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GRADO EN INGENIERÍA EN TECNOLOGÍAS DE TELECOMUNICACIÓN

TRABAJO FIN DE GRADO

# Programming Energy Models in Python for the Decarbonization of the Spanish Energy System


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Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Programming Energy Models in Python for the Decarbonization of the Spanish Energy System

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

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# Programming Energy Models in Python for the Decarbonization of the Spanish Energy System

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# PROGRAMACIÓN DE MODELOS EN PYTHON PARA LA DESCARBONIZACIÓN DEL SISTEMA ENERGÉTICO ESPAÑOL

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## RESUMEN DEL PROYECTO

El presente trabajo introduce openMASTER, un innovador modelo de planificación energética de código abierto desarrollado con Python y Pyomo. El modelo tiene como objetivo maximizar el bienestar social mediante la optimización de la inversión y los costes operativos del sistema energético dentro de las limitaciones ambientales.

**Palabras clave**: Código abierto, modelo energético, transición energética, España.

### 1. Introducción

### 1.1 Presentación del proyecto y su relevancia

La sostenibilidad es un concepto complejo y amplio, pero un aspecto básico es el acceso a recursos energéticos libres de emisiones. A medida que la población mundial crece y aumenta su nivel de vida, la demanda de energía sigue aumentando. Dado que el sector energético genera alrededor de tres cuartas partes de todas las emisiones de gases de efecto invernadero a nivel mundial, descarbonizar el sector energético es crucial para mitigar el cambio climático. Para ello es necesario optimizar la gestión de los recursos energéticos y sustituirlos progresivamente por fuentes de energía sostenibles y de bajas emisiones.

Sin embargo, este reto requiere un esfuerzo colectivo de la sociedad para regular y dirigir el futuro energético del país. En este contexto, entran en juego dos conceptos importantes: la planificación energética y los modelos de código abierto:

- *La planificación energética* consiste en proyectar las necesidades energéticas futuras teniendo en cuenta las actuales. Para ello es necesario tener en cuenta a todos los agentes energéticos, las infraestructuras existentes, las fuentes de generación y demanda y los factores macroeconómicos. Los procesos convencionales son ineficaces para procesar tal cantidad de información, por lo que el uso de modelos avanzados de optimización es crucial para la planificación energética.

- El término *"código abierto"* hace referencia a los programas informáticos diseñados para ser totalmente accesibles al público. Es decir, se trata de software que puede ser estudiado, modificado, mejorado y distribuido libremente, siendo el usuario quien establece los límites.

En consecuencia, los modelos de planificación energética de código abierto son programas desarrollados con la misión de ser accesibles públicamente, promoviendo el progreso y la investigación tecnológica necesarios en el actual contexto de transición energética.

Los modelos energéticos de código abierto son una poderosa herramienta para promover la participación y la colaboración en la sociedad. Accesibles a todos, estos modelos permiten a investigadores, responsables políticos y otras partes interesadas colaborar y contribuir a su desarrollo.

Al promover la transparencia y la reproducibilidad en la modelización de los sistemas energéticos, aumentan la inclusividad al permitir que un mayor número de agentes participen en los procesos de planificación energética. Al eliminar barreras, los modelos de código abierto permiten una toma de decisiones más democrática y colaborativa en el sector energético.

Como resultado, estos modelos de código abierto son cruciales para alcanzar los Objetivos de Desarrollo Sostenible (ODS), en particular el ODS 7, cuyo objetivo es garantizar el acceso universal a una energía asequible, fiable y sostenible (International Energy Agency, 2021). Al evaluar las implicaciones de las políticas energéticas, los avances tecnológicos y la dinámica del mercado, estos modelos proporcionan una base empírica para la toma de decisiones, ayudando a los países a equilibrar las demandas de crecimiento económico, equidad social y protección del medio ambiente. Pueden identificar las estrategias energéticas más eficaces y eficientes para alcanzar los ODS, destacando la importancia de la planificación energética en la agenda del desarrollo sostenible.

## 1.2 Estado del arte de los modelos energéticos de código abierto

Actualmente, existen pocas herramientas de modelado energético que permitan realizar estudios a nivel macroeconómico de forma interpretable y fácilmente comprensible para especialistas ajenos al mundo de la computación o de las matemáticas, es decir, un modelo accesible para decisores políticos, reguladores y empresas.

Muchas entidades poseen modelos de planificación energética a largo plazo, pero son privados. Por otro lado, existen modelos de código abierto como MARKAL-TIMES, pero requieren herramientas de cálculo que no son de código abierto, como GAMS. No obstante, existe una tendencia creciente hacia herramientas de código abierto como OSEMOSYS, TEMOA, openTEPES y MUSE. Estos modelos tienen el potencial de ofrecer una modelización energética más accesible y transparente para un mayor número de usuarios.

## 1.3 Descripción del proyecto

### 1.3.1 El modelo MASTER

En este contexto, el Modelo de Análisis de Energía Sostenible (MASTER) emerge como una solución prometedora. Desarrollado como parte de la tesis doctoral de López-Peña Fernández (2014) en la Universidad Pontificia Comillas (Madrid), en el marco de la Cátedra BP de Energía y Sostenibilidad y el Instituto de Investigación Tecnológica, el MASTER ofrece una valiosa aproximación al análisis de la planificación energética en el contexto de la sostenibilidad.

En este marco, el MASTER.SO es un modelo de optimización para la planificación energética, programado en GAMS, que persigue maximizar el bienestar social. Con este objetivo, el modelo es capaz de representar el funcionamiento del sistema energético y optimizar los costes de inversión y operación. MASTER.SO busca un equilibrio entre simplicidad y precisión para obtener resultados fiables y fácilmente interpretables por los reguladores, sin necesidad de grandes cargas computacionales. El modelo MASTER.SO tiene un gran potencial en el contexto de la planificación energética, ya que cumple con éxito sus dos objetivos principales:

- Optimizar el suministro de energía, la distribución de recursos de un país y las inversiones necesarias para ello, basándose en consideraciones de beneficio social y sostenibilidad.

- Presentar los resultados de forma fácilmente interpretable, permitiendo que las partes interesadas con menos conocimientos técnicos puedan beneficiarse del modelo.

Sin embargo, como ya se ha mencionado, la tendencia actual es la transición hacia soluciones de código abierto. Por lo tanto, para evitar la obsolescencia o el desuso del modelo MASTER.SO, es aconsejable migrarlo de GAMS a herramientas de código abierto de libre acceso.

### 1.3.2 Transformación del modelo MASTER en un modelo de código abierto

La dependencia del modelo MASTER de software propietario como GAMS presenta un desafío potencial a la luz de la creciente popularidad de las soluciones de código abierto. El uso de licencias propietarias limita la replicabilidad, dificultando la creación de conocimiento científico e impidiendo la revisión por pares del modelo. Esto restringe la capacidad de la comunidad científica para revisar, utilizar y mejorar el modelo. Para hacer frente a estas limitaciones, es crucial migrar el modelo MASTER a un marco de código abierto y distribuible, el modelo openMASTER.

Esta transición no sólo contribuirá a evitar una posible obsolescencia, sino que también mejorará la usabilidad y la accesibilidad del modelo para un público más amplio. Al adoptar soluciones de código abierto, el modelo MASTER puede adaptarse eficazmente a las tendencias actuales y mantener su relevancia en este campo.

### 1.3.3 Uso de Python para modelos energéticos de código abierto

La decisión de elegir Python y Pyomo para convertir el modelo MASTER en un entorno de código abierto se fundamenta en varios factores. En primer lugar, la popularidad de Python y el amplio apoyo de la comunidad proporcionan a los desarrolladores una gran cantidad de recursos, documentación y experiencia. Esta red de apoyo facilita la implantación y el mantenimiento del modelo openMASTER. Además, la naturaleza de código abierto de Python y Pyomo fomenta la colaboración y el intercambio de conocimientos entre investigadores, responsables políticos y expertos del sector. Este enfoque colaborativo fomenta la innovación, permite la incorporación de diversas perspectivas y garantiza la mejora y el perfeccionamiento continuos del modelo. La versatilidad, legibilidad y amplio ecosistema de bibliotecas de Python, junto con la solidez y flexibilidad de Pyomo, proporcionan una base sólida para el proceso de conversión (véase Bynum et al., 2021).

### 1.4 Objetivos del trabajo

En este contexto, el presente proyecto establece varios objetivos interconectados, cada uno de los cuales se centra en una faceta distinta de la planificación energética:

- Evaluar el papel de los modelos de planificación energética en la consecución de los Objetivos de Desarrollo Sostenible (ODS) y el establecimiento de una economía de emisiones netas cero.
- Examinar la importancia de la participación de las partes interesadas en la planificación energética para desarrollar un modelo integral y sostenible.
- Destacar las ventajas de los modelos de código abierto para impulsar la transición hacia códigos de código abierto en la planificación energética.
- Formular una metodología de colaboración para mejorar la colaboración interdisciplinar entre investigadores en el desarrollo de modelos de código abierto.
- Colaborar en el desarrollo de openMASTER, un modelo energético de código abierto basado en MASTER.SO, haciendo especial hincapié en el diseño de módulos de datos de entrada y salida robustos y fáciles de usar.
- Llevar a cabo un estudio de caso contextual en España para demostrar la funcionalidad práctica del modelo openMASTER en escenarios reales y apoyar la toma de decisiones basada en pruebas para las estrategias de descarbonización.

## 2. Descripción del modelo openMASTER

### 2.1 Motivaciones para el desarrollo del modelo openMASTER

La motivación que inspira el desarrollo del modelo openMASTER es democratizar la investigación sobre planificación energética y fomentar la colaboración entre profesionales de diversas disciplinas y especialidades. Al involucrar a personas con distintos niveles de conocimientos técnicos y experiencia, el modelo pretende derribar las barreras a la participación en la transición energética. El objetivo es proporcionar herramientas de planificación energética accesibles a nuevas comunidades, garantizando que no se excluyan perspectivas valiosas debido a la limitación de recursos o conocimientos técnicos. La transformación del modelo de software propietario a un lenguaje de código abierto mejora aún más su flexibilidad y adaptabilidad, permitiendo a los usuarios personalizar y encontrar soluciones personalizadas. Este enfoque centrado en el usuario fomenta la contribución activa y crea un entorno colaborativo e integrador para la evolución y mejora continuas del modelo.

### 2.2 Características del modelo openMASTER

Para lograr su objetivo de fomentar un enfoque inclusivo y colaborativo de la transición energética, el modelo openMASTER requiere una serie de características indispensables. Estas características son cruciales para garantizar que el modelo sea accesible a un amplio abanico de participantes, adaptable a diferentes necesidades de modelización, capaz de integrarse con otros sistemas y, en última instancia, relevante e influyente a la hora de abordar los retos energéticos del mundo real. Al incorporar estas cualidades, el modelo openMASTER pretende capacitar a un amplio abanico de partes interesadas para que contribuyan activamente al desarrollo de soluciones innovadoras y eficaces para un futuro energético sostenible. Por ello, el modelo openMASTER incorpora varias características que pueden dividirse en cuatro categorías:

1) Entorno de trabajo y control de versiones
2) Módulos de entrada y salida de datos
3) Gestión de escenarios
4) Visualización y análisis de resultados

### 2.2.1 Entorno de trabajo y control de versiones

Para establecer un entorno de trabajo con control de versiones, se configuró un servidor Git en un repositorio local de la Universidad Pontificia de Comillas. El acceso a este servidor se aseguró a través de una VPN privada proporcionada por la Universidad para proteger la integridad y seguridad del código. Se eligió GitLab como interfaz para interactuar con el servidor Git debido a su plataforma fácil de usar, sus numerosas funcionalidades, el fuerte soporte de la comunidad y el alojamiento en el servidor del IIT de la Universidad. Para garantizar la compatibilidad del software, los investigadores estandarizaron la versión de Python y las bibliotecas utilizadas utilizando entornos virtuales. Se subió al repositorio Git un archivo compartido llamado "requirements.txt", que contenía las versiones de cada librería necesaria. Esto permitió a los colaboradores ser notificados y replicar cualquier actualización, adición o eliminación. Los entornos virtuales desempeñaron un papel crucial a la hora de aislar y gestionar las dependencias y configuraciones específicas del proyecto, garantizando la reproducibilidad y la flexibilidad. También simplificaron el proceso de mantenimiento y actualización, permitiendo al equipo centrarse en mejorar sus modelos de optimización energética sin preocuparse por los conflictos de dependencias del sistema.

