathrm{min}}_{\mathrm{tem}}$, $\phi^{\mathrm{min}}_{\mathrm{tw}}$, and $\phi^{\mathrm{min}}_{maxsp}$ are the utopian points corresponding to total annual cost, total emissions, and total annual water consumption, respectively. At the same time, $\phi^{\mathrm{max}}_{\mathrm{tac}}$, $\phi^{\mathrm{max}}_{\mathrm{tem}}$, $\phi^{\mathrm{max}}_{\mathrm{tw}}$, and $\phi^{\mathrm{max}}_{\mathrm{maxsp}}$ are the Nadir points corresponding to the total annual cost, total emissions, and total annual water consumption, respectively.

$$\Phi_{TAC} = \frac{TAC - \phi^{\mathrm{min}}_{\mathrm{tac}}}{\phi^{\mathrm{max}}_{\mathrm{tac}} - \phi^{\mathrm{min}}_{\mathrm{tac}}} \tag{34}$$

$$\Phi_{TEM1} = \frac{TEM1 - \phi^{\mathrm{min}}_{\mathrm{tem}}}{\phi^{\mathrm{max}}_{\mathrm{tem}} - \phi^{\mathrm{min}}_{\mathrm{tem}}} \tag{35}$$

$$\Phi_{TWater} = \frac{TWater - \phi_{tw}^{min}}{\phi_{tw}^{max} - \phi_{tw}^{min}} \tag{36}$$

$$\Phi_{MAXSP} = \frac{MAXSP - \phi_{maxSP}^{min}}{\phi_{maxsp}^{max} - \phi_{maxsp}^{min}} \tag{37}$$

3.1. Case study

The present mathematical model uses Mexico's National Electric System as a case study as it contemplates the number of generation facilities, and the amount of costs, carbon emissions, and water being consumed. The model also considers the economic compensations for forest plantations that resulted from the program "Planting Life". This Mexican government program provides financial aid to those who reforest areas in order to increase the number of reforestation areas that capture part of the emissions generated. The purpose of this model is to analyze the behavior of the different mentioned objectives in order to best identify the scenario that will allow the accomplishment of the energy demands [39].

Mexico's National Electric System is made up of ten control regions, which are Central, East, West, Northeast, North, Northwest, Peninsular, Baja California, Baja California Sur, and Mulege, where the last three regions are isolated from the other seven. However, in this project, nine control regions are considered due to the integration of the Mulegé region in the Baja California Sur region. These regions are operated by nine regional control centers located in the cities of Mexico, Puebla, Guadalajara, Merida, Hermosillo, Gomez Palacio, Monterrey, Mexicali, La Paz, and the isolated control center in Santa Rosalia Baja California Sur for the Mulegé system [42].

Mexico's National Interconnected System integrates seven regions: Central, Eastern, Western, Northwest, North, Northeast, and Peninsular. These regions share resources and bookings to exchange energy and accomplish their economic and reliable operations [42].

The National Electric System has cross-border interconnections in

Networks and the special users that feed from it. It includes voltages equal to or greater than 69 kW.

II. The General Distribution Network sends energy to general users. This network is integrated by medium voltage networks whose electric source works with levels higher than 1 kV and lower than 35 kV. It also works with low voltage networks whose electric resource is equal to or lower than 1 kV.
III. Private Electric Networks that are not part of the National Transmission Network or the General Distribution Network.

Mexico's Federal Secretary of Energy is the agency responsible for coordinating the electricity sector, leading energy reforms, laws, decreases, and implementations. On the other hand, the National Center of Energy Control (CENACE) is the agency responsible for the National Electric System and for wholesale electricity markets to ensure the minimum cost dispatch of power plants as they take into account free competition, transparency, and efficiency [43].

4. Results

In the results section of the study, a concise analysis of different scenarios in Mexico's electricity sector is presented, each delineated by its unique approach to infrastructure and forestation. From Scenario A's integrated infrastructure-forestation model to the varied infrastructural scales of Scenarios B through F, and the distinct forestation strategies of Scenarios G and H, each scenario distinctively contributes to understanding the sector's dynamic interplay between economic development and environmental sustainability.

The proposed mathematical model is composed of 34,795 single variables, 393 discrete variables, and 73,189 single equations. The optimization model was solved in 0.359 s using GAMS with the CPLEX solver. The model developed in this study is versatile and suitable for application in various geographical contexts by adapting it to local economic and electrical system data. It highlights the critical role of government support, especially in scenarios where direct subsidies are

for the nine control regions (zones) presented in Table 1.

The National Electric System relies on electric networks with different voltage levels; thus, it is integrated into three types of electric networks [42].

I. The National Transmission Network is made from the electric networks used to send energy to the General Distribution

Table 1
Control regions (zones) that integrate Mexico's National Electric System [42].

Identification number	Zone
1	CENTRAL
2	ORIENTAL
3	WESTERN
4	NORTHWEST
5	NORTH
6	NORTHEAST
7	PENINSULAR
8	BAJA CALIFORNIA (BC)
9	BAJA CALIFORNIA SUR (BCS)

Maximization of Social Profit (MAXSP). These scenarios were examined considering the different results achieved by MAXSP, while the value of TAC is limited to various maximum values, ranging between 1.24E+10 and 4.05E+09, which serve as the lower and upper bounds, respectively. Plotting the values that correspond to MAXSP and TAC of each scenario is possible by obtaining the Pareto chart illustrated in Fig. 2. A three-dimensional graphic can also be obtained by plotting the values of MAXSP, TEM1, and TAC (Fig. 3).

The results provided by Scenario A are particularly noteworthy in the context of this study's objectives. This scenario, characterized by the highest Total Annual Costs (TAC) at 1.24E+10 and the maximum Social Profit (MAXSP) of 48,377.50 million USD (MMUSD) among all scenarios considered, offers valuable insights into the potential trade-offs and benefits of specific strategies for optimizing the Mexican electrical system.

Scenario A's substantial TAC indicates that the comprehensive approach it adopts, which includes both the implementation of forest plantations in multiple zones and the construction of 11 new transmission lines (as detailed in Table 2), entails significant upfront investment. This higher cost is attributed to the extensive infrastructure development undertaken in this scenario. The concurrent high MAXSP

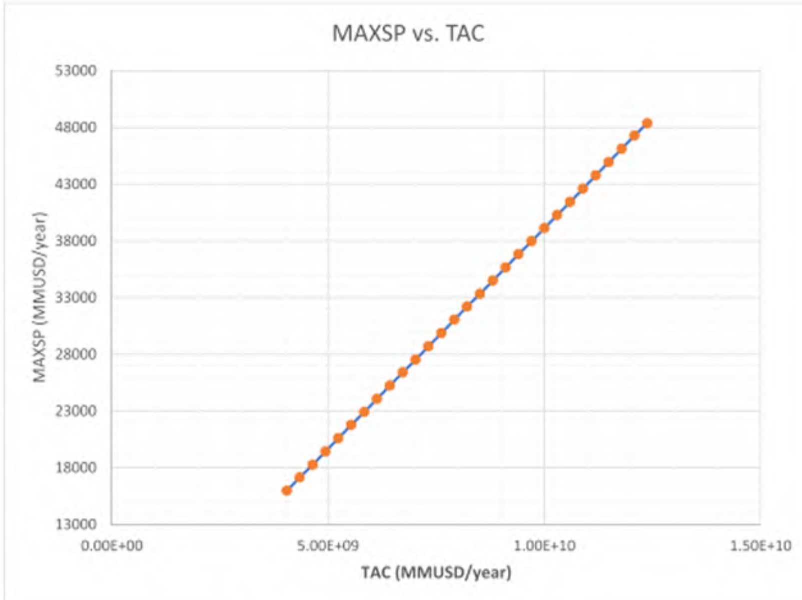

Fig. 2. Pareto chart that relates MAXSP and TAC.

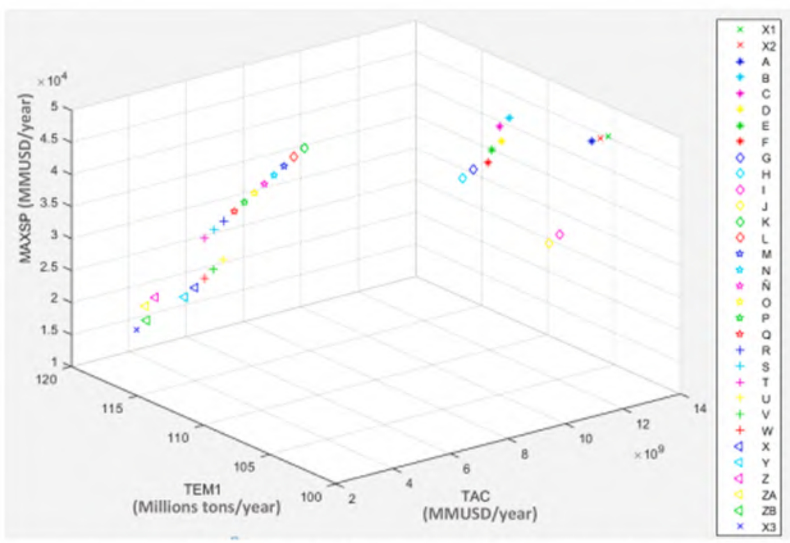

Fig. 3. Three-dimensional graphic of MAXSP, TEM1, and TAC values for each case study.

associated with Scenario A signifies that, while it has a substantial upfront cost, the long-term social benefits, in terms of both economic and environmental gains, are considerable. The substantial MAXSP suggests that the investments made in this scenario are expected to generate significant returns, potentially surpassing the costs incurred. Scenario A's success is attributed to its balanced approach, encompassing forest plantation implementation across multiple zones and the introduction of a significant number of new transmission lines. This comprehensive strategy aims to optimize both carbon emissions reduction and energy demand fulfillment. By strategically placing plantations and expanding transmission lines, the scenario positions itself to meet the dual objectives effectively.

In essence, Scenario A exemplifies the potential benefits of a holistic approach to optimizing the Mexican electrical system. While it may entail higher initial costs, the long-term socioeconomic and environmental advantages are substantial. This outcome underscores the importance of carefully planned infrastructure development and strategic forestation in achieving a sustainable and economically efficient energy system for Mexico. It also serves as a benchmark for evaluating other scenarios with varying degrees of investment and forestation

Table 2
Transmission lines needed for Scenario A.

New transmission Line	Connected zones	
2.1	ORIENTAL	CENTRAL
2.7	ORIENTAL	PENINSULAR
3.1	WESTERN	CENTRAL
4.3	NORTHWEST	WESTERN
4.8	NORTHWEST	BC
4.9	NORTHWEST	BCS
5.3	NORTH	WESTERN
5.4	NORTH	NORTHWEST
5.6	NORTH	NORTHEAST
6.2	NORTHEAST	ORIENTAL
6.3	NORTHEAST	WESTERN

strategies, shedding light on the trade-offs and opportunities inherent in each approach.