### 2.2.2 Módulos de entrada y salida de datos

El sistema de entrada y salida de datos se ha diseñado para que sea fácil de utilizar y versátil, de modo que se adapte a usuarios con distintos conocimientos técnicos. Admite formatos de archivo genéricos y extendidos, con CSV como formato principal y Excel como formato opcional para una modificación sencilla de los datos por parte de los investigadores. Estos formatos se eligieron por su uso generalizado y su gran compatibilidad con un gran número de sistema y dispositivos. Esta metodología permite interpretar fácilmente los resultados sin necesidad de herramientas especializadas, lo que la hace accesible a usuarios sin conocimientos avanzados de gestión de datos.El procesamiento de datos en Python sigue un enfoque modular, lo que permite modificar y personalizar fácilmente componentes específicos sin que ello afecte a la funcionalidad general. Esto favorece la flexibilidad, la adaptabilidad y la reutilización del código.

#### 2.2.2.1 Tipos de datos

En un modelo de optimización intervienen tres tipos de datos: sets, parámetros y variables. Los sets representan grupos o categorías de elementos relacionados, los parámetros son valores constantes que proporcionan información al modelo y las variables son las incógnitas que el modelo trata de determinar para la solución óptima.

Los sets y los parámetros informan al modelo, mientras que las variables están sujetas a restricciones que definen sus relaciones con los sets y los parámetros. En otras palabras, los sets y parámetros representan la entrada del modelo, mientras que las variables representan sus salidas (resultados).

### 2.2.2.2 El módulo de entrada de datos

El modelo Python utiliza un proceso de carga de datos en dos pasos, pasando de Excel a CSV y luego de CSV a Pyomo. Este enfoque mejora la modularidad y permite futuras modificaciones del formato de los datos sin afectar a otras secciones. La carga de datos desde CSV es más rápida y no necesita repetirse a menos que se creen nuevos datos, lo que aumenta la versatilidad y adaptabilidad del modelo. La eficacia del procesamiento de archivos CSV optimiza el rendimiento, especialmente con grandes cargas de datos o cuando se requieren frecuentes actualizaciones.

Dada la naturaleza visual de las tablas de Excel, los lenguajes de programación no pueden interpretarlas directamente. Por ello, se desarrolló un sistema para identificar y procesar automáticamente distintos tipos de tablas. La Figura I ilustra una tabla de datos sin procesar en Excel.

*Figura I: Tabla Excel de datos sin procesar*

*Fuente: Elaboración Propia*

Parameter: PE Cost

Unit: [€ per MWh]

ATENTION: THIS TABLE IS **FORMULATED**. CHANGES SHOULD BE DONE AT THE **FORECASTING TABLE** (IN YELLOW)

pPECost

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ~BOUNDS~ | sPE/sYear | y2020 | y2025 | y2030 | y2035 | y2040 | y2045 | y2050 | y2055 | y2060 | y2065 | y2070 | y2075 | ~BOUNDS~ |
| | sPENUCLE | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | |
| | sPEIMPCO | 10 | 9 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | |
| | sPENAGAS | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | |
| | sPELNGAS | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | |
| | sPECROIL | 40 | 40 | 40 | 37,5 | 35 | 32,5 | 30 | 30 | 30 | 30 | 30 | 30 | |
| | sPEHYDRR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEHYDRC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEMNHY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEWINON | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEWINOF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPESOLPV | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPESOLTE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPESOLTH | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEBIOMEC | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | |
| | sPEBIOMAW | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | |
| | sPEBIOMFW | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | |
| | sPESWAST | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | |
| | sPEBIOETHPI | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | |
| | sPEBIODIEPI | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | |
| | sPEBIOGAS | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | |
| ~BOUNDS~ | sPEHUMANE | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | ~BOUNDS~ |

**Interpol Rule: lineal interpolation between known forecasting values**

Initial and final values (in green) are compulsory

Formula for interpolated values needs to be adjusted in case new values (rows) are included

**FORECASTING TABLE**

| sPE/sYear | 2020 | 2030 | 2050 | 2075 |
|---|---|---|---|---|
| sPENUCLE | 2,88 | 2,88 | 2,88 | 2,88 |
| sPEIMPCO | 10 | 8 | 8 | 8 |
| sPENAGAS | 18,4 | 18,4 | 18,4 | 18,4 |
| sPELNGAS | 37 | 37 | 37 | 37 |
| sPECROIL | 40 | 40 | 30 | 30 |
| sPEHYDRR | 0 | 0 | 0 | 0 |
| sPEHYDRC | 0 | 0 | 0 | 0 |
| sPEMNHY | 0 | 0 | 0 | 0 |
| sPEWINON | 0 | 0 | 0 | 0 |
| sPEWINOF | 0 | 0 | 0 | 0 |
| sPESOLPV | 0 | 0 | 0 | 0 |
| sPESOLTE | 0 | 0 | 0 | 0 |
| sPESOLTH | 0 | 0 | 0 | 0 |
| sPEBIOMEC | 21 | 21 | 21 | 21 |
| sPEBIOMAW | 17 | 17 | 17 | 17 |
| sPEBIOMFW | 8 | 8 | 8 | 8 |
| sPESWAST | 21 | 21 | 21 | 21 |
| sPEBIOETHPI | 54 | 54 | 54 | 54 |
| sPEBIODIEPI | 46 | 46 | 46 | 46 |
| sPEBIOGAS | 104 | 104 | 104 | 104 |
| sPEHUMANE | 175 | 175 | 175 | 175 |

El proceso de carga de datos consta de los siguientes pasos:

1) Identificación del tipo de datos (sets o parámetros) a partir del nombre de la hoja.

2) Definición de los límites de la tabla de datos dentro de cada hoja Excel (véanse los indicadores ~BOUNDS~ en la Figura I).

3) Identificar el formato de la tabla y procesarla correctamente en función de su tipología, definida en varias dimensiones (sets).

4) Convertir los datos de entrada en formato CSV para su posterior tratamiento por el programa Python. La Figura II muestra el archivo CSV formateado tras procesar los datos Excel brutos a través de la canalización de entrada.

*Figura II: Tabla CSV de datos procesados*

*Fuente: Elaboración Propia*

```
sPE,sYear,pPECost
sPENUCLE,y2020,2.88
sPEIMPCO,y2020,10.0
sPENAGAS,y2020,18.4
sPELNGAS,y2020,37.0
sPECROIL,y2020,40.0
sPEHYDRR,y2020,0.0
sPEHYDRC,y2020,0.0
```

### 2.2.2.3 El módulo de salida de datos

En el proceso de carga de datos del modelo, los sets y los parámetros son los principales tipos de datos implicados. Sin embargo, en la salida de datos, la atención se desplaza a las variables, que representan las incógnitas determinadas durante el proceso de optimización. La salida de datos puede dividirse en dos ramas: el almacenamiento de los datos de salida del modelo y la carga de los datos almacenados para su posterior visualización.

#### 2.2.2.3.1 Almacenamiento de los datos de salida del modelo

El proceso de salida de datos del modelo se definió de forma que replicara la canalización de los datos de entrada, pero a la inversa:

1) Tras ejecutar el modelo, cada variable se asocia a sus respectivos sets y se almacena en tablas de datos Python independientes. Estas tablas se organizan en un diccionario Python, con el nombre de la variable como clave y los correspondientes conjuntos de datos como valores. Este formato permite una fácil representación y visualización de los datos.

2) Simultáneamente, la información de las variables se exporta en formato CSV. Esto elimina la necesidad de volver a ejecutar el modelo para acceder a los datos y representarlos, lo que proporciona comodidad y eficacia. De nuevo, el formato CSV permite además poder exportar los resultados a otras herramientas de visualización o tratamiento que no requieran licencia.

3) Por último, para obtener los resultados de forma visual e interpretable, los archivos CSV que contienen las variables se convierten a un formato Excel consolidado. Esta consolidación reúne todos los resultados en un único archivo, lo que facilita el análisis y la interpretación de los datos. La Figura III muestra un ejemplo del resultado generado automáticamente.

*Figura III: Ejemplo de una variable de salida del modelo en Excel*

*Fuente: Elaboración Propia*

| sST / sYear | sES / sYear | y2020 | y2025 | y2030 | y2035 | y2040 | y2045 | y2050 |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| sST_DSIND_IAL | sES_DSIND_IAL | 0,789975 | 0,869972 | 0,94997 | 0,957469 | 0,964969 | 0,972469 | 0,979969 |
| sST_DSIND_IIS | sES_DSIND_IIS | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| sST_DSOTH_RESCOOK_ELECONV | sES_DSOTH_RES_COOK | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| sST_DSOTH_RESCOOK_NGAS | sES_DSOTH_RES_COOK | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| sST_DSOTH_RESDIWA_CONV | sES_DSOTH_RES_DIWAC | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| sST_DSOTH_RESDIWA_CONV | sES_DSOTH_RES_DIWAH | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

#### 2.2.2.3.2 Carga de variables de salida desde archivos CSV

Una vez ejecutado el modelo y almacenados los resultados, no es necesario volver a ejecutar el cálculo a menos que se produzcan cambios en los datos de entrada. Se diseñó un módulo para cargar datos de archivos CSV con el fin de preparar eficazmente los datos para su futura representación y visualización, haciéndolos accesibles sin necesidad de ejecutar código. Este sistema modular de entrada y salida mejora la accesibilidad, la adaptabilidad y la eficiencia del flujo de trabajo en la gestión y visualización de los resultados del modelo.

### 2.2.3 Gestión de escenarios

La gestión de escenarios en la planificación energética implica simular y analizar diversas condiciones y posibilidades para evaluar diferentes cursos de acción. Es un proceso que combina cálculos matemáticos precisos con decisiones estratégicas tomadas por expertos y partes interesadas. Estas decisiones garantizan que el modelo represente con precisión el sistema energético del mundo real y refleje las consideraciones prácticas. Además, la gestión de escenarios implica seleccionar y definir distintos escenarios para evaluar y comparar sus implicaciones.

openMASTER incorpora un sistema diseñado para la gestión de escenarios y utiliza un sistema de carpetas para almacenar el código y los datos de entrada y salida de cada escenario. Este enfoque garantiza la persistencia y el control de versiones, permitiendo un fácil acceso a los registros históricos y la comparación entre diferentes escenarios. El diseño modular e independiente de los sistemas de entrada y salida en openMASTER mejora aún más su usabilidad. Permite a los usuarios cargar datos de cualquier escenario con fines de visualización simplemente cambiando la ruta del archivo mientras se mantienen los pasos restantes sin cambios.

### 2.2.4 Visualización y análisis de resultados

Uno de los principales objetivos del modelo openMASTER es desarrollar una aplicación que sea relevante y aplicable para abordar los requisitos actuales de la planificación energética. Para lograrlo, el modelo ofrece cuatro utilidades principales de visualización:

- *Representación de datos con Excel*: El modelo openMASTER permite exportar y representar los datos de los resultados mediante hojas de cálculo Excel. Esto facilita el análisis y la visualización de los datos relacionados con la planificación energética.

- *Plantillas de gráficos:* El modelo proporciona plantillas de gráficos predefinidas que permiten crear visualizaciones claras y convincentes de los datos energéticos. Estas plantillas facilitan la interpretación de los resultados en diferentes plataformas y la comunicación de la información a diferentes audiencias. Algunas de las plantillas proporcionadas incluyen diagramas de Sankey, gráficos de barras, gráficos de áreas, diagramas de sectores y líneas evolutivas.

- *Generador de gráficos para informes:* openMASTER incluye una función de generación de gráficos que permite crear gráficos personalizados para informes y presentaciones. Esta herramienta ofrece una interfaz visual que permite modificar el aspecto formal y visual de los gráficos para mejorar la usabilidad de los datos para distintos tipos de usuarios (véase la Figura IV).

A su vez, la Figura V ejemplifica las capacidades de la Herramienta Gráfica de Informes, mostrando su habilidad para realizar fácil y eficientemente cambios formales simples para adaptarse a formatos o apariencias específicas requeridas.

*Figura IV: Generador de gráficos para informes*

*Fuente: Elaboración Propia*

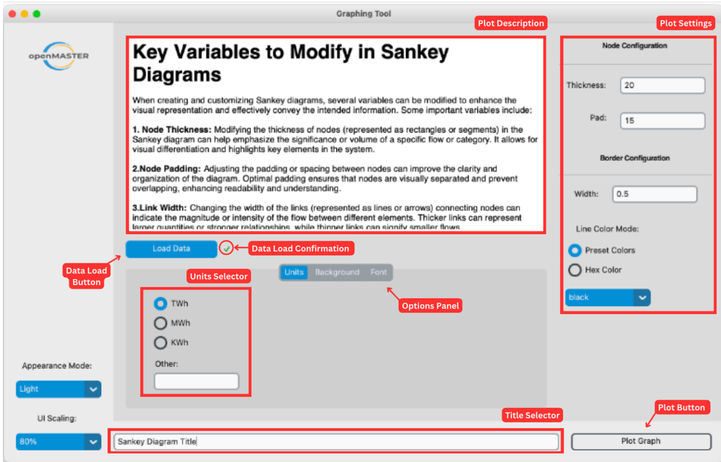
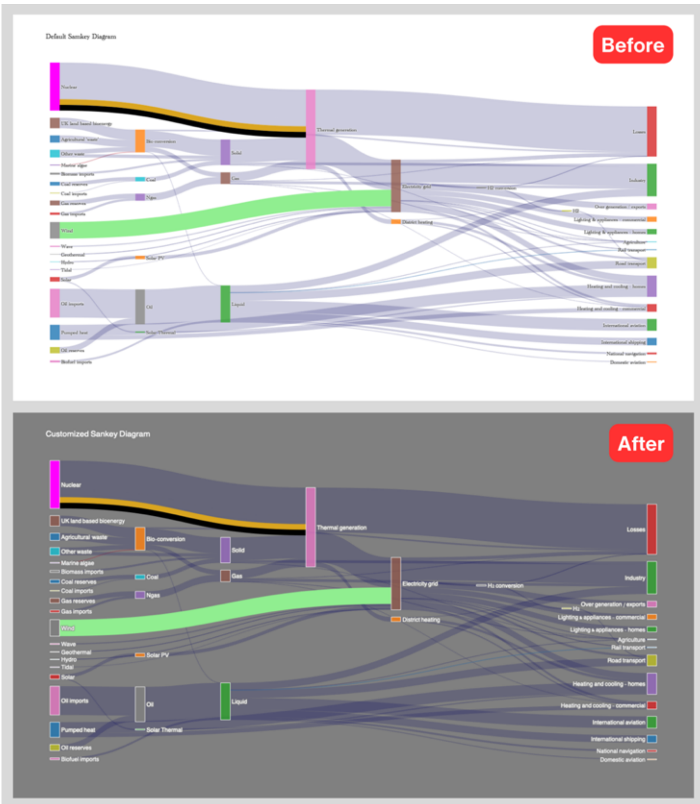



*Figura V: Utilización del generador de gráficos sobre un diagrama de Sankey*

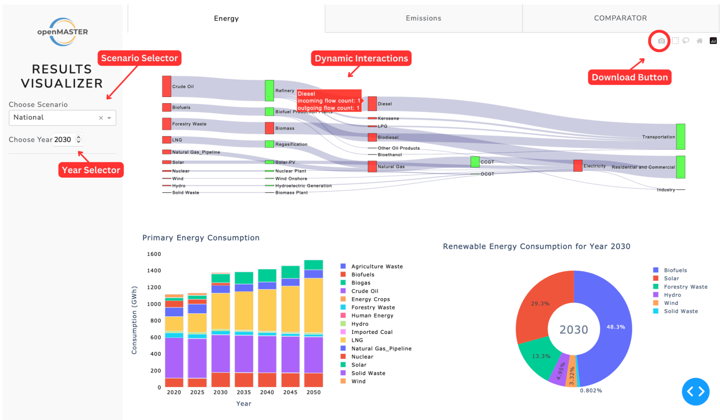
*Fuente: Elaboración Propia*



- *Integración de dashboards de Plotly:* openMASTER incluye un panel de control Plotly que ofrece una visión unificada de las visualizaciones de datos energéticos. Las capacidades interactivas de Plotly permiten a los usuarios comparar y analizar rápidamente los resultados de diferentes años y escenarios. Esta interfaz dinámica facilita el análisis en profundidad al permitir a los usuarios manipular fácilmente los datos y realizar comparaciones (véase la Figura VI).

*Figura VI: Integración de dashboards de Plotly*

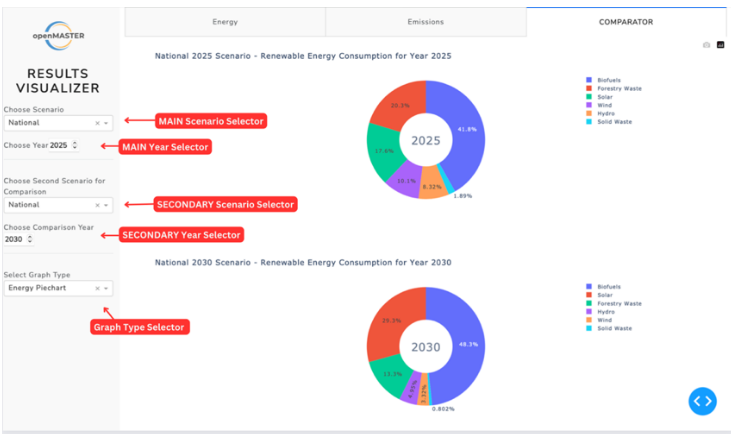
*Fuente: Elaboración Propia*




Además, como se muestra en la Figura VII, el panel de control de Plotly incluye la pestaña "COMPARADOR", que permite a los usuarios comparar datos de distintos escenarios dentro del mismo periodo de tiempo y seguir la evolución de un mismo escenario a lo largo de varios periodos. Esta adaptabilidad proporciona información valiosa para la toma de decisiones estratégicas y la evaluación de políticas en el ámbito de la planificación energética, mejorando en última instancia la eficacia de la herramienta.

*Figura VII: Pestaña "COMPARADOR" del dashboard de Plotly*

*Fuente: Elaboración Propia*




# 3. Caso de estudio

## 3.1 Contextualización del caso de estudio

### 3.1.1 Introducción al Plan Nacional Integrado de Energía y Clima (PNIEC)

El Plan Nacional Integrado de Energía y Clima (PNIEC) es un marco estratégico establecido por el Gobierno español para cumplir los objetivos de reducción de emisiones de gases de efecto invernadero y de transición a una economía baja en carbono. Esboza medidas y políticas específicas que deben aplicarse en diversos sectores, como la energía, el transporte, la industria y la agricultura, para alcanzar estos objetivos. El PNIEC sirve de hoja de ruta para las políticas energéticas y climáticas de España, guiando al país hacia un futuro sostenible y descarbonizado.

### 3.1.2 Exploración de casos de uso de modelos de código abierto en el contexto del PNIEC

La consecución de los objetivos del PNIEC requiere la colaboración y el compromiso de organismos gubernamentales, empresas, organizaciones de la sociedad civil y particulares. Los modelos de código abierto desempeñan un papel crucial a la hora de promover la colaboración entre estas partes interesadas, ya que proporcionan una visión detallada y cuantificada del sistema energético y de las posibles vías de transición. Estos modelos facilitan la identificación de estrategias óptimas y sostenibles para la transición energética, reducen la incertidumbre y el riesgo y fomentan la participación ciudadana y la innovación.

Además, los modelos de código abierto benefician a diferentes actores al permitir la personalización y el desarrollo de soluciones alineadas con sus necesidades. Por ejemplo, los gobiernos regionales pueden formular estrategias de transición energética utilizando datos específicos de la región, mientras que las empresas privadas pueden evaluar el impacto de las políticas. Los medios de comunicación y las instituciones educativas pueden crear visualizaciones interactivas e involucrar a los estudiantes en la comprensión de las implicaciones de la transición energética. Estos modelos mejoran el compromiso público y facilitan la transición hacia una economía sostenible que se ajuste a las necesidades sociales.

## 3.2 Utilización del modelo openMASTER en un escenario real

### 3.2.1 Definición de un escenario real

El escenario de estudio forma parte de la investigación de un grupo como es la Cátedra BP para un Net Zero Sostenible del Instituto de Investigación Tecnológica (IIT) de la Universidad Pontificia Comillas, cuyo objetivo es desarrollar escenarios de transición energética y recomendaciones políticas dentro de los objetivos sectoriales de emisiones establecidos en el PNIEC. En consecuencia, este grupo está interesado en comprender los efectos de la transición energética sobre la demanda de energía en los sectores residencial, comercial, servicios y transporte.

Para alcanzar los objetivos de emisiones sectoriales establecidos en el PNIEC, el escenario se centra en analizar estos sectores a través del prisma de la demanda energética. Utilizando el modelo de código abierto, los investigadores pueden simular diferentes escenarios de transición energética y obtener información sobre cómo influirán estos escenarios en la demanda de cada sector. Este análisis permite explorar y evaluar estrategias como la implantación de tecnologías de eficiencia energética, la electrificación de las flotas de transporte o la integración de fuentes de energía renovables. Adoptando estas estrategias, el grupo de investigación puede contribuir activamente a los esfuerzos de reducción de emisiones y alinear sus recomendaciones con los objetivos del PNIEC.

### 3.2.2 Resolución del escenario mediante el modelo openMASTER

El escenario propuesto pone de manifiesto la importancia de ofrecer visualizaciones y representaciones de los datos que no sólo puedan utilizar los reguladores, sino también las personas no expertas en el sector energético. El modelo openMASTER se presenta como una solución para superar estos retos, permitiendo a las personas sin experiencia en el sector energético comprender las complejidades del sistema energético. El modelo openMASTER comprende un conjunto de visualizaciones cuidadosamente seleccionadas para promover la accesibilidad y facilitar una comprensión clara del sistema energético a expertos y no expertos.

### 3.2.3 Extracción de conocimiento a partir de las visualizaciones de openMASTER

La Tabla I ofrece una visión general de cómo las plantillas de gráficos disponibles contribuyen a extraer valiosas percepciones de la empresa de una manera accesible y directa. El modelo openMASTER utiliza visualizaciones claras para representar el panorama energético del país en beneficio de la sociedad.