The analysis of Scenarios B, C, D, E, and F, which advocate for the implementation of forest plantations in the same zones as Scenario A but with the addition of four new transmission lines (2.1, 4.3, 4.8, 6.3, as for the ones of Table S36 in the Supporting Information), provides valuable insights into the trade-offs between infrastructure investment and social profit within the context of optimizing the Mexican electrical system. Meanwhile, Scenarios G and H, which share the same set of four new transmission lines as the previously mentioned scenarios, but differ in their forestation strategies by either expanding plantations to zones 1, 2, 3, 4, 6, and 9 (Scenario G) or focusing on zones 1, 2, 3, 4, and 9 (Scenario H), highlight the significance of strategic forestation planning (Table 3).

Scenarios B, C, D, E, and F all introduce the same four new transmission lines while maintaining forestation strategies similar to Scenario A. The results show that an increase in transmission infrastructure, even with a modest addition of four lines, has a discernible effect on both TAC and Maximum Social Profit (MAXSP). Generally, as the number of transmission lines increases, TAC tends to rise, which is expected as infrastructure development involves costs. However, this is accompanied by a corresponding increase in MAXSP, indicating that the expanded infrastructure leads to greater social benefits. Scenarios G and H offer a clear illustration of the importance of strategic forestation planning in relation to social profit. While both scenarios share the same transmission lines, they differ in their forestation strategies. Scenario G expands forest plantations to include zones 1, 2, 3, 4, 6, and 9, while Scenario H focuses on zones 1, 2, 3, 4, and 9. The results emphasize that the placement of forest plantations in specific zones significantly affects the economic and environmental outcomes. This highlights the need for careful consideration of where these plantations are located to maximize their carbon sequestration potential and, consequently, the overall social profit.

These scenarios underline the intricate relationship between infrastructure development, forestation strategies, and social profit. The results indicate that while increasing transmission infrastructure generally incurs higher costs, it can lead to greater social benefits in terms of MAXSP. Furthermore, the choice of which zones to prioritize for forest plantations is crucial, as it can have a substantial impact on both economic and environmental outcomes. These findings underscore the importance of a nuanced and strategic approach to infrastructure expansion and forestation within the Mexican electrical system, taking into account both the upfront costs and long-term social advantages.

The analysis of Scenarios I and J, which propose forest plantation creation in zones 2, 3, 4, 5, 6, and 9 along with the addition of only one new transmission line between the northeast and oriental zones (6.2), as well as Scenarios K to T, introducing five new forest plantations in regions 2, 3, 4, 5, and 9, and several transmission lines (4.3, 4.8, 4.9, and 6.2 according to Table S36 in the Supporting Information), and Scenarios U to ZB, which feature the same new transmission lines as Scenarios K to T but with variations in forest plantation locations, reveal important insights into the intricate balance between infrastructure development and forestation strategies within the context of optimizing the Mexican electrical system.

Scenarios I and J demonstrate the potential for cost-efficient optimization by introducing a limited number of new transmission lines alongside strategic forest plantation expansion. The addition of only one transmission line, 6.2, in these scenarios, suggests a relatively modest investment in infrastructure. This is reflected in lower TAC. However, the challenge here is achieving a balance between cost reduction and social profit (MAXSP). While the TAC is lower, the MAXSP may not be as high as scenarios with more extensive infrastructure, indicating that there is room for optimization in terms of social benefit.

Scenarios K to T, which propose five new forest plantations and several transmission lines, underline the significance of forestation location. The choice of specific zones for forestation significantly influences both TAC and MAXSP. By targeting regions 2, 3, 4, 5, and 9, these scenarios aim to maximize carbon sequestration potential, contributing to environmental goals. The investment in multiple transmission lines is associated with higher costs (TAC), but it also leads to higher social profits (MAXSP) compared to Scenarios I and J, indicating that the broader infrastructure development enhances overall benefits.

Variations in Forestation Strategy: Scenarios U to ZB, which retain the same transmission lines as Scenarios K to T but vary forestation locations, reveal the impact of variations in forestation strategy. By assuming different combinations of forest plantations at zones 2, 4, 5, and 9 (Scenarios U to Y) or zones 2, 4, and 9 (Scenarios Z and ZA), and zone 2 and 9 (Scenario ZB), these scenarios illustrate the trade-offs between forestation extent and social profit. The results suggest that variations in forestation strategy can influence economic and environmental outcomes, emphasizing the importance of careful planning in this regard.

Three scenarios were analyzed out of the TAC limits, scenarios X1 and X2 suggest the same forest plantation sites and new transmission lines as scenario A, while scenario X3 and scenario ZB remain the same.

Table 3
Description of each studied scenario.

Scenario	TAC (MMUSD/ year)	TWATER (hm^3/ year)	TEM1 (Millions tons/ year)	MAXSP (MMUSD/ year)
X1	1.30E+10	398.2769	103.2641	48,377.4987
X2	1.27E+10	398.2769	103.2641	48,377.4987
A	1.24E+10	398.2769	103.2641	48,377.4987
B	1.21E+10	394.4041	108.7843	47,278.3096
C	1.18E+10	394.4041	108.8870	46,115.5596
D	1.15E+10	394.9146	108.0854	44,951.1115
E	1.12E+10	394.9146	108.1883	43,786.1115
F	1.09E+10	392.0480	107.8027	42,600.745
G	1.06E+10	391.3752	108.2536	41,437.9949
H	1.03E+10	386.9296	108.4661	40,274.9418
I	1.00E+10	358.4708	100.4612	39,123.6284
J	9.70E+09	358.4708	100.5641	37,960.8784
K	9.41E+09	412.8597	118.4781	36,834.082
L	9.11E+09	412.8597	118.5810	35,668.082
M	8.81E+09	412.8777	118.7068	34,501.0053
N	8.51E+09	412.8777	118.8097	33,333.6719
Ñ	8.22E+09	412.8777	118.9092	32,205.2497
O	7.92E+09	412.8777	119.0121	31,037.9164
P	7.62E+09	412.8777	119.1150	29,870.5831
Q	7.32E+09	412.8777	119.2179	28,703.2497
R	7.02E+09	412.8777	119.3208	27,535.9164
S	6.73E+09	412.8777	119.4203	26,407.4942
T	6.43E+09	412.8777	119.5232	25,240.1608
U	6.13E+09	409.2414	117.4833	24,070.2405
V	5.83E+09	409.2414	117.5862	22,904.2405
W	5.54E+09	408.4881	117.5786	21,777.041
X	5.24E+09	408.4881	117.6814	20,608.541
Y	4.94E+09	408.4881	117.7843	19,440.041
Z	4.64E+09	409.8843	119.3974	18,267.5573
ZA	4.35E+09	409.8843	119.4969	17,140.424
ZB	4.05E+09	407.7369	118.7133	15,971.8122
X3	3.75E+09	407.7369	118.8162	14,798.8122

The analysis of Fig. 4, which plots TAC against TWATER (Total Annual Water Consumption) and TEM1 (Total Annual Emissions), reveals important insights into the relationship between infrastructure costs and environmental factors in the context of optimizing the Mexican electrical system.

Fig. 4 illustrates that both TWATER and TEM1 exhibit constant behavior until reaching a specific threshold value of TAC. This initial phase suggests that within a certain range of infrastructure investment, there is limited impact on both water consumption and emissions. In practical terms, this implies that the early stages of infrastructure development do not significantly affect water consumption or emissions, allowing for some degree of flexibility in system optimization without immediate environmental repercussions.

Beyond the identified threshold value of TAC, both TWATER and TEM1 begin to deviate from their initial constant behavior. This threshold effect highlights a critical point at which further infrastructure investment leads to a more pronounced impact on water consumption and emissions. As TAC increases beyond this threshold, both TWATER and TEM1 start exhibiting non-constant behavior, indicating that additional infrastructure development results in a more substantial environmental footprint. This threshold provides a valuable reference point for decision-makers, suggesting when environmental considerations should be given more attention in the optimization process.

The findings from Fig. 4 emphasize the importance of considering the environmental consequences of infrastructure expansion. While there is an initial range of investment where water consumption and emissions remain relatively stable, beyond a certain point, it becomes essential to conduct comprehensive assessments of the environmental impact. This implies that decision-makers should exercise caution when planning extensive infrastructure development, as it may have significant environmental implications. The study introduces an innovative strategy to harmonize Mexico's escalating energy needs with environmental preservation, effectively creating a win-win scenario. It proposes a synergy of infrastructure expansion, exemplified by new transmission lines, and ecological initiatives such as reforestation, aligned with programs like "Planting Life". This approach not only satisfies immediate energy requirements but also fosters long-term ecological sustainability. By integrating these elements, the strategy offers a blueprint for an environmentally sensitive energy sector, where every step towards infrastructure enhancement also contributes positively to environmental health, ensuring mutual benefits for both the energy sector and ecological sustainability.

The graph underscores the challenge of striking a balance between economic objectives (represented by TAC) and environmental goals (represented by TWATER and TEM1) in optimizing the electrical system. The optimal point of balance is where the environmental impact becomes more sensitive to further investment. Decisions about infrastructure expansion should consider both economic benefits and potential environmental consequences, aiming for a sustainable equilibrium. It can be identified that, points around 1.00E+10 require fewer transmission lines to satisfy in comparison with the other scenarios which in consequence imply minor water consumption and emissions due to power facilities' operation.

The study suggests that strategically aligning energy infrastructure development with reforestation incentives can significantly benefit the Mexican electricity sector in several ways. By analyzing various scenarios using a comprehensive mathematical model, the study demonstrates that investments in energy infrastructure, such as new transmission lines, can be effectively complemented by reforestation initiatives.

This strategic alignment is evident in scenarios like Scenario A, which, despite its high Total Annual Cost (TAC) due to substantial infrastructure development, results in a notable increase in Social Profit (MAXSP). This increase is attributed to the long-term economic and environmental benefits derived from forest plantations, which are integral to the scenario. These plantations not only contribute to carbon sequestration, enhancing environmental sustainability, but also align with the "Planting Life" program, providing economic incentives for reforestation.

Moreover, scenarios that incorporate varying degrees of infrastructure development and forestation strategies further underscore the importance of this strategic alignment. While increased infrastructure development typically leads to higher costs, it also facilitates greater social benefits, particularly when combined with well-planned forestation strategies. These strategies not only offset carbon emissions but also potentially contribute to economic gains through government incentives.