*Tabla I: Extracción de conocimiento a partir de las visualizaciones del modelo*

*Fuente: Elaboración Propia*

| Tipo de Visualización | Variables Comparadas | Ideas Extraídas del Modelo |
|---|---|---|
| **Diagrama de Sankey** | Flujo de energía desde las fuentes primarias (como la solar, la eólica, la hidráulica, el carbón o el gas) hasta los usuarios finales (como los sectores residencial, comercial o del transporte). | Identifica qué fuentes de energía dominan la combinación energética, lo que permite tomar decisiones estratégicas sobre posibles inversiones en tecnologías renovables. Revela los sectores de alto consumo energético, orientando las mejoras de eficiencia y las medidas de ahorro energético. |
| **Gráfico de Barras/ Áreas** | Consumo de diferentes fuentes de energía (como gas natural, carbón, nuclear, hidráulica, eólica, solar) a lo largo del tiempo. Comparación del consumo de energía en diferentes sectores (residencial, comercial, servicios, transporte). | Muestra las fuentes de energía históricas y actuales, lo que ayuda a evaluar el impacto medioambiental de cada sector y a planificar futuras transiciones hacia fuentes de energía más ecológicas. Además, al conocer los sectores de mayor consumo energético, los investigadores pueden orientar esos sectores con productos o servicios energéticamente eficientes. |
| **Diagrama de Sectores** | Proporción de diferentes fuentes de energía renovables (como la solar, la eólica o la hidráulica) en el consumo total de energía renovable del país. | Destaca las tecnologías de energías renovables predominantes en el país. Esta información puede orientar las decisiones de inversión de la empresa, por ejemplo, instalando paneles solares o turbinas eólicas si estas fuentes son dominantes en el país. |
| **Gráfica de Emisiones** | Emisiones de CO2 por sectores (residencial, comercial, transporte, etc.) a lo largo del tiempo, transporte) a lo largo del tiempo. | Señala los sectores que más contribuyen a las emisiones de gases de efecto invernadero. El grupo de investigación puede entonces desarrollar estrategias y recomendaciones para la reducción de emisiones, como la creación de productos o servicios energéticamente eficientes para estos sectores. El control periódico de las emisiones también puede garantizar el cumplimiento de la normativa medioambiental del país y mejorar su reputación como líder en sostenibilidad. |

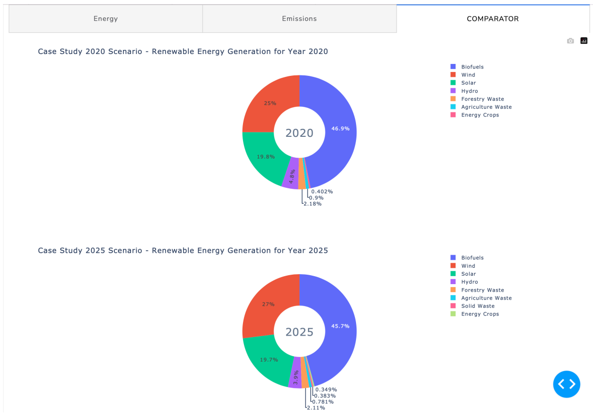
### 3.2.4 Creación de representaciones relevantes mediante la herramienta de cuadros de mando de Plotly

El modelo openMASTER ofrece una serie de potentes soluciones de visualización que mejoran enormemente la capacidad para utilizar y presentar los datos de forma eficaz. Una de estas soluciones es el panel de control Plotly, que permite la visualización simultánea de múltiples gráficos. Esta función es especialmente valiosa para compartir los resultados del modelo en reuniones con reguladores o presentaciones a inversores, ya que permite una representación completa y visualmente impactante de los resultados del modelo.

La Figura VIII muestra las disparidades en la distribución de la generación de energía renovable entre 2020 y 2025. Estas avanzadas capacidades de visualización no sólo mejoran la capacidad analítica de la empresa, sino que también refuerzan su capacidad para comunicar los resultados y tomar decisiones con conocimiento de causa.

*Figura VIII: Comparación de la generación de energía renovable entre 2020 y 2025*

*Fuente: Elaboración Propia*




### 3.2.5 Publicación de los resultados del modelo

Por último, la incorporación de gráficos en los artículos publicados por la Cátedra o en su sitio web puede transmitir eficazmente el compromiso de los investigadores con los objetivos medioambientales. La herramienta de generación de gráficos para informes ofrece un valioso recurso para aprovechar todo el potencial de la visualización en estas comunicaciones (véase la Figura IX). Aprovechando esta herramienta, el grupo de investigación puede comunicar con éxito su dedicación a los objetivos medioambientales y mejorar la comprensión de sus iniciativas de sostenibilidad por parte de las partes interesadas.

*Figura IX: Publicación de los resultados*

*Fuente: Elaboración Propia*

## 4. Conclusiones

El presente trabajo pone de relieve la importancia de los modelos energéticos para alcanzar los objetivos de desarrollo sostenible fijados por las Naciones Unidas. Hace hincapié en la necesidad de un esfuerzo colectivo de todos los miembros de la sociedad, más allá de los gobiernos y las grandes empresas. El estudio se centra en los modelos de código abierto y evalúa sus ventajas y limitaciones para diferentes necesidades y objetivos energéticos. Se subraya el valor de los modelos de código abierto y se propone convertir el modelo MASTER en un modelo de código abierto para mejorar la accesibilidad y fomentar la colaboración. La tesis establece un marco para futuros proyectos, esbozando una metodología basada en el control de versiones para garantizar la accesibilidad, adaptabilidad e interoperabilidad de los modelos. Se presenta el desarrollo del modelo openMASTER, mostrando sus funcionalidades y proporcionando un enfoque de fácil uso para abordar los retos energéticos de un país. El caso de estudio demuestra cómo poder alcanzar los objetivos energéticos del Plan Nacional Integrado de Energía y Clima, identificando estrategias óptimas de transición. En general, la tesis subraya la importancia de la colaboración y el compromiso de las partes interesadas a la hora de desarrollar estrategias sostenibles y socialmente responsables, y anima a adoptar y utilizar openMASTER en diversos contextos para facilitar la transición energética y avanzar hacia una sociedad más sostenible.

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# PROGRAMMING ENERGY MODELS IN PYTHON FOR THE DECARBONIZATION OF THE SPANISH ENERGY SYSTEM

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## ABSTRACT

This paper introduces openMASTER, an innovative open-source energy planning model developed using Python and Pyomo. The model aims to maximize social welfare by optimizing investment and operational costs of the energy system within environmental constraints.

**Keywords**: Open-source, energy model, energy transition, Spain.

### 1. Introduction

#### 1.1 Presentation of the work and its relevance

Sustainability is a complex and broad concept, but one basic aspect is access to emissions-free energy resources. As the world's population grows and living standards continue to rise, the demand for energy continues to rise. Given that the energy sector generates about three-quarters of all greenhouse gas emissions globally, decarbonizing the energy sector is crucial for mitigating climate change. This necessitates optimizing energy resource management and progressively replacing them with low-emission and sustainable energy sources.

However, this challenge requires a collective effort from society to regulate and direct the future of our country's energy. In this context, two important concepts come into play: energy planning and open-source models:

- *Energy planning* involves projecting future energy needs while considering present ones. This requires taking into account all energy stakeholders, existing infrastructure, generation and demand sources, and macroeconomic factors. Conventional processes are inefficient for processing such vast amounts of information, making the use of advanced optimization models crucial for energy planning.

- *Open-source* refers to computer software that is designed to be fully accessible to the public. That is, it is software that can be studied, modified, improved, and freely distributed, with the user setting the limits.

Consequently, open-source energy planning models are programs developed with the mission to be publicly accessible, promoting the necessary progress and technological research within the current energy transition context.

Open-source energy models are a powerful tool for promoting participation and collaboration in society. Accessible to all, these models allow researchers, policymakers, and other stakeholders to collaborate and contribute to their development. In addition to promoting transparency and reproducibility in energy system modelling, they enhance inclusivity by allowing a wider range of actors to participate in energy planning processes. By removing barriers, open-source models enable more democratic and collaborative decision-making in the energy sector.

As a result, these open-source models are crucial for achieving the Sustainable Development Goals (SDGs), particularly SDG 7, which aims to ensure universal access to affordable, reliable, and sustainable energy (International Energy Agency, 2021). By evaluating the implications of energy policies, technological advancements, and market dynamics, these models provide an empirical basis for decision-making, helping countries balance the demands of economic growth, social equity, and environmental protection. They can identify the most effective and efficient energy strategies to achieve the SDGs, highlighting the importance of energy planning in the sustainable development agenda.

## 1.2 State-of-the-art of open-source energy models

Currently, there is a lack of energy modelling tools that are user-friendly for non-experts in computing and mathematics, making it difficult for policymakers, regulators, and businesses to understand and utilize them. While some organizations have long-term energy planning models, they are often proprietary and not accessible to the public. On the other hand, open-source models like MARKAL-TIMES exist but require non-open-source tools for computation, such as GAMS. Nevertheless, there is a growing trend towards open-source tools like OSEMOSYS, TEMOA, openTEPES, and MUSE. These models have the potential to provide more accessible and transparent energy modelling for a wider range of users.

## 1.3 Description of the project

### 1.3.1 The MASTER model

In this context, the Model for Analysis of Sustainable Energy (MASTER) emerges as a promising solution. Developed as part of the doctoral thesis of López-Peña Fernández (2014) at the Pontifical University of Comillas (Madrid), under the BP Chair of Energy and Sustainability and the Technological Research Institute, the MASTER offers a valuable approach to energy planning analysis in the context of sustainability.

Within this framework, the MASTER.SO is an optimization model for energy planning, programmed in GAMS, that aims to maximize social welfare. With this objective in mind, the model is capable of representing the functioning of the energy system and optimizing investment and operational costs. The MASTER.SO seeks a balance between simplicity and precision in order to obtain reliable and easily interpretable results for regulators, without the need for heavy computational burdens. The MASTER.SO model has great potential in the context of energy planning as it successfully fulfils its two main objectives:

- Optimize the energy supply, resource allocation and investments required for a country based on considerations of societal benefit and sustainability.

- Present the results in an easily interpretable manner, allowing stakeholders with less technical background to benefit from the model.

However, as mentioned earlier, the current trend is transitioning towards open-source solutions. Therefore, to avoid obsolescence or disuse of the MASTER.SO model, it is advisable to migrate it from GAMS to freely available open-source tools.

### 1.3.2 Transforming the MASTER model into an open-source framework

The reliance of the MASTER model on proprietary software like GAMS presents a potential challenge in light of the growing popularity of open-source solutions. The use of proprietary licenses limits replicability, hindering the creation of scientific knowledge and preventing peer review of the model. This restricts the ability of the scientific community to review, utilize, and improve the model. To address these limitations, it is crucial to migrate the MASTER model to an open-source and distributable framework, the openMASTER model.

This transition will not only protect against potential obsolescence but also enhance usability and accessibility to a wider audience. By embracing open-source solutions, the MASTER model can effectively adapt to current trends and maintain its relevance in the field.

### 1.3.3 Using Python for open-source energy models

The decision to choose Python and Pyomo for the conversion of the MASTER model to an open-source framework was based on several factors. Firstly, Python's popularity and extensive community support provide developers with a wealth of resources, documentation, and expertise. This support network facilitates the implementation and maintenance of the openMASTER model. Additionally, the open-source nature of Python and Pyomo promotes collaboration and knowledge sharing among researchers, policymakers, and industry experts. This collaborative approach fosters innovation, allows for the incorporation of diverse perspectives, and ensures the continuous improvement and refinement of the model. Python's versatility, readability, and extensive library ecosystem, combined with Pyomo's robustness and flexibility, provide a solid foundation for the conversion process (see Bynum et al., 2021).

## 1.4 Objectives of the thesis

In this context, the thesis sets forth several interconnected goals, each targeting a distinct facet of energy planning:

- Assess the role of energy planning models in achieving Sustainable Development Goals (SDGs) and establishing a net-zero emissions economy.
- Examine the importance of stakeholder engagement in energy planning to develop a comprehensive and sustainable model.
- Highlight the benefits of open-source models in driving the transition to open-source codes in energy planning.
- Formulate a collaborative methodology to enhance cross-disciplinary collaboration among researchers in the development of open-source models.

- Collaborate in the development of openMASTER, an open-source energy model based on the MASTER.SO, with a specific emphasis on the design of user-friendly and robust input and output data modules.

- Conduct a contextual case study in Spain to demonstrate the practical functionality of the openMASTER model in real-world scenarios and support evidence-based decision-making for decarbonization strategies.

## 2. Description of the openMASTER model

### 2.1 Motivations behind the development of the openMASTER model

The motivation behind the development of the openMASTER model is to democratize energy planning research and foster collaboration among professionals from diverse backgrounds. By engaging individuals with varying levels of technical knowledge and expertise, the model aims to break down barriers to participation in the energy transition. The objective is to provide accessible energy planning tools to new communities, ensuring that valuable perspectives are not excluded due to limited resources or technical skills. The transformation of the model from proprietary software to an open-source language further enhances its flexibility and adaptability, allowing users to customize and find personalized solutions. This user-centric approach encourages active contribution and creates a collaborative and inclusive environment for the continuous evolution and improvement of the model.

### 2.2 Features and characteristics of the openMASTER model

In order to achieve its objective of fostering an inclusive and collaborative approach to the energy transition, the openMASTER model must possess a set of indispensable characteristics. These characteristics are crucial in ensuring that the model is accessible to a diverse range of participants, adaptable to different modelling needs, capable of integrating with other systems, and ultimately relevant and impactful in addressing real-world energy challenges. By embodying these qualities, the openMASTER model aims to empower a wide array of stakeholders to actively contribute to the development of innovative and effective solutions for a sustainable energy future. Hence, the openMASTER model incorporates several features that can be divided into four categories:

1) Working environment and version control

2) Input and output data modules

3) Scenario management

4) Visualization and analysis of results

#### 2.2.1 Working environment and version control

To establish a working environment with version control, a Git server was set up on a local repository at the Universidad Pontificia de Comillas. Access to this server was secured through a private VPN provided by the University to protect the integrity and security of the code. GitLab was chosen as the interface for interacting with the Git server due to its user-friendly platform, comprehensive features, strong community support, and hosting on the University's IIT server. To ensure software compatibility, researchers standardized the Python version and libraries used by utilizing virtual environments. A shared file called "requirements.txt" was uploaded to the Git repository, containing the versions of each required library. This allowed collaborators to be notified and replicate any updates, additions, or deletions. Virtual environments played a crucial role in isolating and managing project-specific dependencies and configurations, ensuring reproducibility and flexibility. They also simplified the process of maintenance and updates, enabling the team to focus on enhancing their energy optimization models without concerns about system dependency conflicts.

### 2.2.2 Input and output data modules

The data input and output system was designed to be user-friendly and versatile, accommodating users with varying technical expertise. It supports both generic and extended file formats, with CSV as the primary format and Excel as an optional format for convenient modification. These formats were chosen for their widespread usage and compatibility. The system allows for easy interpretation of results without specialized tools, making it accessible to users without advanced data management knowledge. The data processing in Python follows a modular approach, enabling easy modification and customization of specific components without affecting the overall functionality. This promotes flexibility, adaptability, and code reusability.

#### 2.2.2.1 Data types

In an optimization model, there are three types of data: sets, parameters, and variables. Sets represent groups or categories of related elements, parameters are constant values that provide information to the model, and variables are the unknowns that the model seeks to determine for the optimal solution. Sets and parameters inform the model, while variables are subject to constraints that define their relationships with sets and parameters. In other words, sets and parameters represent the input of the model, while variables represent its outputs (results).

#### 2.2.2.2 The input data module

The Python model utilizes a two-step data loading process, transitioning from Excel to CSV and then from CSV to Pyomo. This approach enhances modularity and allows for future modifications to the data format without impacting other sections. Loading data from CSV is faster and does not need to be repeated unless new data is created, increasing the model's versatility and adaptability. The efficiency of CSV file processing optimizes performance, especially with large data loads or frequent updates.

Given the visual nature of Excel tables, programming languages cannot directly interpret them. Therefore, a system was developed to identify and process different types of tables automatically. Figure I illustrates a raw data table in Excel.

*Figure I: Raw data table in Excel*

*Source: Own Elaboration*

Parameter: PE Cost
Unit: [€ per MWh]

ATENTION: THIS TABLE IS **FORMULATED**. CHANGES SHOULD BE DONE AT THE **FORECASTING TABLE** (IN YELLOW)

**pPECost**

| ~BOUNDS~ | **sPE/sYear** | y2020 | y2025 | y2030 | y2035 | y2040 | y2045 | y2050 | y2055 | y2060 | y2065 | y2070 | y2075 | ~BOUNDS~ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | sPENUCLE | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | |
| | sPEIMPCO | 10 | 9 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | |
| | sPENAGAS | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | |
| | sPELNGAS | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | |
| | sPECROIL | 40 | 40 | 40 | 37,5 | 35 | 32,5 | 30 | 30 | 30 | 30 | 30 | 30 | |
| | sPEHYDRR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEHYDRC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEMNHY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEWINON | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEWINOF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPESOLPV | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPESOLTE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPESOLTH | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEBIOMEC | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | |
| | sPEBIOMAW | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | |
| | sPEBIOMFW | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | |
| | sPESWAST | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | |
| | sPEBIOETHPI | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | |
| | sPEBIODIEPI | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | |
| | sPEBIOGAS | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | |
| ~BOUNDS~ | sPEHUMANE | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | ~BOUNDS~ |

**Interpol Rule: lineal interpolation between known forecasting values**

Initial and final values (in green) are compulsory

Formula for interpolated values needs to be adjusted in case new values (rows) are included

**FORECASTING TABLE**

| **sPE/sYear** | 2020 | 2030 | 2050 | 2075 |
|---|---|---|---|---|
| sPENUCLE | 2,88 | 2,88 | 2,88 | 2,88 |
| sPEIMPCO | 10 | 8 | 8 | 8 |
| sPENAGAS | 18,4 | 18,4 | 18,4 | 18,4 |
| sPELNGAS | 37 | 37 | 37 | 37 |
| sPECROIL | 40 | 40 | 30 | 30 |
| sPEHYDRR | 0 | 0 | 0 | 0 |
| sPEHYDRC | 0 | 0 | 0 | 0 |
| sPEMNHY | 0 | 0 | 0 | 0 |
| sPEWINON | 0 | 0 | 0 | 0 |
| sPEWINOF | 0 | 0 | 0 | 0 |
| sPESOLPV | 0 | 0 | 0 | 0 |
| sPESOLTE | 0 | 0 | 0 | 0 |
| sPESOLTH | 0 | 0 | 0 | 0 |
| sPEBIOMEC | 21 | 21 | 21 | 21 |
| sPEBIOMAW | 17 | 17 | 17 | 17 |
| sPEBIOMFW | 8 | 8 | 8 | 8 |
| sPESWAST | 21 | 21 | 21 | 21 |
| sPEBIOETHPI | 54 | 54 | 54 | 54 |
| sPEBIODIEPI | 46 | 46 | 46 | 46 |
| sPEBIOGAS | 104 | 104 | 104 | 104 |
| sPEHUMANE | 175 | 175 | 175 | 175 |

The data-loading pipeline is composed of the following steps:

1) Identifying the data type (sets or parameters) based on the sheet name.

2) Defining the boundaries of the data table within each Excel sheet (see the *~BOUNDS~* indicators in Figure I).

3) Identifying the table format and correctly processing it based on its typology, which is defined in various dimensions (sets)

4) Converting the input data into CSV format for subsequent processing by the Python program. Figure II showcases the formatted CSV file after processing the raw Excel data through the input pipeline.

*Figure II: Processed input table in CSV*

*Source: Own Elaboration*

```
sPE,sYear,pPECost
sPENUCLE,y2020,2.88
sPEIMPCO,y2020,10.0
sPENAGAS,y2020,18.4
sPELNGAS,y2020,37.0
sPECROIL,y2020,40.0
sPEHYDRR,y2020,0.0
sPEHYDRC,y2020,0.0
```

### 2.2.2.3 The output data module

In the data loading process of the model, sets and parameters are the main data types involved. However, in the data output, the focus shifts to variables, which represent the unknowns determined during the optimization process. The data output can be divided into two branches: the storage of model output data and the loading of stored data for subsequent visualization.

#### 2.2.2.3.1 Storage of the model's output data

The output data of the model was defined to mirror the input data pipeline but in reverse:

1) After executing the model, each variable is associated with its respective sets and stored in separate Python data tables. These tables are organized in a Python dictionary, with the variable name as the key and the corresponding dataframes

as the values. This format allows for easy representation and visualization of the data.

2) Simultaneously, the variable information is exported in CSV format. This eliminates the need to re-run the model to access and represent the data, providing convenience and efficiency. Again, the CSV format also allows the results to be exported to other visualization or processing tools that do not require a license.

3) Finally, to maintain a visual and interpretable view, the CSV files containing the variables are converted to a consolidated Excel format. This consolidation brings all the results together in a single file, facilitating analysis and interpretation of the data. Figure III shows an example of the automatically generated output.

*Figure III: Example of a model's output variable in Excel*

*Source: Own Elaboration*

| sST / sYear | sES / sYear | y2020 | y2025 | y2030 | y2035 | y2040 | y2045 | y2050 |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| sST_DSIND_IAL | sES_DSIND_IAL | 0,789975 | 0,869972 | 0,94997 | 0,957469 | 0,964969 | 0,972469 | 0,979969 |
| sST_DSIND_IIS | sES_DSIND_IIS | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| sST_DSOTH_RESCOOK_ELECONV | sES_DSOTH_RES_COOK | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| sST_DSOTH_RESCOOK_NGAS | sES_DSOTH_RES_COOK | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| sST_DSOTH_RESDIWA_CONV | sES_DSOTH_RES_DIWAC | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| sST_DSOTH_RESDIWA_CONV | sES_DSOTH_RES_DIWAH | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

#### 2.2.2.3.2 Loading output variables from CSV files

Once the model is executed and results are stored, rerunning the computation is unnecessary unless there are changes in the input data. A module for loading data from CSV files was designed to effectively prepare the data for future representation and visualization, making it accessible without code execution. This modular input and output system enhances accessibility, adaptability, and workflow efficiency in managing and visualizing the model's outputs.

### 2.2.3 Scenario management

Scenario management in energy planning involves simulating and analyzing various conditions and possibilities to evaluate different courses of action. It is a process that combines precise mathematical calculations with strategic decisions made by experts and stakeholders. These decisions ensure that the model accurately represents the real-world energy system and captures practical considerations. In addition, scenario management involves selecting and defining different scenarios to assess and compare their implications.

OpenMASTER incorporates a system designed for scenario management and utilizes a folder system to store code, input, and output data for each scenario. This approach ensures persistence and version control, allowing easy access to historical records and comparison between different scenarios. The modular and independent design of the input and output systems in OpenMASTER further enhances its usability. It enables users to load data from any scenario for visualization purposes by simply changing the file path while keeping the remaining steps unchanged.

### 2.2.4 Visualization and Analysis of Results

One of the main objectives of the openMASTER model is to develop an application that is relevant and applicable to address the current requirements of energy planning. To achieve this, the model offers four main visualization utilities:

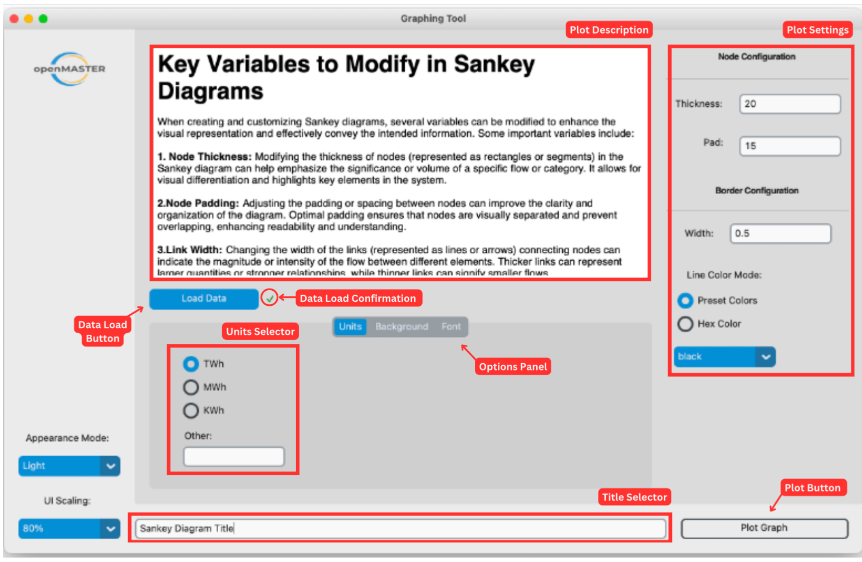
- *Data representation with Excel:* The openMASTER model allows for the export and representation of results data using Excel spreadsheets. This facilitates the analysis and visualization of energy planning-related data.

- *Chart templates:* The model provides predefined chart templates that enable the creation of clear and compelling visualizations of energy data. These templates make it easier to interpret the results and communicate the information to different audiences. Some of the templates provided include Sankey diagrams, bar charts, area charts, sector diagrams and evolutionary lines.

- *Chart generator for reports:* openMASTER includes a chart generation feature that allows for the creation of custom charts for reports and presentations. This tool provides a visual interface that allows modifying the formal and visual appearance of the graphs to enhance the usability of the data for different types of users (see Figure IV).