The study indicates that a balanced approach, which combines infrastructure development with strategic forestation, can lead to significant socio-economic and environmental benefits for the Mexican electricity sector. This approach not only addresses the immediate need for energy infrastructure expansion to meet growing demands but also

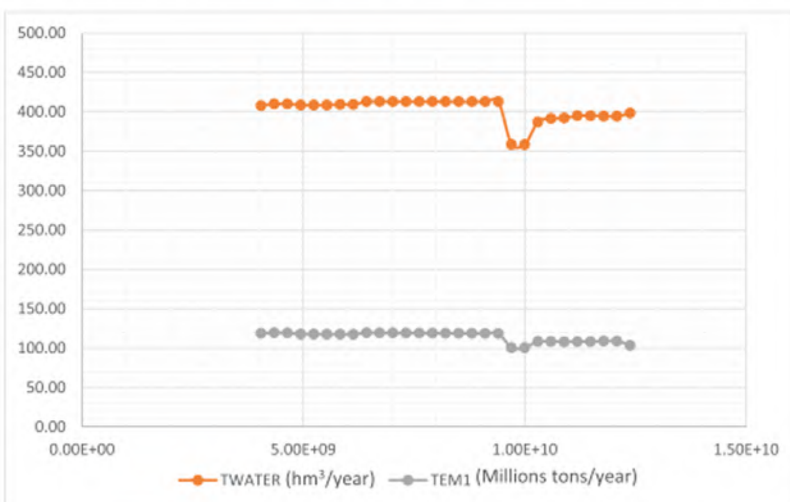

Fig. 4. Graphic of TAC vs. TWATER and TEM1.

ensures long-term sustainability and profitability through enhanced environmental stewardship and economic incentives.

The successful integration of PI principles into the Forest Plantations for Carbon Reduction and Energy Optimization is evident throughout the study. The core concept of PI revolves around the pursuit of optimal trade-offs between economic objectives and environmental goals. In the context of this research, these principles are effectively realized.

The study's results, as previously discussed, emphasize the importance of carefully planning infrastructure development and forestation strategies. This approach mirrors the central idea of PI, which seeks to streamline and optimize processes to achieve desired outcomes more efficiently. In this case, the process of optimizing the Mexican electrical system is intensified by strategically placing forest plantations and expanding transmission lines to maximize carbon sequestration and social benefits.

Furthermore, the study's findings illustrate a sustainable equilibrium where the environmental consequences of infrastructure investment intensify as spending increases. This reflects the essence of process intensification, which seeks to balance the intensification of processes with environmental considerations. The trade-offs between economic and environmental factors are inherently part of the process intensification framework, and this balance is achieved by evaluating infrastructure investment in the context of its impact on water consumption and emissions.

Forest Plantations for Carbon Reduction and Energy Optimization study effectively integrates the principles of PI by applying a strategic and comprehensive approach to infrastructure development and forestation planning. The study demonstrates how this approach aligns with the core idea of PI, which is to improve processes and achieve a balance between economic and environmental goals. This, in turn, contributes to the sustainable equilibrium sought in the context of the Mexican electrical system.

Certainly, the relationship between reduced total annual costs (TAC) and increased social profits (MAXSP) in the study indicates that higher infrastructure investments lead to greater social profits. This is evident from the analysis of various scenarios, particularly Scenario A, which shows the highest TAC at 1.24E+10 correlating with a substantial MAXSP of 48,377.50 MMUSD. This scenario involves significant investment in infrastructure, including extensive forest plantations and new transmission lines, highlighting that while such strategies incur higher initial costs, they offer notable long-term social and environmental returns. The findings across all scenarios consistently reveal that strategic planning in infrastructure development and forestation is key, as it balances upfront costs with enhanced social benefits, essential for optimized decision-making in the Mexican electricity sector.

4.1. Analysis of infrastructure selection beyond forest area differences in various scenarios

In the context of optimizing Mexico's electricity sector, the study delves into the impact of diverse infrastructure selections in various scenarios, providing an analysis that extends beyond just the differences in forest area. The scenarios examined, each with its unique blend of infrastructure choices, offer insights into how these elements can influence the sector's efficiency, cost, and environmental impact.

For instance, Scenario A, notable for its high Total Annual Cost (TAC) of 1.24E+10 and a Maximum Social Profit (MAXSP) of 48,377.50 million USD, showcases the implications of extensive infrastructure development, including the construction of 11 new transmission lines. This scenario underlines the potential for significant social and environmental returns from substantial infrastructure investments, despite the high upfront costs.

Contrastingly, Scenarios B through F, which mirror the forestation strategies of Scenario A but differ in infrastructure by adding only four new transmission lines, demonstrate that even incremental enhancements in infrastructure can result in noticeable gains in social benefits and cost implications. This finding emphasizes the importance of transmission line expansion in energy distribution efficiency and its ripple effects on the sector's overall performance.

The scenarios also explore the outcomes of varying forestation strategies combined with identical transmission infrastructure. For instance, Scenarios G and H, while sharing the same transmission infrastructure, differ in their approaches to forestation. The distinct strategies adopted in these scenarios significantly affect both the economic and environmental outcomes, highlighting the critical role of strategic forestation in conjunction with infrastructure development.

Scenarios I and J, proposing a more cost-efficient approach with limited new transmission lines and expanded forest plantations, offer a perspective on balancing cost reduction with social profit. These scenarios suggest a trade-off between the scale of infrastructure development and the attainable social benefits, pointing to the need for careful planning in infrastructure expansion to optimize social returns.

Moreover, the comprehensive infrastructure development approach in Scenarios K to T, involving multiple new forest plantations and several transmission lines, illustrates the advantages of a broader infrastructure strategy. This approach, targeting specific zones for forestation and including multiple transmission lines, indicates a direct correlation between larger-scale infrastructure development and enhanced social profits.

The study's analysis of these varied scenarios underscores the complex interplay between infrastructure development, strategic forestation, and their combined effects on economic and environmental parameters. It reveals the necessity of a nuanced approach to infrastructure planning in Mexico's electricity sector, where decisions on expansion must consider immediate needs, long-term sustainability, and profitability.

5. Conclusions

This study provides valuable insights into optimizing the Mexican electrical system, particularly in the face of rising energy demand and the imperative to reduce carbon emissions. The research demonstrates the feasibility of integrating forest plantation incentives, carbon emissions mitigation, and efficient energy demand fulfillment within the framework of process intensification. Key findings indicate an inverse relationship between total annual costs (TAC) and maximum social profit (MAXSP), underscoring the significance of strategic planning, where infrastructure investments and forestation locations can yield economically favorable outcomes. The analyzed scenarios offer essential guidance. For instance, Scenario A, featuring multiple forest plantation implementations and the construction of 11 new transmission lines, exhibits the highest TAC of 1.24E+10 but also the greatest MAXSP at 48,377.50 million USD. This suggests that substantial infrastructure investment can prove profitable over the long term. Scenarios B to F, building upon Scenario A with the addition of only four new transmission lines, consistently demonstrate the trend of lower TAC coinciding with higher MAXSP. Scenarios G and H, maintaining the same four transmission lines but differing in forestation locations, emphasize the importance of strategic forestation planning in relation to economic efficiency. Furthermore, Scenarios I and J, introducing a single new transmission line alongside forestation expansion in distinct locations, and Scenarios K to T, proposing multiple new transmission lines with forestation in specific regions, highlight the significant influence of forestation locations and quantities on economic outcomes. These results underscore the potential for optimizing Mexico's energy infrastructure from both an economic and environmental standpoint. Strategic planning, considering forestation locations and transmission line expansion, can achieve a favorable balance between cost and social benefit, thereby supporting informed decision-making in the country's electrical sector. In the future, a combination of infrastructure investment and forestation expansion, aligned with the principles of process intensification, could pave the way for a more sustainable, cost-effective, and resilient system, contributing to Mexico's sustainable development goals.

CRediT authorship contribution statement

Thelma Posadas-Paredes: Writing – original draft, Methodology, Investigation. **Edgar Geovanni Mora-Jacobo:** Writing – review & editing, Methodology, Investigation. **César Ramírez-Márquez:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **José María Ponce-Ortega:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cep.2024.109694.

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7.3. ÁPENDICE C

resources

MDPI

Review

Natural Resource Optimization and Sustainability in Society 5.0: A Comprehensive Review

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Abstract: In this study, we examine Society 5.0, defined as a future framework where advanced technologies like Artificial Intelligence (AI), the Internet of Things (IoT), and other digital innovations are integrated into society for sustainable resource management. Society 5.0 represents an evolution from the industrial focus of Industry 4.0, aiming for a harmonious balance between technological progress and human-centric values, consistent with the United Nations Sustainable Development Goals. Our methodology involves a detailed literature review, focusing on identifying and evaluating the roles of AI, IoT, and other emerging technologies in enhancing resource efficiency, particularly in the water and energy sectors, to minimize environmental impact. This approach allows us to present a comprehensive overview of current technological advancements and their potential applications in Society 5.0. Our study's added value lies in its synthesis of diverse technological strategies, emphasizing the synergy between circular economy practices and sustainable economic development. We highlight the necessity for resilience and adaptability to ecological challenges and advocate for a collaborative, data-informed decision-making framework. Our findings portray Society 5.0 as a holistic model for addressing contemporary global challenges in resource management and conservation, projecting a future where technology aligns with sustainable, equitable, and human-centered development.

Keywords: Sustainable Resource Management; Society 5.0 and Human-Centric Development; Collaborative Solutions for Ecological Sustainability.

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1. Introduction

As we move forward in the early decades of the 21st century, we are experiencing astonishing changes in our world. These changes are remarkable, transforming the way we live, work, and interact with each other and our environment [1]. The latter part of the 2010s saw the rise of a concept in Japan that quickly garnered global attention: Society 5.0 [2]. This concept is not merely a sequel to the technological advancements of Industry 4.0 and Industry 5.0, which started reshaping our reality in the early 2010s [3]. Rather, it is a holistic vision that advocates for a society where advanced technology is intricately woven into the fabric of everyday life [4-5].

Society 5.0 represents a notable progression beyond the industrial orientations of Industry 4.0 and 5.0 [6]. It aims to harmonize state-of-the-art technologies, including automation and digitalization, with essential human requirements, especially in addressing environmental and resource management challenges [7-9]. This model blends technological advancements with a human-centered approach, striving to improve life quality and foster sustainable engagement with the environment. A crucial element of Society 5.0 involves optimizing resources while aligning with the United Nations' Sustainable Development Goals (SDGs) [10], detailed in documents [11-15], striving for a balance between

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economic development, ecological preservation, and social welfare. Our study primarily focuses on this integrative approach, linking technological progress with environmental and societal considerations.

The ethos of Society 5.0, in addressing these challenges, offers a revolutionary approach to technology utilization, one that transcends traditional paradigms. It advocates for the deployment of advanced technologies — from AI and IoT to renewable energy solutions — not merely as tools for economic advancement but as instruments for ecological balance and societal enrichment [16]. This approach entails developing and implementing inherently sustainable technologies, promoting circular economies, and enhancing resource efficiency.

Moreover, Society 5.0's vision emphasizes the need to rethink our relationship with natural resources. It propels us to move beyond the conventional 'take-make-dispose' model, urging a shift towards sustainable resource utilization that encompasses recycling, upcycling, and responsible consumption [17-19]. This paradigm shift is aimed at minimizing waste, reducing the depletion of non-renewable resources, and mitigating environmental impacts, thereby aligning technological advancements with the principles of sustainability.