*Figure IV: Report Graphing Tool*

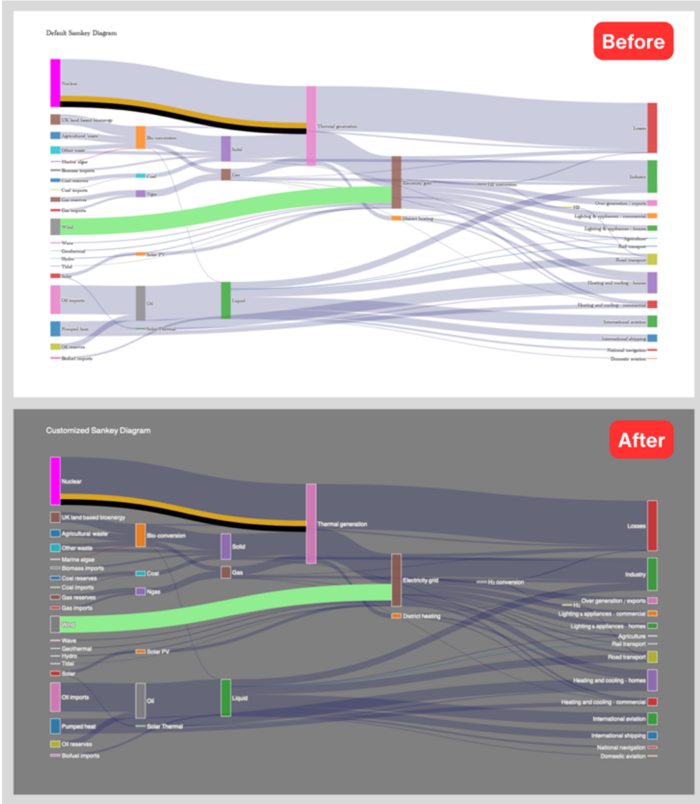
*Source: Own Elaboration*




Furthermore, Figure V exemplifies the capabilities of the Report Graphing Tool, showcasing its ability to easily and efficiently make simple formal changes to adapt to specific required formats or appearances.

*Figure V: Example usage of the Report Graphing Tool on a Sankey Diagram*

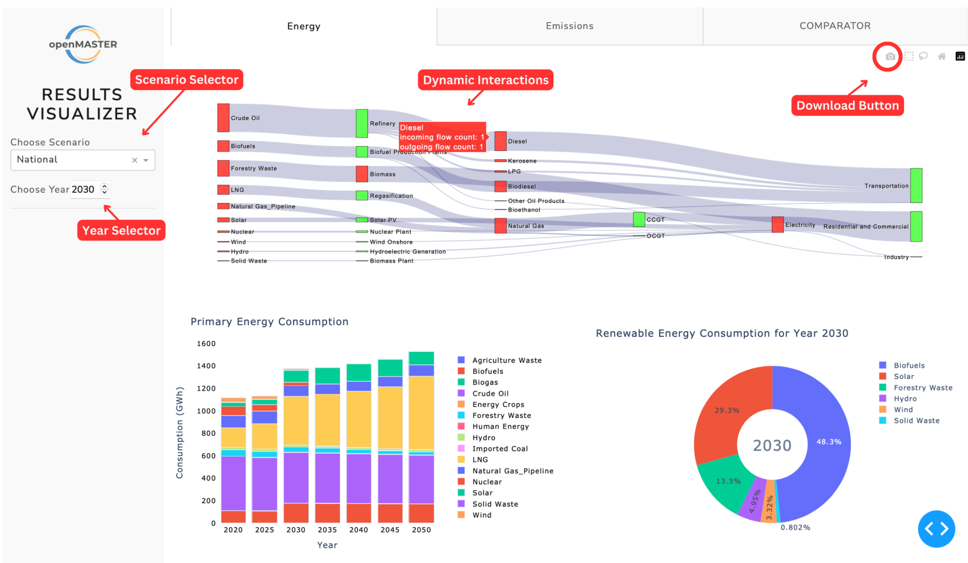
*Source: Own Elaboration*




- *Plotly dashboard integration:* openMASTER includes a Plotly dashboard that offers a unified view of energy data visualizations. The interactive capabilities of Plotly allow users to quickly compare and analyze results from different years and scenarios. This dynamic interface facilitates in-depth analysis by allowing users to easily manipulate data and make comparisons (see Figure VI).

*Figure VI: Plotly dashboard integration*

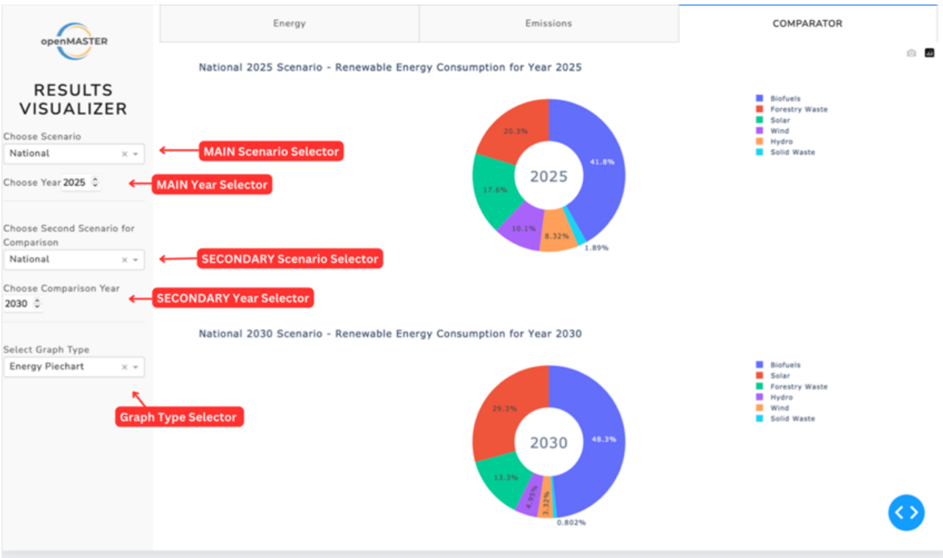
*Source: Own Elaboration*



Additionally, as depicted in Figure VII, the Plotly dashboard includes the "COMPARATOR" tab, which enables users to compare data from different scenarios within the same time period and track the evolution of a single scenario across multiple time periods. This adaptability provides valuable insights for strategic decision-making and policy assessment in the energy planning domain, ultimately improving the effectiveness of the tool.

*Figure VII: Plotly dashboard COMPARATOR tab*

*Source: Own Elaboration*




## 3. Case Study

### 3.1 Contextualization of the case study

#### 3.1.1 Introduction to the National Integrated Energy and Climate Plan (PNIEC)

The National Integrated Energy and Climate Plan (PNIEC) is a strategic framework established by the Spanish Government to meet greenhouse gas emissions reduction targets and transition to a low-carbon economy. It outlines specific measures and policies to be implemented in various sectors, such as energy, transport, industry, and agriculture, to achieve these objectives. The PNIEC serves as a roadmap for Spain's energy and climate policies, guiding the country towards a sustainable and decarbonized future.

#### 3.1.2 Exploring use cases of open-source models within the context of the PNIEC

Achieving the objectives of the PNIEC requires collaboration and engagement from government bodies, businesses, civil society organizations, and individuals. Open-source models play a crucial role in promoting collaboration among these stakeholders by providing a detailed and quantified view of the energy system and potential transition pathways. These models facilitate the identification of optimal and sustainable strategies for the energy transition, reduce uncertainty and risk, and foster citizen engagement and innovation.

Furthermore, open-source models benefit different actors by enabling customization and development of solutions aligned with their needs. For instance, regional governments can formulate energy transition strategies using region-specific data, while private companies can assess policy impacts. Media outlets and educational institutions can create interactive visualizations and engage students in understanding energy transition implications. These models enhance public engagement and facilitate the transition to a sustainable economy that aligns with social needs.

### 3.2 Utilizing the openMASTER Model in a Real-World Scenario

#### 3.2.1 Definition of a Real-World Scenario

The study scenario is part of the research of a group such as the BP Chair for a Sustainable Net Zero of the Institute for Research in Technology (IIT) at Comillas Pontifical University, whose objective is to develop energy transition scenarios and policy recommendations within the sectoral emissions targets established in the PNIEC. Consequently, this group is interested in understanding the effects of the energy transition on energy demand in the residential, commercial, services and transportation sectors.

To achieve the sectoral emission targets outlined in the PNIEC, the scenario focuses on analyzing these sectors through the lens of energy demand. By utilizing the open-source model, researchers can simulate different energy transition scenarios and gain insights into how these scenarios will influence the demand in each sector. This analysis enables to explore and evaluate strategies such as implementing energy efficiency technologies, electrifying transportation fleets, or integrating renewable energy sources. By adopting these strategies, the research group can actively contribute to emission reduction efforts and align its recommendations with the objectives of the PNIEC.

#### 3.2.2 Resolving the scenario utilizing the openMASTER model

The proposed scenario highlights the importance of providing visualizations and representations of data that can be used not only by regulators, but also by non-experts in the energy sector. The openMASTER model is presented as a solution to overcome these challenges, allowing non-experts in the energy sector to understand the complexities of the energy system. The openMASTER model comprises a set of visualizations carefully selected to promote accessibility and facilitate a clear understanding of the energy system for experts and non-experts.

#### 3.2.3 Deriving insights from openMASTER's output visualizations

Table I offers a comprehensive overview of how the available chart templates contribute to extracting valuable insights from the company in an accessible and straightforward manner. The openMASTER model utilizes clear and holistic visualizations to depict the country's energy landscape in the benefit of society.

*Table I: Insights extracted from the output visualizations*

*Source: Own Elaboration*

| Visualization Type | Variables Being Compared | Specific Insights Gained from the Model |
|---|---|---|
| **Sankey Diagram** | Flow of energy from primary sources (such as solar, wind, hydro, coal, gas) to end-users (like residential, commercial, transportation sectors). | Identifies which energy sources dominate the energy mix, enabling strategic decisions about potential investments in renewable technologies. Reveals high energy consumption sectors, guiding efficiency improvements and energy-saving measures. |
| **Bar Chart/Area Chart** | Consumption of different energy sources (like natural gas, coal, nuclear, hydro, wind, solar) across time. Comparison of energy consumption across different sectors (residential, commercial, services, transportation). | Shows the historical and current energy sources relied upon, helping to assess the environmental impact of each sector and plan future transitions towards greener energy sources. Also, by understanding the sectors of high energy usage, researchers can target those sectors with energy-efficient products or services. |
| **Pie Chart** | Proportion of different renewable energy sources (such as solar, wind, hydro) in the country's total renewable energy consumption. | Highlights the prevalent renewable energy technologies in the country. This information can guide the company's investment decisions, for example, by installing solar panels or wind turbines if these sources are dominant in the country. |
| **Emissions Chart** | Sector-wise CO2 emissions (from sectors like residential, commercial, transportation) over time. | Pinpoints sectors that are major contributors to greenhouse gas emissions. The research group can then develop strategies and recommendations for emission reduction, such as creating energy-efficient products or services for these sectors. Regular monitoring of emissions can also ensure compliance with the country's environmental regulations and enhance its reputation as a sustainability leader. |

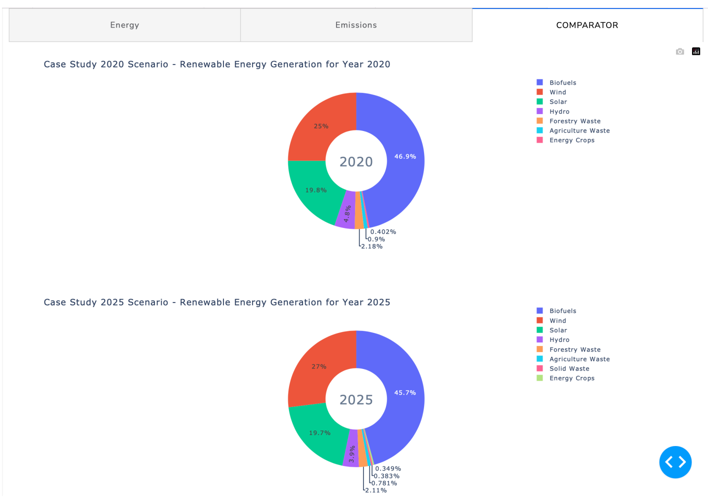
### 3.2.4 Creating impactful representations through the Plotly dashboarding tool

The openMASTER model offers a number of powerful visualization solutions that greatly enhance the ability to use and present data effectively. One of these solutions is the Plotly control panel, which allows the simultaneous display of multiple plots. This feature is especially valuable for sharing model results in meetings with regulators or presentations to investors, as it allows for a comprehensive and visually stunning representation of model results.