In implementing these strategies, Society 5.0 is poised to address some of the most pressing issues identified in the SDGs, such as combating climate change, ensuring clean water and sanitation, promoting sustainable industrialization, and fostering responsible consumption and production patterns [20-22]. The integration of advanced technologies within Society 5.0 is envisaged to play a pivotal role in this process, offering innovative solutions for sustainable resource management. These solutions range from precision agriculture that optimizes water and fertilizer use to smart grids that enhance energy efficiency, and from waste-to-energy technologies to advanced materials that reduce environmental footprints [23].

In essence, the approach of Society 5.0 to technology and resource management marks a significant departure from traditional practices. It embodies a holistic, forward-thinking framework that is not only responsive to current environmental challenges but also proactive in anticipating future needs and opportunities. This comprehensive strategy, informed by the SDGs and empowered by technological innovation, holds the potential to transform our world, making the ambitious vision of a sustainable, efficient, and equitable society a tangible reality [24].

In this comprehensive review, we delve into the transformative impact of Society 5.0 on our perceptions of resource optimization and sustainability. Our primary aim is to explore the innovative ways in which this societal model employs technology not just for economic growth, but also to foster a sustainable balance. This exploration includes insights into how businesses and industries are transitioning to a reality where sustainability is seamlessly integrated into their operational fabric, rather than being an optional addendum.

The purpose of this research is to uncover the intricate relationship between Society 5.0 and sustainable resource management, highlighting how this new societal framework can lead to significant positive changes in our world. In doing so, we pose several key research questions: How does Society 5.0 redefine our approach to resource optimization and sustainability? What are the tangible impacts of this societal model on environmental and resource management practices? How are technological advancements under Society 5.0 facilitating a shift towards more sustainable business and industrial practices?

2. Essential Resources for Advancing Society 5.0

In the era of Society 5.0, the sustainable management of natural resources becomes crucial for technological advancement and societal well-being. This section delves deeper into these resources (see **Figure 1**), exploring their future implications and necessity.

In Society 5.0, the connection between energy resources from different areas and the society's progress is key. In Section 2.1, it's shown how managing energy well is important for Society 5.0's overall plan. Section 2.2 talks about how various kinds of energy are needed to power the technology Society 5.0 uses. Section 2.3 connects mineral resources, which are important for making energy systems, to technological growth. Water, discussed in Section 2.4, is an essential energy resource and is necessary for both society and industry. In Section 2.5, the focus is on how energy-efficient methods are needed for sustainable agriculture and forestry, showing energy's role in keeping the environment healthy. Lastly, Section 2.6 highlights that human creativity and growth are supported by a good energy system. This structure was methodologically chosen to highlight the multifaceted nature of energy resources and their critical roles in various aspects of society and technology. It emphasizes the interconnectedness of energy systems, technology, and sustainable practices, underlining the holistic approach required to build Society 5.0. Together, these sections show that using energy wisely and sustainably is central to building Society 5.0, where technology and the environment exist together in balance.

In our methodology, we selected energy, mineral, water, sustainable agriculture and forestry, and human and intangible resources as focal points for Society 5.0, due to their interconnected roles in shaping a sustainable, technologically advanced society. Energy resources are crucial for powering innovation and maintaining a sustainable future; minerals form the backbone of technological infrastructure; water, as an indispensable resource, supports both societal needs and industrial processes; sustainable agriculture and forestry ensure a balance between human consumption and environmental health; and human and intangible resources, including knowledge and creativity, drive the evolution and adaptation of Society 5.0. This holistic approach in our methodology highlights the significance of these diverse yet interconnected resources in realizing the vision of a harmonious, forward-thinking society.

2.1. Society 5.0 and Sustainable Resource Management: A Combined Approach

The intersection of Society 5.0's defining characteristics with natural resource management represents a critical area of study and action. The integration of advanced technologies, a human-centric focus, sustainability, resilience, collaboration, data-driven decision-making, and the balance between cyber and physical worlds – all these elements of Society 5.0 significantly impact how we approach the utilization and conservation of natural resources [25].

Within the framework of Society 5.0, the use of advanced technologies like AI and IoT becomes a vital tool for the efficient management of natural resources. These technologies enable more precise monitoring and better prediction in the use of resources such as water, energy, and materials, optimizing their use and reducing waste [26]. For instance, smart agriculture systems, which utilize sensors and data analysis, can enhance the efficiency of water and fertilizer use, contributing to the conservation of water resources and the reduction of environmental impacts [27].

The human-centric approach of Society 5.0 highlights the importance of considering human needs and well-being in natural resource management. This implies developing strategies that are not only technologically efficient but also sustainable and equitable from a social perspective [28].

Sustainability, as a fundamental pillar of Society 5.0, plays a pivotal role in shaping the development of resource management practices that are not only environmentally responsible but also economically viable over the long term. Emphasizing sustainable development, Society 5.0 encourages the creation of systems and practices that balance ecological health with economic prosperity. This includes the promotion of circular economies, a transformative concept that advocates for the reuse and recycling of resources, thereby significantly minimizing the extraction and consumption of non-renewable natural resources [29]. In these circular economies, waste materials are viewed not as trash, but as valuable resources that can be continuously reintegrated into production cycles, leading to a substantial reduction in environmental impact. This shift towards circular economies under Society 5.0 represents a crucial step in achieving a more sustainable future, where resource efficiency and environmental stewardship are paramount.

Resilience and adaptability, essential characteristics of Society 5.0, are also crucial in natural resource management. In a world where environmental challenges such as climate change and ecosystem degradation are increasingly prominent, the ability to adapt and respond effectively to these changes is key to ensuring the sustainability of resources [30]. This resilience and adaptability are not only about reacting to changes but also about proactively shaping resource management strategies that can withstand future environmental uncertainties.

Collaboration and data-driven decision-making are equally important. Cooperation across different sectors and the use of advanced data analytics can lead to more innovative and effective solutions in natural resource management [31]. This collaborative approach, which brings together stakeholders from various fields, including technology, ecology, and social sciences, ensures that the solutions developed are beneficial for both communities and the environment. Additionally, the integration of data analytics helps in accurately assessing resource needs and environmental impacts, fostering a more sustainable and efficient resource management paradigm. Lastly, the balance between the cyber and physical worlds in Society 5.0 allows for greater harmonization between technology and the natural environment. This opens up new possibilities for resource management, where technological solutions complement and enrich interactions with the natural world [32].

With these considerations in mind, the next section of the article will focus exclusively on natural resources within the context of Society 5.0. It will explore how the convergence of these characteristics can lead to more innovative and sustainable methods in the management and conservation of natural resources, a critical aspect for the future of our planet and society [33].

2.2. Energy Resources: Diverse Origins for a Sustainable Future

Solar Energy: At the heart of this energy mix is solar power, harnessed mainly through photovoltaic cells which heavily depend on purified silicon, derived from common quartz. The global market for solar panels is largely influenced by countries like China, the US, and Russia, which are major players in providing silicon. The IEA has projected that solar PV capacity could skyrocket, reaching around 930 GW by 2024, a clear sign of its growing footprint in our global energy landscape [34].

Wind Energy: Wind power, another key player in the renewable scene, relies on materials like steel (from iron ore) and concrete (from limestone) for building turbines, and uses rare minerals like neodymium for the magnets. China stands out as a major supplier of these rare earth elements. GWEC's reports show that the global wind power capacity hit 743 GW in 2021, underscoring its rising star in renewable energy [35].

Fossil Fuels: Even as we pivot towards renewable sources, it's undeniable that fossil fuels – coal, oil, and natural gas – still have a significant footprint in our current global energy mix. The BP Statistical Review of World Energy 2022 indicates that over 80% of the world's energy consumption in 2021 was from fossil fuels. Yet, there is a noticeable shift to cleaner energy, especially in more developed countries [36].

Nuclear Energy: Then there is nuclear power, a substantial low-carbon energy player. As of 2021, around 440 nuclear reactors were operational worldwide, supplying about 10% of global electricity, as reported by the World Nuclear Association [37]. Nuclear energy is pivotal in many countries' energy strategies, particularly for those aiming to cut down greenhouse gas emissions.

Biofuels: Lastly, biofuels – made from plants and animal waste – are becoming an increasingly vital part of the renewable energy sector. The IEA points out that biofuel production has been on a steady rise, expected to jump by 25% by 2024, largely driven by policies advocating for sustainable transport fuels [38].

Hydrogen: An emerging player in the energy landscape is hydrogen, often touted as the fuel of the future. With the global hydrogen market valued at approximately $150 billion in 2021 and projected to reach $2.5 trillion by 2050, hydrogen has the potential to revolutionize the energy sector [39]. Its ability to store and deliver energy in a usable form without direct emissions makes it a promising candidate for a clean energy future. Research and investment in hydrogen technologies are intensifying, as evidenced by the significant increase in green hydrogen projects worldwide, expected to reach a production capacity of 50 million tons per annum [40]. This trend indicates its possible pivotal role in meeting the energy demands of Society 5.0, adapting to a variety of applications from transportation to industrial power generation.

Looking at the energy landscape of Society 5.0, it is marked by a diverse and evolving mix of sources. While renewables like solar and wind are climbing up the ladder, traditional energy forms like fossil fuels and nuclear power are still in play. Our future energy matrix is likely to be a tailored blend of these sources, catering to the specific needs and strengths of various regions, all converging towards the shared goal of sustainability and technological progress.

2.3. *Mineral Resources: Essential for the Technological Infrastructure of Society 5.0*

The evolution of technology in Society 5.0 hinges on a range of critical minerals, each playing a unique role in the development of high-tech infrastructure.

Lithium: Take lithium, for instance, a star player in the battery technology arena. Its story is intricately woven with the rise of electric vehicles and renewable energy storage systems. Global lithium reserves are estimated to be around 22 million metric tons. Alongside Australia, Chile and China emerged as the world's other leading lithium-producing countries, collectively spearheading the supply to meet the soaring global appetite for lithium [41]. This number is not just a statistic; it echoes the world's accelerating shift towards sustainable energy solutions.

Cobalt: Cobalt's tale, though, is tinged with complexity. Predominantly sourced from the Democratic Republic of Congo, which produced about 95,000 metric tons in 2021, cobalt's story is one of both abundance and ethical challenges [42]. This mineral is indispensable in crafting high-density batteries, but its procurement often raises concerns about responsible sourcing and the impact on local communities.

Rare earth elements: The narrative of rare earth elements is equally compelling. Dominated by China, which produced around 168,000 metric tons in 2021, these elements are the unsung heroes in various technologies, from smartphones to electric vehicles [43]. China's stronghold on rare earth elements not only underscores its global importance but also highlights the strategic need for diversified supply chains.

Copper: Copper's journey, known for its excellent conductivity, is essential in a myriad of applications, from electrical wiring to renewable energy systems. Chile, as the largest copper producer with a production of 5.7 million metric tons in 2020, plays a crucial role in this narrative [44]. Peru follows, adding its significant contribution to the global copper saga.

Aluminum: Aluminum, famed for its lightweight and corrosion-resistant properties, is vital in industries ranging from transportation to construction. In 2025, China solidified its leading position in the global aluminum production arena, producing an impressive 40 million metric tons [45]. This substantial figure not only emphasizes China's critical role in the aluminum market but also reflects the country's significant influence on the worldwide aluminum narrative.

Silicon: Silicon's tale is equally fascinating. As a cornerstone of the semiconductor industry, its production is crucial for the tech world. In 2022, the global production of industrial silicon reached 7.783 million tons, a figure that also indicates the amount of silicon-containing solid waste generated at each step of the production process [46]. This figure is not just about quantity; it is about the centrality of silicon in our digitally-driven era.

Each of these minerals (lithium, cobalt, rare earth elements, copper, aluminum, and silicon) are more than just elements on the periodic table. They are the keystones in the edifice of Society 5.0, playing pivotal roles in everything from energy storage to digital devices. Their stories, interwoven with global economics, sustainability, and technological progress, highlight the intricate tapestry of our modern world.

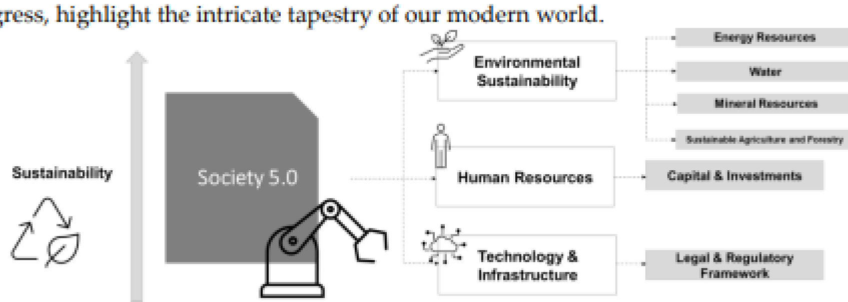

Figure 1. Towards Society 5.0: Envisioning the Integration of Resources for a Sustainable Future.

2.4. *Water: The Lifeblood of Society and Industry*

Water, in its multifaceted role, is not just indispensable for sustaining life but also a crucial resource for industrial applications. Freshwater, primarily sourced from aquifers and river basins, is under increasing pressure from factors like climate change and overconsumption. This scenario necessitates innovative solutions for water management. Desalination, a key technology particularly prevalent in the Middle East, has seen a significant rise in adoption. Currently, there are about 21,123 desalination plants operational globally, serving the daily water needs of over 300 million people around the world [47].

The importance of water recycling cannot be overstated in addressing water scarcity. In countries like Israel, water recycling contributes to more than 85% of agricultural water use, showcasing its potential in sustainable water management [48]. Moreover, advanced irrigation techniques are gaining traction in agriculture, a sector responsible for approximately 70% of global freshwater withdrawals. Techniques like drip irrigation, which can increase water efficiency by up to 90%, and precision agriculture, are becoming essential tools for sustainable agriculture [49]. In regions like California, the adoption of drip irrigation has led to a 20-50% reduction in water usage for certain crops [50].

As water scarcity becomes a more pressing issue, these technologies and methods are vital in ensuring the efficient and sustainable use of water resources. The integration of such techniques across various sectors is crucial for managing the world's freshwater supply effectively, especially considering the growing demands of an increasing global population.

Building further on these strategies, the integral role of water extends beyond agriculture into the realms of energy production and industrial processes. Water is a key element in generating hydroelectric power, a clean and renewable energy source. In industries, water is extensively used for cooling and processing, highlighting its indispensability in various manufacturing sectors. Moreover, the concept of water-smart cities is emerging as a crucial development. These cities integrate efficient water usage into their urban design and infrastructure, addressing the unique water challenges of urban environments.

This comprehensive approach to water management, which encompasses rural areas with their agricultural needs and urban settings with their distinct requirements, is vital for a sustainable water future. The strategy involves not just conserving water but also optimizing its use across different sectors. This includes adopting water-efficient technologies in homes and industries, and promoting policies that support water conservation and sustainable usage.

As the global population continues to grow and the impacts of climate change become more pronounced, the need for effective water management strategies becomes more critical. It's not just about having enough water; it's about ensuring that water is used in the most efficient and sustainable way possible. This means balancing the water needs of communities, industries, and ecosystems in a way that supports the health of the planet and its inhabitants.

The integration and application of these varied water-related technologies and methodologies across different sectors is essential. It's about creating a cohesive system that manages the world's water resources in a way that is both effective and sustainable, meeting the needs of today without compromising the ability of future generations to meet their own needs.

2.5. *Sustainable Agriculture and Forestry: The Balancing Act*

The essence of sustainable agriculture deeply roots itself in nurturing topsoil and judiciously managing the land fit for farming. This crucial land is not uniformly spread across our planet. In countries like the United States, Brazil, and India, significant strides are being made in the field of crop genetics and soil health. These innovations are pivotal, not just in boosting crop yields but also in fortifying the resilience of agriculture against the backdrop of a changing climate. Consider Brazil's progress in soybean production; in 2022, the nation achieved a remarkable output of 269 million metric tons, a testament to the effectiveness of these advancements [51].

In the same breath, let's consider forestry, which straddles the line between commercial exploitation and environmental conservation. The challenge here is to strike a delicate balance, especially in critical ecosystems like the Amazon Basin and the expansive boreal forests of Russia and Canada. These areas are not just forests; they are global assets in carbon sequestration and biodiversity preservation. The Amazon, with its sprawling 4.27 million square kilometers, is a prime example of nature's prowess in offsetting carbon emissions and harboring a rich tapestry of life [52].

It is clear that our approach to agriculture and forestry is more than a matter of policy or practice; it is a commitment to the health of our planet, aligning human development with the needs of the environment.

Moving deeper into our analysis, we connect the dots between sustainable agriculture, forestry, and the vision of Society 5.0. This concept of an advanced society puts a strong emphasis on balancing technological innovation with environmental care. Agroforestry, blending trees with crops or livestock, is an excellent example of this balance. It shows how we can use land in a way that's good for nature and still helps us grow food or raise animals, using technology to manage resources better. This matches Society 5.0's idea of mixing old ways with new tech to create healthier, more productive environments.

In forestry, keeping forests healthy for the future is crucial. This means managing them in a way that helps with climate change by storing carbon and keeping the forests for years to come. This kind of care for forests fits right into Society 5.0's goal of having economic growth without hurting the environment.

The link between farming, managing forests, and taking care of the environment in Society 5.0 shows a real commitment to our planet. It's about making systems and ways of doing things that help people and the planet. In Society 5.0, farming and forests are not just about making things or protecting nature; they are key to a future where we live sustainably, use technology wisely, and look after our environment.

2.6. *Empowering Society 5.0: Human and Intangible Resources*

The foundation of Society 5.0 lies in its Human Resources. The future demands a workforce skilled in AI, robotics, data analysis, and cybersecurity. Industry 5.0 highlights the collaboration between humans and machines, requiring a workforce that is technically skilled and adaptable to rapid technological changes [53]. Developing this talent is key to innovation and competitiveness in an advanced society.

Another crucial aspect is Technology and Infrastructure. Investing in high-speed networks, data centers, and IoT platforms supports the large data volumes and connectivity needed for modern industrial and social models [54]. These elements are vital for a digitally connected world, enabling efficient communication and integration of technologies into daily life.

Environmental Sustainability is equally important. As technology impacts the environment, focusing on emission reduction, waste recycling, and sustainable agriculture is essential. These practices protect the environment and ensure the sustainability of technological advancements [55].

Capital and Investments also play a significant role. Funding for research, development, and implementation of advanced technologies is crucial for ongoing innovation [56]. A combination of public and private investments is necessary for sustainable and progressive technology development.

An effective Legal and Regulatory Framework is indispensable. Addressing issues like data privacy, cybersecurity, labor rights in automated environments, and AI ethics requires a strong legal structure [57]. This framework protects individual and societal rights and encourages technological innovation and adoption.

Realizing Society 5.0 needs a coordinated approach to managing diverse natural resources. Understanding the unique origins and roles of each resource highlights the complexity and interconnectedness of our global ecosystem. Strategic resource management, aligned with technological advancements, is essential for a sustainable, resilient, and equitable society.

3. Society 5.0 Resources: An In-Depth Review

In the endeavor to propel Society 5.0 forward, achieving a profound comprehension of its core resources takes center stage. These resources encompass a wide spectrum, ranging from the tangible and technological elements to the intangible facets deeply intertwined with human-centric considerations. In pursuit of this comprehensive exploration, we have meticulously curated a selection of numerous articles authored by esteemed experts and visionary thought leaders hailing from diverse domains. Each article delves rigorously into a distinct facet of Society 5.0, offering not only distinctive insights, empirical substantiation, and forward-thinking perspectives but also a strong emphasis on sustainability. Within **Table 1**, presented below, we provide an overarching view of these articles, laying the foundation for an exhaustive scrutiny of the multifaceted resources that not only drive but sustain the evolution of Society 5.0.

In **Table 1**, our analysis of Society 5.0-related literature encompasses seven distinct areas, reflecting the multifaceted nature of this concept. To ensure a comprehensive and nuanced understanding, we adopted a systematic and rigorous approach in our literature review. This involved meticulously searching through several academic databases, employing a combination of keywords that encapsulated the essence of Society 5.0 and its associated sectors.

For our analysis, we established specific selection criteria focused on the relevance of the articles to Society 5.0, their contribution to the field, and the novelty of the research. We prioritized studies that offered innovative insights or presented new angles on the application and impact of Society 5.0 concepts. The period from 2017 to the present was chosen strategically to capture the most recent advancements and discussions in the field, marking a significant phase in the evolution of Society 5.0.

The method of analysis involved a thorough reading and categorization of the selected articles. Each article was evaluated for its core content, thematic relevance, and the depth of its analysis regarding Society 5.0. We then synthesized the findings to draw out key themes and trends, which were categorized into the seven sections represented in **Table 1**. This structured approach allowed us to not only compile a diverse range of viewpoints but also to critically assess the interconnections and differences within the literature, thereby providing a holistic overview of the current state and future prospects of Society 5.0.

Table 1. Society 5.0 Resources Articles Overview.