Figure VIII shows the disparities in the distribution of renewable energy generation between 2020 and 2025. These advanced visualization capabilities not only enhance the company's analytical capabilities, but also strengthen its ability to communicate results and make informed decisions.

*Figure VIII: Comparation of the renewable energy generation between 2020 and 2025*

*Source: Own Elaboration*



### 3.2.5 Publishing the results of the model

Lastly, integrating graphics in the Chair's published articles, or website can effectively convey the researchers' commitment to environmental objectives. The Report Graphing Tool provides a valuable resource for harnessing the full potential of visualization in these communications (see Figure IX). By leveraging this tool, the research group can successfully communicate its dedication to environmental goals and enhance stakeholder comprehension of its sustainability initiatives.

*Figure IX: Publishing the results*

*Source: Own Elaboration*


## 4. Conclusions

This paper highlights the importance of energy models for achieving the sustainable development goals set by the United Nations. It emphasizes the need for a collective effort by all members of society, beyond governments and large companies. The study focuses on open source models and assesses their advantages and limitations for different energy needs and objectives. It highlights the value of open source models and proposes to convert the MASTER model into an open source model to improve accessibility and foster collaboration. The thesis establishes a framework for future projects, outlining a methodology based on version control to ensure accessibility, adaptability and interoperability of the models. The development of the openMASTER model is presented, showing its functionalities and providing a user-friendly approach to address a country's energy challenges. The case study demonstrates how to achieve the energy objectives of the National Integrated Energy and Climate Plan by identifying optimal transition strategies. Overall, the thesis highlights the importance of collaboration and stakeholder engagement in developing sustainable and socially responsible strategies, and encourages the adoption and use of openMASTER in a variety of contexts to facilitate the energy transition and move towards a more sustainable society.

## 5. References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# Chapter 1. INTRODUCTION

## *1.1 OBJECTIVES*

With the global population and energy demands on the rise, it is crucial to decarbonize the energy sector, which is responsible for a significant portion of greenhouse gas emissions. This necessitates improved energy resource management and a shift towards sustainable, low-emission energy sources. Addressing this complex challenge requires collective action and the strategic utilization of open-source energy planning models. These models, developed with the goal of public accessibility, play a vital role in driving technological progress and research within the context of our ongoing energy transition. To achieve these objectives, the thesis sets forth several interconnected goals, each targeting a distinct facet of energy planning:

- *Objective 1: Assessing the Role of Energy Planning Models:* The first objective involves evaluating the significance of energy planning models in relation to Sustainable Development Goals (SDGs) and the establishment of a net-zero emissions economy. The goal is to understand how these models can effectively guide sustainable development strategies and contribute to achieving climate targets.
- *Objective 2: Examining Stakeholder Engagement:* The second objective focuses on the importance of involving diverse stakeholders in the planning, design, and execution of energy solutions. By incorporating the perspectives and expertise of various stakeholders, a comprehensive and sustainable energy planning model can be developed. This approach aims to optimize societal well-being and ensure an inclusive and equitable energy transition.
- *Objective 3: Highlighting the Impact of Open-Source Models:* The third objective aims to emphasize the significance and benefits of open-source models in driving the transition from traditional optimization paradigms to open-source codes. Open-source models foster innovation, collaboration, and accessibility in energy planning.

By showcasing the effectiveness of these models, this objective seeks to encourage their wider adoption in the field.

- *Objective 4: Formulating a Collaborative Methodology:* The fourth objective involves developing a robust and scalable methodology that enables cross-disciplinary collaboration among researchers with varying technical expertise. By establishing a collaborative framework, researchers can effectively work together to address complex energy planning challenges. This objective aims to enhance the efficiency and effectiveness of energy planning processes and the development of open-source energy models.
- *Objective 5: Transforming the MASTER.SO Model into Open-Source:* The fifth objective focuses on the development of openMASTER, an open-source energy model based on the MASTER.SO, with a specific emphasis on the design of user-friendly and robust input and output data modules. This transformation aims to enhance the functionalities of the model, including the development of an autonomous module for data preprocessing and management, the creation of a user-friendly interface, and the design of an intuitive mechanism for result visualization and interpretation. These enhancements seek to improve the usability and accessibility of the model.
- *Objective 6: Conducting a Contextual Case Study:* The final objective of this research is to conduct a detailed case study in relation to the decarbonization plans in Spain. This case study will provide a practical example to demonstrate how diverse stakeholders can effectively leverage the enhanced capabilities of the openMASTER model in real-world scenarios. The case study aims to showcase the practical functionality of the openMASTER model and highlight its potential to support evidence-based decision-making and facilitate the successful implementation of decarbonization strategies.

## *1.2 MOTIVATION*

The challenge of energy transition is a global task, and therefore, it is necessary to collectively build tools capable of capturing dynamics at different levels. This is why open-source models enable different stakeholders to participate and contribute their perspectives, while also driving research and adapting energy planning models to the real needs of society.

The objective of energy transition is to design a solution that is real and inclusive for all. In this context, open-source models bring these tools closer to new communities and segments. As free tools that do not require paid languages or programs, students, independent analysts, government specialists, and researchers from different institutions can contribute to the creation of sustainable energy policies for everyone.

Inspired by all the mentioned reasons, the motivation of this work is to transform a model that uses a paid software (GAMS) into an open-source language. The aim is to bring transparency and focus the efforts of society on creating and improving a universal model that pursues the common good. This way, it avoids the need for the community to allocate resources and time to design a tool from scratch when one is already available but not accessible.

## *1.3 METHODOLOGY*

The methodology employed in the present study is designed to be robust, rigorous, and application-oriented. The approach encompasses theoretical understanding, model development, and practical application.

The initial phase of the methodology involves establishing a theoretical framework to provide a comprehensive understanding of energy planning models, their significance, and their applications. This framework also explores the role of these models in achieving net-zero targets and the seventh Sustainable Development Goal (SDG), with a specific focus on the importance of open-source models within this context.

Moving into the development phase, the thesis introduces the MASTER model. This stage involves an exploration of the model's objectives and a comprehensive discussion on the necessity and benefits of transforming it into an open-source framework. This transformation aligns with the objective of promoting accessibility, collaboration, and democratization of energy planning, which are fundamental aims of this study.

The core part of the methodology revolves around developing the openMASTER model. This stage focuses on the definition and exploration of characteristics and functionalities of the model, with particular attention given to scenario management, data input and output modules, and visualization techniques. This stage involves iterative development and testing to ensure the model's robustness and usability, which are crucial for its successful application in energy planning scenarios.

The final stage of the methodology involves the practical application of the developed model in the context of Spain's National Integrated Energy and Climate Plan (PNIEC). This stage highlights the potential of open-source models like openMASTER in real-world scenarios, demonstrating their usage, adaptability, and impact on various stakeholders involved in the energy planning process.

Through this structured and integrative methodology, the study ensures a comprehensive exploration of the openMASTER model, with a strong emphasis on practical application. The methodology effectively aligns the research with the identified objectives, underscoring the relevance of open-source models in contemporary energy planning and addressing critical issues such as achieving net-zero targets, the seventh SDG, and democratizing the planning process.

## *1.4 STRUCTURE*

The thesis is structured into five sections, each contributing to a thorough exploration of energy planning models. The first section, "Theoretical Framework," provides a strong foundation by introducing energy planning models, net-zero targets, the seventh Sustainable

Development Goal, and the significance of open-source models. The second section focuses on the "MASTER Model," discussing its objectives, descriptions, and its transformation into an open-source framework. The third section, "Development of the openMASTER Model," delves into the motivation, requirements, and characteristics of the model. The fourth section, "Case Study: Plan Nacional Integrado de Energía y Clima (PNIEC)," presents a real-world application of the openMASTER model, highlighting its use by different actors within the context of the PNIEC. Finally, the thesis concludes with the "Conclusions" section, which summarizes the findings and discusses the implications of the work in the field.

# Chapter 2. THEORETICAL FRAMEWORK

## *2.1 AN INTRODUCTION TO ENERGY PLANNING MODELS*

In the context of the escalating global energy demand and the urgent imperative to reduce carbon emissions, strategic energy planning assumes paramount significance in the pursuit of sustainable development. As a fundamental process, energy planning employs an exhaustive methodology to unravel the intricacies of the energy sector and establish a trajectory towards a sustainable energy paradigm.

The relevance of energy planning arises from its capacity to anticipate, prepare for, and navigate the uncertainties inherent in the energy landscape. Moreover, it plays a pivotal role in reconciling the often-conflicting objectives of energy security, economic viability, and environmental sustainability.

This section explores the intricacies of Energy Planning Models (EPMs). The objective is to clarify the indispensable role of energy planning within our contemporary context and shed light on how EPMs contribute to a more informed and empirical approach to decision-making within the energy sector.

### 2.1.1 THE IMPORTANCE OF ENERGY PLANNING MODELS

In a world that is constantly growing and expanding, the demand for energy continues to increase. This rise in energy demand, coupled with the urgent need to mitigate greenhouse gas emissions, compels governments, businesses, and society to think strategically about how to meet these energy needs without compromising the planet's future. Therefore, energy planning emerges as a pathway towards achieving sustainable and low-carbon energy futures, which have become an imminent necessity for the sustainability and well-being of the global community.

Moreover, energy planning plays a pivotal role in optimizing the utilization of available resources. By conducting a comprehensive assessment of the existing energy infrastructure, forecasting future energy needs, and evaluating potential policies and technologies, planners can identify opportunities to enhance energy efficiency and reduce costs. Hence, energy planning yields economic benefits and contributes to reducing reliance on fossil fuels, thereby mitigating the adverse impacts of climate change. Through effective energy planning, it is possible to pave the way for a more sustainable and resilient energy system that aligns with environmental goals and ensures a prosperous future for generations to come.

### 2.1.2 DEFINING ENERGY PLANNING MODELS (EPMS)

Energy Planning Models (EPMs) are fundamental analytical tools in the energy planning process. They provide a systematic framework for evaluating and projecting energy scenarios, enabling informed decision-making based on quantitative analyses that help understand the intricacies and complexities of each particular outlook. EPMs play a crucial role in energy planning by analyzing the complex interactions of various factors on the current and future energy landscape, such as energy demand, prices, government policies, and technological advancements.

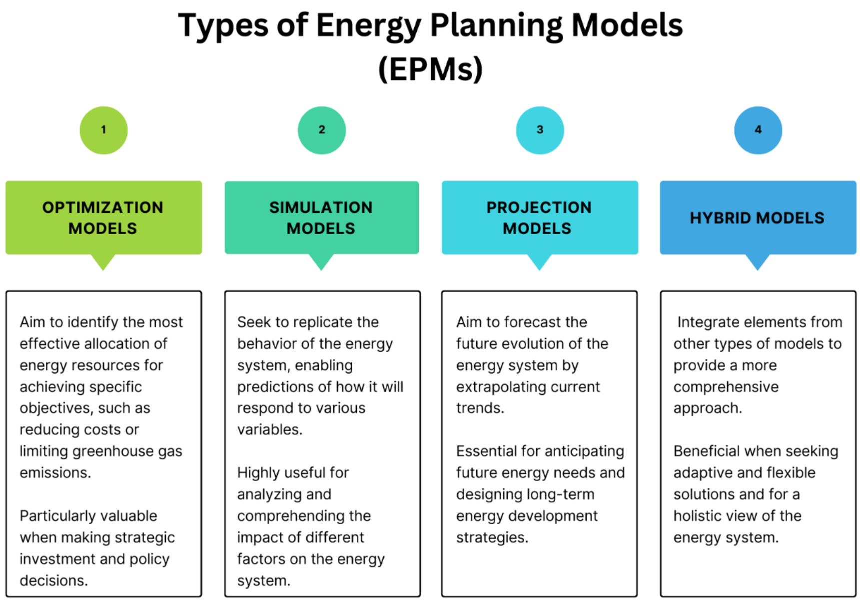
EPMs incorporate mathematical models, algorithms, and data analysis techniques to simulate and optimize energy systems under different scenarios. By considering multiple variables and constraints, EPMs can assess the potential impacts of different policy interventions, technological advancements, and market dynamics on energy supply, demand, and environmental outcomes.