Society 5.0	Articles
Sustainable Energy and Resource Efficiency	**Carayannis et al. [58], Nižetić et al. [59], Petrescu et al. [60].**
Environmental Sustainability and Society 5.0	**Kasinathan et al. [61], Mourtzis et al. [62], Turner et al. [63].**
Smart Solutions for Ecological Challenges	**Fukuda [64], Onu et al. [65], Wang et al. [66].**
Society 5.0 and Human-Centric Approaches to Nature	**Deguchi et al. [67], Narvaez Rojas et al. [68], Phuyal et al. [69].**
Integrating Technology and Environmental Management	**Calp & Bütüner [70], Maddikunta et al. [71], Villar et al. [72].**
Technological Advancements in Industry 4.0 and 5.0	**Ali et al. [73], Beier et al. [74], Javaid et al. [75], Liang et al. [76], Xu et al. [77].**
Societal Impacts and Development in Society 5.0	**Fukuyama [78], Gustiana et al. [79], Kusiak [80], Masoomi et al. [81], Nahavandi [82], Pascoal-Faria et al. [83], Pereira et al. [84], Potočan et al. [85], Ptak et al. [86], Roblek et al. [87], Serpa & Ferreira [88], Skobelev & Borovik [89], Smuts & Van der Merwe [90], Zengin et al. [91].**

3.1. *Sustainable Energy and Resource Efficiency*

Carayannis et al. [58] highlight the significance of nuclear fusion energy in the context of Society 5.0, especially with the International Thermonuclear Experimental Reactor (ITER) project's advancement in 2020. They propose a 'Global Commission for Urgent Action on Fusion Energy' to foster international collaboration and accelerate the shift from fossil fuels to a fusion-based economy, aligning with Society 5.0's sustainable energy goals.

Nižetić et al. [59] discuss the vital role of smart technologies in addressing global warming and promoting balanced economic development, as highlighted at the SpliTech2018 conference. Their review emphasizes interdisciplinary collaboration for efficient resource utilization and energy conversion, focusing on green buildings, solar energy, and smart cities. This aligns with Society 5.0's goals of sustainable and intelligent resource management.

Petrescu et al. [60] discuss the essence of Industry 5.0 in aligning with the sustainable goals of Society 5.0. They emphasize the reintegration of the human element into industrial processes, advocating for advanced technologies that not only support human endeavors but also cater to their needs and interests. Industry 5.0, according to them, is not just about technological advancement but also about fostering a sustainable industry, aiming for a "totally sustainable society". The paper also delves into the sustainability of the industrial sector, highlighting its dependence on the planet's energy resources. It stresses the multifaceted nature of the energy transition, which, while protecting the environment, also brings economic, social, and technical challenges. Addressing these challenges necessitates the collective effort of companies, consumers, investors, and educational institutions to foster a change in mentality and behavior toward sustainability.

3.2. *Environmental Sustainability and Society 5.0*

Kasinathan et al. [61] explore the role of disruptive technologies in achieving SDGs within the framework of Society 5.0 and Industry 5.0. They emphasize the heightened need for societal changes towards sustainability, a process where technology is key, especially in the wake of the pandemic. The study delves into how disruptive technologies influence SDGs through various domains like product development, healthcare, and smart cities. Particularly, it maps these technologies' impacts on SDGs 3, 8, 9, and 11. The research suggests that integrating Industry 5.0 and Society 5.0 to develop smart cities and villages enhances the prospects of attaining SDGs due to the synergy of these integrated frameworks. The study also includes a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis to evaluate this integrated approach, providing valuable insights for industrialists, policymakers, and researchers in aligning technological advancements with the goals of environmental sustainability.

In their research, Mourtzis et al. [62] explore the evolution from Industry 4.0 to Society 5.0, emphasizing a shift towards human-centric and sustainable resource management. While Industry 4.0 focuses on digital efficiency in manufacturing, Industry 5.0 integrates human aspects into these technologies, aiming for a sustainable and resilient design. This approach is crucial in Society 5.0, where the emphasis is on harmonizing technological advancement with sustainable resource utilization and human well-being.

Turner et al. [63] discuss Industry 5.0's focus on integrating human decision-making into digital manufacturing, aligning with the environmental and social goals of Society 5.0. Their study highlights the importance of dynamic Life Cycle Assessment (LCA) facilitated by intelligent products, particularly in managing resources efficiently and achieving net-zero carbon goals. The paper emphasizes the critical role of human involvement in the sustainable reuse and disassembly of products, essential for resource conservation and addressing environmental concerns in the manufacturing process.

3.3. *Smart Solutions for Ecological Challenges*

Fukuda [64] examines Society 5.0, a concept initiated by Japan, envisioning a new human-centered society. The paper analyzes the transformation of Japan's Science, Technology, and Innovation (STI) ecosystem, comparing it with Germany and the United States. It identifies key socio-economic risks affecting Japan's STI ecosystem, such as labor, capital, and spatial challenges. To address these risks, the paper suggests transitioning from a push-based to a pull-based STI ecosystem, focusing on creating societal value. This approach is pivotal in enhancing system resilience, revitalizing productivity, and promoting growth in Society 5.0. Central to this transition is the efficient utilization and management of resources, ensuring that technological and innovative advancements contribute to ecological solutions and sustainable development within the framework of Society 5.0.

Onu et al. [65] delve into the implications of Industry 4.0 for optimizing renewable energy and materials development, highlighting the potential for increased efficiency and sustainability. Their study emphasizes how Industry 4.0 technologies, such as IoT and AI, can enhance resource management, contributing to a more sustainable, low-carbon future. By addressing economic, regulatory, and technical challenges, the study underscores the crucial role of Industry 4.0 in advancing the efficient use and development of renewable resources. This research is particularly relevant for those looking to implement strategies that align technological innovation with sustainable resource utilization.

Wang et al. [66] examine the role of artificial intelligence (AI) in advancing the construction industry within the Industry 4.0 framework, particularly in enhancing the sustainability and efficiency of construction materials. The study highlights AI's application in improving concrete, composites, and metals, focusing on durability, safety, and recyclability. They foresee a future where AI, integrated with big data, revolutionizes the design, manufacturing, and operation of construction materials, contributing significantly to resource efficiency and sustainable development in the construction sector.

3.4. *Society 5.0 and Human-Centric Approaches to Nature*

Deguchi et al. [67] explore the concept of Society 5.0, particularly focusing on its implications for future urban living and resource management. Their research, conducted under the H-UTokyo Lab, delves into how a technology-based, human-centered society, emerging from the fourth industrial revolution, can transform city life. The study emphasizes the importance of a data-driven, knowledge-intensive, and non-monetary approach in shaping urban environments. Central to their analysis is how Society 5.0 can lead to more efficient use of resources in urban settings, aligning technological advancements with sustainable, human-centric urban development. This research provides insights into the directionality of Japan's national vision for Society 5.0, highlighting its potential to foster sustainable resource management in future cities.

Narvaez Rojas et al. [68] discuss Japan's Society 5.0, focusing on utilizing technological advancements to address critical societal challenges and contribute to sustainable development. The study links Society 5.0's goals with the SDGs, emphasizing the importance of using modern technology sustainably to ensure efficient resource utilization and to create an inclusive society where technological benefits reach everyone.

Phuyal et al. [69] explore the concept of smart manufacturing, which leverages interconnected machines and tools enhanced by big data processing, artificial intelligence, and advanced robotics. Their paper examines the current state of smart manufacturing systems, identifying gaps between existing manufacturing systems and future smart manufacturing technologies. The study highlights how these technologies contribute to improving manufacturing performance, particularly in optimizing energy use and workforce efficiency. The paper also presents a survey of recent developments in smart manufacturing, analyzing its impacts, challenges, opportunities, and future directions. This research underscores the potential of smart manufacturing in revolutionizing resource utilization and efficiency in the manufacturing sector.

3.5. *Integrating Technology and Environmental Management*

Calp & Bütüner [70] analyze the evolution of industrial revolutions, culminating in Society 5.0, which integrates technologies like AI, cyber-physical systems, and cloud computing from Industry 4.0. They emphasize Society 5.0's aim to enhance living conditions and foster social development through these technologies, focusing on sustainable welfare and smart societal solutions. The chapter reviews the history of industrial revolutions, defines Society 5.0's goals, innovations, and its synergy with AI, and discusses the challenges in implementing this latest revolution. The study highlights Society 5.0's role in improving resource management and environmental sustainability through effective technological integration.

Maddikunta et al. [71] present a survey-based tutorial on Industry 5.0, emphasizing its role in combining human creativity with intelligent machines for resource-efficient manufacturing. They introduce new concepts and definitions of Industry 5.0, discussing its potential applications in areas like intelligent healthcare, cloud manufacturing, and supply chain management. The paper also covers supporting technologies for Industry 5.0, including edge computing, digital twins, and blockchain. It concludes by identifying research challenges and open issues essential for realizing Industry 5.0, highlighting the importance of this evolution in achieving efficient resource management and sustainability in Society 5.0.

Villar et al. [72] investigate the impact of Industry 5.0 on supply chain management, introducing the concept of 'Supply Chain 5.0'. Their study, based on a systematic literature analysis of documents from 2016 to 2022, presents a framework for understanding the key technologies and trends in Supply Chain 5.0. They emphasize how Industry 5.0 can optimize supply chains, aiding companies in efficiently managing resources and maintaining competitiveness in a rapidly evolving industrial environment.

3.6. Technological Advancements in Industry 4.0 and 5.0

Ali et al. [73] discuss the use of graphene nanoparticles in Industry 4.0, highlighting their potential to enhance sensory capabilities in various industries. This advancement is significant for the transition to Society 5.0, where graphene's role in smart factories can contribute to greater digitalization and efficiency. The study focuses on integrating these materials with AI and blockchain, emphasizing their importance in evolving towards a more connected and technologically advanced society.

Beier et al. [74] analyze the incorporation of sustainability within Industry 4.0, focusing on its alignment with the SDGs. Their findings indicate a predominant focus on economic aspects, with limited evidence of Industry 4.0 advancing sustainable production. This gap underscores the necessity of integrating sustainability more profoundly into Industry 4.0, which is crucial for transitioning towards the more holistic, sustainability-focused goals of Society 5.0.

Javaid et al. [75] emphasize the importance of Cyber-Physical Systems (CPS) in Industry 4.0 for enhancing real-time data analysis and manufacturing efficiency. The integration of CPS, along with IoT and Digital Twin technologies, is crucial for smart manufacturing and decision-making. This advancement in interconnected systems and automation is key to progressing toward Society 5.0, where digital and physical integration drives industrial efficiency and sustainability.

Liang et al. [76] explore the use of Landfill Gas (LFG) from municipal solid waste as a sustainable energy source for data centers in Xiamen, China, aligning with the circular economy concept. Their study assesses the environmental and economic impacts of this approach, utilizing LFG for energy while recovering waste heat. This method not only recycles waste effectively but also reduces primary energy use and CO_2 emissions. The reuse of waste heat enhances energy efficiency and provides socio-economic benefits. This innovative strategy of using LFG and waste heat for data centers supports resource recovery and energy efficiency, contributing to the sustainable development of urban cities. This approach resonates with the goals of Society 5.0, which aims to integrate technological advances with sustainable resource management for societal benefit.

Xu et al. [77] discuss the transition from the technology-driven Industry 4.0 to the value-driven Industry 5.0. They analyze key questions surrounding the coexistence of these two industrial revolutions, aiming to stimulate debate on their differentiation and integration. This discussion is crucial in understanding the shift towards Society 5.0, where the focus is on harmonizing technological advancements with human-centered values and sustainable resource management.

3.7. Societal Impacts and Development in Society 5.0

In a rapidly evolving digital landscape, Fukuyama [78] highlights the transformative role of ICT in shaping society and industry, particularly focusing on Society 5.0. This concept, as an integral part of Japan's industrial policy, aims to create new values and sustainable growth strategies, addressing global trends and challenges. Within this framework, Gustiana et al. [79] propose a novel digital platform design using a Sociotechnical System (STS) approach. Their work aims to address multifaceted poverty issues, contributing to Society 5.0's vision of a more inclusive technological world where no individual is excluded from advancements.

Kusiak [80] delves into the nuances of smart manufacturing, emphasizing digitization, sustainability, and resilience. These concepts are pivotal in the shift towards Society 5.0, where smart manufacturing becomes a cornerstone for sustainable and efficient industrial practices. In line with this, Masoomi et al. [81] explore the potential of Industry 5.0 to enhance sustainable practices in the renewable energy supply chain. Their study aligns with Society 5.0's goals, focusing on adaptability, human-centered orientation, and addressing social and environmental issues.

Nahavandi [82] introduces Industry 5.0, highlighting the synergy between human workers and robotics, a collaboration that promises increased productivity and job creation, resonating with the core values of Society 5.0. This human-robot collaboration underlines the shift towards a society that values both technological advancement and human input.

Pascoal-Faria et al. [83] discuss the transition from prototyping to rapid manufacturing within Industry 4.0, underlining the importance of sustainable materials in manufacturing. Their focus on reducing carbon footprint and integrating digitalization in material science contributes to the environmental sustainability goals of Society 5.0. They emphasize the need for a unified approach to digitalizing material science, considering the diverse range of materials and their unique properties. This approach is instrumental in developing digital twins for the entire manufacturing cycle, extending to future life cycle stages, including reuse and recycling.

Pereira et al. [84] examine the promises of Industry 4.0 in revolutionizing industrial production, emphasizing its role in enhancing life quality and productivity. The emergence of Society 5.0 from Industry 4.0, particularly in Japan, is driven by the aging population and the need to use Industry 4.0 tools and technologies for human benefit. Society 5.0, as envisioned, positions humans at the center of innovation, leveraging advanced technology for societal well-being.

Potočan et al. [85] report that addresses how Society 5.0 balances Industry 4.0 with responsible economic development and social problem resolution through Corporate Social Responsibility (CSR). Their findings advocate the integration of technology into CSR models, tailored to address individual social problems regionally. This study provides practical guidance for improving CSR practices in organizations, aligning with the environmental and social circumstances of modern society.

Ptak et al. [86] investigate the potential of renaturalized lakes in Poland, a significant step towards increasing water resources and offering new ecosystem services. Their methodology complements water-management efforts aimed at increasing retention, presenting a less invasive and more economically justified approach compared to new investments in artificial hydro-technical infrastructure. This aligns with Society 5.0's focus on sustainable natural resource management.

Roblek et al. [87] analyze the technological developments in internet and internet technologies, highlighting their significance for sustainable development and the emergence of Society 5.0. Their automated content analysis of scientific articles reveals themes central to the development and impact of internet technologies on sustainable development, contributing to the conceptualization of Society 5.0.

Serpa & Ferreira [88] reflect on the increasing presence of digital technology in contemporary societies, emphasizing its impact on human relationships and sustainability innovations within Society 5.0. Their document analysis underscores the importance of recognizing the non-neutrality of technological phenomena, and mobilizing appropriate instruments to maximize the efficiency of sustainable digital innovations.

Skobelev & Borovik [89] discuss the current phase of Industry 4.0, characterized by the integration of the physical and virtual worlds, and the emerging paradigm of Industry 5.0. This new phase envisions the deep penetration of Artificial Intelligence in everyday life, enhancing human capacity and positioning humans at the center of technological advancements. Their work outlines the convergence of modern technologies, from IoT to emergent intelligence, which will facilitate the transformation from Industry 4.0 to Industry 5.0.

Smuts & Van der Merwe [90] address the need for organizations to navigate Society 5.0, a knowledge-intensive society where sustainable balance is achieved through systems integrating cyberspace and physical space. Their research, using automated content analysis, identifies key knowledge management aspects related to sustainability in Society 5.0, mapping them to the triple bottom line of environment, society, and economic performance.

Lastly, Zengin et al. [91] explore the concept of Society 5.0 and its effectiveness in Turkey, particularly concerning the SDGs. Their research, based on a survey among academicians, assesses the influence of SDGs on Industry 4.0 and Society 5.0, revealing that Turkey is still progressing by focusing on outdated processes rather than leading in the field of Society 5.0 and Industry 4.0.

Together, these studies provide a comprehensive view of the multifaceted impact of Society 5.0 on various aspects of life, emphasizing the integration of technological advancements with a focus on sustainable development and human-centered approaches.

3.8 Smart Solutions for Environmental Challenges

In addressing environmental challenges within the context of Society 5.0, smart solutions play a pivotal role, focusing on new technology to enhance energy efficiency, effectively manage resources, and support sustainability (**Table 2**). Central areas include green technology in businesses, urban planning for smart cities, and renewable energy production.

Smart cities are integral to this approach, utilizing innovative technologies for efficient resource management, such as water and energy, while reducing waste and pollution. Energy-efficient buildings in these cities use renewable sources like solar power, aiding in environmental protection and resource conservation.

The shift towards renewable energy sources, such as solar and wind power, is critical in the energy sector. This transition combats global warming and fosters balanced economic growth, with advanced technologies optimizing the use and distribution of these resources, leading towards a sustainable and reliable energy future.

Moreover, these smart solutions signify more than technological advancements; they represent a paradigm shift in how we think and act toward the environment. This involves educating communities, businesses, and governments about these technologies and their application, aiming to cultivate a society that is advanced, sustainable, and environmentally conscious.

In this context, the development of sustainable business models (SBMs) has gained momentum, driven by increased environmental awareness. As Karuppiah et al. [92] highlight, SBMs are becoming a significant topic in both industrial and academic realms. Their analysis using the PRISMA framework on 63 articles from the Scopus database reveals emerging areas in SBMs, including strategies, challenges, drivers, the role of innovation, and digital technologies' impact. This study provides a comprehensive view of SBMs, emphasizing their quantitative focus in the manufacturing industry and suggesting future research directions.

Furthermore, the concept of circular bioeconomy (CBE) practices, as explored by Karuppiah et al. [93], demonstrates its capability to improve sustainable industrial performance. Their systematic literature review assesses the impact of CBE practice on industry sustainability, identifying challenges such as limited understanding, technological and financial support, and the need for a well-established reverse supply chain network. This study contributes significantly by highlighting the challenges industries face in adopting CBE practices and the synergy between CBE practice and sustainability.

These insights into SBMs and CBE practices align with the principles of Society 5.0, where technological innovation is harmonized with ecological and social considerations. They underscore the need for continuous innovation and adaptability in various sectors, emphasizing the importance of sustainable practices in achieving a future that is not only technologically advanced but also ecologically responsible and equitable.

Table 2. Smart Solutions for Environmental Sustainability in Society 5.0.

Solution Category	**Description**	**Impact**
Smart Cities	Use of new technologies to efficiently manage resources like water and energy, reduce waste and pollution. Energy-efficient buildings using renewable energy like solar power.	Reduces resource consumption, lowers carbon footprint, and promotes sustainable urban living.
Renewable Energy	Increased use of solar and wind power to combat global warming and promote balanced economic growth. Enhanced distribution and optimization of these energy sources through new technology.	Leads to sustainable and reliable energy solutions, helps in reducing the effects of global warming.
Cultural & Behavioral Shift	Fostering a change in how people, businesses, and governments think and act towards the environment. Promoting the adoption and effective use of sustainable technologies.	Encourages a society-wide adoption of sustainable practices, mindful of ecological impact.

4. Perspectives on Society 5.0: Evaluating Key Resources

In Society 5.0, addressing the sustainable management of essential resources, including both rare and common minerals, is a pressing challenge. Rare minerals such as neodymium, dysprosium, and terbium are crucial for high-tech applications, while common minerals like copper, iron, and aluminum play a vital role in various industries. The demand for these minerals, driven by technological advancements and green initiatives, contrasts with environmental and geopolitical concerns. For instance, the global market for neodymium was valued at approximately $11.3 billion in 2019 and is expected to grow, reflecting its importance in technologies like wind turbines and electric vehicles [94].

Strategic diversification of supply sources is essential to mitigate supply risks. Exploring new mineral deposits in stable regions can alleviate dependencies, while enhancing recycling and reuse can reduce mining reliance and environmental degradation. Material science innovations could significantly decrease the demand for scarcity-prone minerals, with research indicating potential alternative materials [95].

Efficient water management is another crucial aspect. Implementing smart irrigation and industrial recycling can considerably reduce water wastage. Given the impact of climate change on water availability, such strategies are vital for a resilient water supply [96].

In the energy sector, the transition to renewable sources like solar and wind necessitates advancements in storage and efficiency. The renewable energy market is projected to reach $1.1 trillion by 2025, highlighting the growing need for innovative energy solutions [97].

Beyond tangible resources, human capital, technological innovation, and adaptability are indispensable in Society 5.0. Human capital, with its wealth of knowledge and creativity, becomes a pivotal asset. Continuous learning is essential, preparing individuals for advanced technologies and evolving environments. Skills development in critical thinking and problem-solving is crucial for fostering innovation [98].

Technological innovation, with the ongoing evolution of AI, IoT, and robotics, will increase efficiency across sectors and address complex challenges. This wave of innovation, if aligned with human-centric approaches, can significantly improve life quality. However, technology must be developed and applied to serve human interests sustainably [16].

Adaptability and continuous learning are vital in this era. The ability to quickly adapt extends beyond technologies to policies, regulations, and business strategies. In a constantly changing world, the capacity for continuous evolution will be a key differentiator [99].

Society 5.0 advocates for a blend of innovation, global cooperation, and sustainable resource management practices. This approach aims to create a balance where technology serves human needs without compromising environmental health. The envisioned future is one where technological progress and resource sustainability support a more equitable world, demonstrating that technological and ecological goals can be aligned [100].

5. Conclusions

In concluding our extensive review of resource optimization and sustainability within the framework of Society 5.0, we propose a conceptual model that encapsulates the intricate and interconnected dynamics of this transition. Society 5.0 represents a profound shift, moving beyond mere technological advancements to fundamentally alter how we perceive and interact with our resources and environment.

Our conceptual model situates Society 5.0 at the confluence of three critical domains: advanced technology, human-centric development, and sustainable resource management. The essence of this model lies in the synergy among these domains, where each element supports and enhances the others. Advanced technology, including AI and IoT, acts as the driving force for efficiency and innovation in resource management. However, this technological impetus is guided by a human-centric approach, ensuring that advancements align with societal needs and ethical considerations. The third domain, sustainable resource management, represents the ultimate objective, aiming to ensure that both technological and human-centric developments contribute to a healthier planet and society.

The role of minerals, both rare and common, is integrated into this model as the fundamental components of this technological evolution. The responsible sourcing, use, and recycling of these minerals create a cycle that not only supports the technological infrastructure of Society 5.0 but also maintains environmental integrity.

Water and energy management are identified as pivotal elements within this model. Their sustainable management is essential to ensure that these vital resources bolster the societal and technological advancements of Society 5.0. The model advocates for cutting-edge solutions in these areas, like smart grids and water conservation technologies, which are emblematic of the principles of Society 5.0.

Our literature review highlights a shared recognition among experts regarding the critical importance of harmonizing technological progress with sustainable resource management. This harmony is key to the success of Society 5.0 and vital for ensuring the long-term health and prosperity of our environment and society.

However, it's important to acknowledge the limitations of our study. The rapid evolution of technologies and societal structures means that our findings represent a snapshot in a continually changing landscape. Future research should focus on the ongoing development of these technologies and their societal implications, as well as the practical challenges of implementing the principles of Society 5.0 globally.

Society 5.0 envisions a future where technology and sustainability are intertwined, leading us toward a more efficient, equitable, and sustainable existence. This journey is fraught with challenges, but through collective efforts and a steadfast commitment to innovation and sustainability, these challenges can be transformed into opportunities for progress and development. This model not only theorizes the central concepts of Society 5.0 but also serves as a roadmap for future research, policy-making, and societal transformation.

Author Contributions: Conceptualization, C.R.M., T. P.P., A.Y. R.T., and J. M. P.O.; methodology, C.R.M., T. P.P., A.Y. R.T., and J. M. P.O..; formal analysis, C.R.M., T. P.P., A.Y. R.T., and J. M. P.O..; investigation, C.R.M., T. P.P., A.Y. R.T., and J. M. P.O.; resources, J. M. P.O..; data curation, C.R.M., T. P.P., A.Y. R.T., and J. M. P.O..; writing—original draft preparation, C.R.M., T. P.P., A.Y. R.T., and J. M. P.O.; writing—review and editing, C.R.M., T. P.P., A.Y. R.T., and J. M. P.O.; visualization, C.R.M., T. P.P., A.Y. R.T., and J. M. P.O.; supervision, J. M. P.O.; project administration, J. M. P.O.; funding acquisition, J. M. P.O. All authors have read and agreed to the published version of the manuscript.

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Incorporating Machine Learning in Clustering of Spatiotemporal Patterns of Dam Filling

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Author Contributions

Methodology, Investigation, Writing - Original Draft: Alma Yunuen Raya-Tapia. Investigation, Writing - Original Draft: Thelma Posadas-Paredes. Conceptualization, Supervision, Writing - Review & Editing: César Ramírez-Márquez. Supervision, Writing - Review & Editing: José María Ponce-Ortega.

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7.5. ÁPENDICE E

Clustering-Based Classification of Global Natural Resource Utilization Patterns for Sustainable Development

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7.6. ÁPENDICE F

resources MDPI

Communication

From Resource Abundance to Responsible Scarcity: Rethinking Natural Resource Utilization in the Age of Hyper-Consumption

César Ramírez-Márquez [1,*], Thelma Posadas-Paredes, [1] José María Ponce-Ortega [1,*]

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Abstract: The global economy is experiencing an unsustainable increase in resource extraction and material consumption, largely driven by hyper-consumption and linear production systems. This communication article argues for a conceptual shift from the paradigm of resource abundance toward responsible scarcity. The analysis highlights recent trends in material throughput, the transgression of planetary boundaries, and the structural and geopolitical inequalities underlying global resource use. A framework is proposed to guide sustainable resource governance based on ecological constraints, equity, and long-term resilience. The communication article concludes with a research and policy agenda to support the transition to more sustainable and just modes of resource utilization.

Keywords: Natural resource governance; Hyper-consumption; Planetary boundaries; Ecological economics; Responsible scarcity.

1. Introduction

Over the last half-century, global material extraction has increased at an unprecedented rate, driven by economic expansion, industrialization, and shifting consumption patterns [1]. According to the United Nations Environment Programme's International Resource Panel, global material extraction increased from 27 billion tonnes in 1970 to 92 billion tonnes in 2017. More recent estimates indicate that extraction reached approximately 106 billion tonnes by 2020 [2]. This trend is indicative of a global economy becoming increasingly dependent on natural resources, despite growing awareness of environmental degradation and climate change. Notably, material productivity, defined as the ratio of Gross Domestic Product (GDP) to domestic material consumption, has stagnated since the early 2000s, signaling that economic growth continues to be closely coupled with resource use [3]. In this way, **Figure 1** shows a notable growing tendency for the GDP per capita over the years, thus indicating a notable upward trend in natural resources consumption [4].

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7.7. ÁPENDICE G

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Septiembre Diciembre 2025
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CONSUMISMO DESMEDIDO, PELIGRO LATENTE

Thelma Posadas-Paredes [a], César Ramírez-Márquez [a*], José María Ponce-Ortega [a]

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Resumen

En la actualidad la cultura del consumismo ha llevado a una explotación desmedida de los recursos naturales, desatando como consecuencia serios problemas y/o desastres naturales. Continuar con dichas tendencias de consumo, sin lugar a dudas llevará al colapso de nuestro planeta. Por ello, es fundamental adoptar políticas públicas y acciones cotidianas que contribuyan al desarrollo sostenible, como reducir el consumo innecesario, optar por productos reutilizables y reciclables, disminuir el uso de plásticos desechables, ahorrar energía y agua, fomentar una alimentación responsable basada en productos locales y de temporada, y apostar por medios de transporte sustentables. Implementar estos cambios no solo ayuda a mitigar el impacto ambiental, sino que también promueve una cultura de consumo más consciente y responsable que vele por el cuidado del medio ambiente.

Palabras clave: Consumismo; Recursos naturales; Desarrollo sostenible.

Excessive Consumerism, a Latent Threat

Abstract

Nowadays consumer culture has led to the excessive exploitation of natural resources, resulting in serious problems and/or natural disasters. Continuing with these consumer trends will undoubtedly lead to the collapse of our planet. Therefore, it is essential to adopt public policies and daily actions that contribute to sustainable development, such as reducing unnecessary consumption, opting for reusable and recyclable products, reducing the use of single-use plastics, saving energy and water, promoting responsible eating based on local and seasonal products, and opting for sustainable modes of transportation. Implementing these changes not only helps mitigate the environmental impact but also promotes a more conscious and responsible consumer culture that cares for the environment.

7.8. ÁPENDICE H

Integrated Strategies for Developing Sustainable Energy Systems

From Carbon Capture to Energy System Optimization

1st Edition - October 1, 2025 • Imprint: Elsevier

Authors: Esbeydi Villicaña-García, Edgar Geovanni Mora-Jacobo, Thelma Posadas-Paredes, Aurora de Fátima Sánchez-Bautista, César Ramírez-Márquez, José Maria Ponce-Ortega

Language: English • Paperback ISBN: 9780443342868 • eBook ISBN: 9780443342875

Description

Integrated Strategies for Developing Sustainable Energy Systems: From Carbon Capture to Energy System Optimization brings together insights into sustainable energy production and carbon capture technologies, as well as strategies for more sustainable chemical processes, from all aspects from process design and optimization strategies, through to effective implementation. This book equips readers with the knowledge and tools to implement sustainable chemical processes, providing them with the knowledge and tools needed to advance sustainability and energy optimization in their respective fields. The content combines a strong theoretical foundation, methodology details, real-world case studies and calculations to offer detailed process design theory and methodology, integrated strategies, carbon-capture technologies and eco-friendly energy system designs. This is a valuable resource for all those with an interest in sustainable energy systems and related practices, including researchers, faculty, industry professionals, policy makers, decision makers, and environmental advocacy groups.

8. ANEXOS

8.1. ANEXO 1

Thelma Posadas Paredes

ANÁLISIS DE LA PRODUCCIÓN Y EL CONSUMO SOSTENIBLES MEDIANTE INTELIGENCIA ARTIFICIAL PARA UNA SOCIEDA

Universidad Michoacana de San Nicolás de Hidalgo

Detalles del documento

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8.2. ANEXO 2

Formato de Declaración de Originalidad y Uso de Inteligencia Artificial

Coordinación General de Estudios de Posgrado
Universidad Michoacana de San Nicolás de Hidalgo

A quien corresponda,

Por este medio, quien abajo firma, bajo protesta de decir verdad, declara lo siguiente:

- Que presenta para revisión de originalidad el manuscrito cuyos detalles se especifican abajo.
- Que todas las fuentes consultadas para la elaboración del manuscrito están debidamente identificadas dentro del cuerpo del texto, e incluidas en la lista de referencias.
- Que, en caso de haber usado un sistema de inteligencia artificial, en cualquier etapa del desarrollo de su trabajo, lo ha especificado en la tabla que se encuentra en este documento.
- Que conoce la normativa de la Universidad Michoacana de San Nicolás de Hidalgo, en particular los Incisos IX y XII del artículo 85, y los artículos 88 y 101 del Estatuto Universitario de la UMSNH, además del transitorio tercero del Reglamento General para los Estudios de Posgrado de la UMSNH.

Datos del manuscrito que se presenta a revisión		
Programa educativo	Maestría en Ciencias en Ingeniería Química	
Título del trabajo	"ANÁLISIS DE LA PRODUCCIÓN Y EL CONSUMO SOSTENIBLES MEDIANTE INTELIGENCIA ARTIFICIAL PARA UNA SOCIEDAD RESILIENTE"	
	Nombre	**Correo electrónico**
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Formato de Declaración de Originalidad y Uso de Inteligencia Artificial

Coordinación General de Estudios de Posgrado
Universidad Michoacana de San Nicolás de Hidalgo

Uso de Inteligencia Artificial		
Rubro	**Uso (sí/no)**	**Descripción**
Asistencia en la redacción	Sí	Utilicé Quillbot, que es una herramienta de escritura basada IA, para el parafraseo de algunas oraciones. Sin embargo, una vez parafraseadas las oraciones por Quillbot, yo las volví a modificar y adecuar a lo que quería expresar.
Traducción al español	No	
Traducción a otra lengua	No	
Revisión y corrección de estilo	No	
Análisis de datos	Sí	El proyecto se centra en el análisis de datos haciendo uso de k-means clustering que es una herramienta de IA, programada en Python.
Búsqueda y organización de información	Sí	Utilice Elicit, para saber cuáles son los artículos sobresalientes y recientes sobre determinados temas.
Formateo de las referencias bibliográficas	No	Utilicé el software Mendeley para la gestión de las referencias bibliográficas, pero no se cataloga como IA.
Generación de contenido multimedia	No	
Otro	No	

Datos del solicitante	
Nombre y firma	Thelma Posadas Paredes
Lugar y fecha	Morelia, Michoacán, a 14 de julio de 2025.