The use of EPMs allows energy planners and regulators to explore various future pathways and evaluate the trade-offs associated with different energy planning decisions. They provide valuable insights into the potential risks, costs, and benefits of alternative energy strategies, helping policymakers and stakeholders make informed choices aligned with sustainability goals.

In summary, EPMs serve as powerful tools for understanding the complexities of the energy system, supporting evidence-based decision-making, and guiding the transition towards more sustainable and resilient energy futures. Figure I showcases the various types of energy planning models.

*Figure I: Types of energy planning models*

*Source: Own Elaboration*




### 2.1.3 APPLICATIONS OF ENERGY PLANNING MODELS

Energy Planning Models are versatile tools with a wide range of applications in the field of energy planning. They are used to identify opportunities for improving energy efficiency, evaluate the impact of different energy policies, , assess the potential of renewable energy sources, and analyze the economic, environmental, and social implications of energy decisions. The following enumeration provides an overview of the diverse applications of Energy Planning Models:

- *Identification of opportunities to improve energy efficiency:* EPMs enable the evaluation of potential energy efficiency measures across different sectors and determine the most effective actions to reduce energy consumption.

- *Evaluation of the impact of different energy policies:* EPMs assist in assessing the impact of energy policies, such as incentives for renewable energy, emissions taxes, or energy efficiency regulations. These models quantify the benefits and costs associated with different policies and evaluate their effectiveness in achieving energy and environmental objectives.
- *Assessment of the potential of renewable energy sources:* EPMs aid in evaluating the potential of renewable energy sources, such as solar, wind, or hydroelectric power. These models identify optimal locations for renewable energy projects and assess their contribution to the energy supply.
- *Analysis of the economic, environmental, and social implications of energy decisions:* EPMs enable the evaluation of the economic, environmental, and social impacts of different energy decisions. These models quantify the costs, benefits, and externalities associated with various energy options, assisting decision-makers in assessing the implications and trade-offs of different energy strategies.

## *2.2 NET ZERO TARGETS AND THE SEVENTH SUSTAINABLE DEVELOPMENT GOAL*

### 2.2.1 INTRODUCTION TO THE SEVENTH SUSTAINABLE DEVELOPMENT GOAL AND ITS RELATIONSHIP WITH ENERGY PLANNING GOALS

The seventh Sustainable Development Goal (SDG) seeks to guarantee universal access to affordable, dependable and sustainable energy by 2030 (International Energy Agency, 2021). This goal recognizes the critical role of energy in driving economic growth, improving living standards, and promoting sustainable development. To achieve this goal, countries must adopt effective energy planning strategies considering the complex interplay between energy systems, environmental sustainability, and socio-economic factors.

In this context, energy planning models play a crucial role in facilitating the development and implementation of such strategies by providing a systematic framework for analyzing and optimizing energy systems.

### 2.2.2 THE IMPORTANCE OF THE SEVENTH SUSTAINABLE DEVELOPMENT GOAL

The importance of the seventh SDG lies in its wide-ranging implications for global development. Access to affordable and sustainable energy is a fundamental prerequisite for achieving several other SDGs, including poverty eradication, health and well-being, education, gender equality, and climate action. Energy is an enabler for economic growth, enabling industries to thrive, creating job opportunities, and improving overall living standards. Moreover, sustainable energy solutions can help mitigate climate change by reducing greenhouse gas emissions and promoting the transition to low-carbon economies.

### 2.2.3 NET ZERO TARGETS AND THE ROLE OF ENERGY PLANNING MODELS IN ACHIEVING NET ZERO EMISSIONS

Net zero targets have emerged as a key strategy to address climate change and achieve the objectives of the seventh SDG. These targets involve balancing the amount of greenhouse gas emissions produced with the amount removed from the atmosphere, ultimately aiming for a state where emissions are offset by removals. By adopting net zero targets, countries commit to taking significant actions to reduce their carbon footprint and transition to low-carbon and sustainable energy systems.

Energy planning models play a crucial role in supporting the development and implementation of net zero targets. These models offer several advantages in the context of achieving net zero targets and the seventh SDG:

1) Identifying the most effective and cost-efficient pathways towards achieving net zero targets.
2) Identifying the most appropriate technologies for achieving net zero targets and making informed investment decisions.

3) Assessing the effectiveness and cost-effectiveness of different policy interventions, such as renewable energy incentives, energy efficiency programs, carbon pricing mechanisms, and infrastructure investments.

### 2.2.4 CHALLENGES IN ACHIEVING NET ZERO TARGETS

Despite the multiple advantages brought by energy planning models, some challenges and considerations need to be addressed in the use of EPMs for achieving net-zero targets. Some of these challenges include data availability and quality, uncertainty and complexity, stakeholder engagement, and policy integration.

Data availability and quality are essential for accurate modelling and decision-making in the field of energy planning. To ensure reliable and robust models, efforts should be focused on improving data collection, sharing, and standardization processes. This can involve implementing standardized data collection protocols, enhancing data sharing mechanisms, and promoting data quality assurance measures.

In the context of the uncertainty and complexity inherent in energy systems, it is crucial to integrate uncertainty analysis techniques into energy planning models. This involves considering various sources of uncertainty, such as fluctuating energy prices, technological advancements, and policy changes. By incorporating uncertainty analysis, decision-makers can better understand the potential risks and uncertainties associated with different energy planning scenarios.

Furthermore, energy planning models should consider multiple scenarios and sensitivities. This means exploring a range of possible future conditions and evaluating the performance of different strategies under various scenarios. By considering multiple scenarios, decision-makers can gain insights into the robustness and flexibility of different energy planning options.

In addition, stakeholder engagement is a vital aspect of energy planning models. Engaging stakeholders, including local communities, industry representatives, and policymakers, ensures that the models reflect diverse perspectives and incorporate local knowledge. This participatory approach enhances the acceptance and ownership of resulting strategies, leading to more effective and sustainable energy planning outcomes.

Lastly, integrating energy planning models into the broader policy-making process is crucial. By aligning energy planning models with policy objectives and decision-making processes, the insights and recommendations generated by the models can be effectively translated into actionable policies. This integration facilitates the implementation of evidence-based energy policies and enhances the overall effectiveness of the energy planning process.

## *2.3 OPEN-SOURCE ENERGY MODELS*

### 2.3.1 DEFINITION AND IMPORTANCE OF OPEN-SOURCE ENERGY MODELS

Open-source models in the context of energy planning refer to energy system models developed and made available to the public under an open-source license. These models are typically constructed using open-source software and are freely accessible for anyone to use, modify, and distribute. Open-source models facilitate open science in energy system modelling (Hilpert et al., 2018). They enable researchers, policymakers, and other stakeholders to collaborate, participate, and contribute to the development and improvement of energy system models, thereby promoting transparency and openness in the field.

Open-source models are important for several reasons. Firstly, they promote reproducibility and transparency in energy system modelling. By making the models and their underlying data and assumptions openly available, other researchers can replicate and validate the results, ensuring the robustness and reliability of the modelling outcomes (Hilpert et al., 2018). This transparency also allows for the identification and correction of potential errors or biases in the models, leading to more accurate and trustworthy results.

Secondly, open-source models foster collaboration and knowledge sharing among researchers and stakeholders. By providing a common platform and language for energy system modelling, these models enable researchers from different institutions and backgrounds to collaborate, exchange ideas, and build upon each other's work (Gardumi et al., 2018). This collaborative approach can lead to the development of more comprehensive and sophisticated models that capture the complexities of energy systems more effectively.

Furthermore, open-source models enhance the accessibility and inclusivity of energy system modelling. By removing barriers such as high licensing costs and proprietary software requirements, these models enable a more comprehensive range of stakeholders, including policymakers, NGOs, and community groups, to engage in energy planning processes (Gardumi et al., 2018). This inclusivity promotes democratic decision-making and allows for a more diverse set of perspectives and expertise to be incorporated into energy system modelling.

Open-source models also facilitate innovation and the development of new modelling approaches. By providing a flexible and customizable framework, these models encourage researchers to explore novel methodologies and incorporate cutting-edge technologies and research findings into their models. This dynamic and iterative process of model development can lead to more accurate and comprehensive representations of energy systems, enabling better-informed decision-making and policy development.

In summary, open-source models in energy planning are valuable tools that promote transparency, collaboration, inclusivity, and innovation in energy system modelling. They enable researchers and stakeholders to collaborate, share knowledge, and develop robust and comprehensive models to inform evidence-based decision-making in the energy sector.

### 2.3.2 STATE-OF-THE-ART OF OPEN-SOURCE ENERGY MODELS

Many existing energy planning models are privately owned, making it difficult for researchers and decision-makers to access and utilize them. On the other hand, some models are open-source, but they are often implemented in proprietary tools such as GAMS. For example, MARKAL-TIMES, one of the most widely used energy planning models, is open-source but requires using GAMS for computation. This limitation hinders the widespread adoption and customization of these models.

Traditionally, many energy planning models have been proprietary and not easily accessible to non-experts. However, there is a need for interpretable and easily understandable models for decision-makers who may not have a background in computer science or mathematics. Several open-source energy planning and optimization models have emerged to address this gap. These models aim to provide user-friendly interfaces and documentation, making them accessible to a broader audience, including policymakers, regulators, and businesses (Sikder et al., 2016).

OSeMOSYS, Calliope, openTEPES, and MUSE are examples of state-of-the-art open-source energy system modelling tools widely used in academic research and policy analysis. Each model has unique features, strengths, and potential limitations.

OSeMOSYS is valued for its simplicity, flexibility, and open-source nature, allowing for an explicit description of energy systems and accommodating various technologies and fuels. However, its simplicity may limit its ability to capture the intricacies of complex or emerging energy technologies and systems (Howells et al., 2011).

On the other hand, Calliope stands out for its high level of spatial and temporal detail, making it suitable for modelling national or regional energy systems. Furthermore, It offers a declarative approach and emphasizes ease of use, making it accessible to a wide range of users. Nonetheless, its detailed and flexible nature can lead to computational intensity (Pfenninger & Pickering, 2018).

Similarly, openTEPES focuses on optimal planning of generation, storage, and transmission, with a detailed representation of the network and time-dependent decisions, but it may be computationally intensive and require expertise (Ramos et al., 2022).

Finally, MUSE employs an agent-based approach, capturing competitive dynamics between technologies, but its setup, calibration complexity, and significant data requirements may pose challenges in regions with limited data availability (Giarola et al., 2022).

In particular, OSeMOSYS has gained popularity in recent years. Due to its user-friendly and accessible design, with extensive documentation and a growing community of users and developers (see Gardumi et al., 2018), this model has already been used in various applications, including analyzing the electrification potential in Africa (Taliotis et al., 2015) or in the integration of power systems in Brazil (de Moura et al., 2018).

While it is important to recognize the potential drawbacks of these models, they should not overshadow their value. Each model is designed for specific goals and purposes, and the right tool's choice depends on the task's requirements. All in all, a growing movement towards open-source models aims to bridge the gap between energy experts and decision-makers by providing interpretable and easily understandable energy planning and optimization tools. As a result, it is essential to continue advancing open-source models and solutions to ensure the widespread adoption and effectiveness of energy planning and optimization models.

# Chapter 3. THE MASTER MODEL

## *3.1 INTRODUCTION TO THE MASTER MODEL*

Currently, there is a limited availability of energy modelling tools that are accessible and comprehensible to specialists who are not familiar with computer science or mathematics. This poses a challenge for policymakers, regulators, and companies who wish to conduct macroeconomic studies in the energy sector in an interpretable and easily understandable manner.

The need for accessible energy models stems from the importance of involving various stakeholders in decision-making processes related to energy policy. Policymakers and regulators must understand the implications and effects of proposed energy policies, while companies need to assess the economic and operational impacts of their strategic decisions in the energy sector.

In this context, the Model for Analysis of Sustainable Energy (MASTER) emerges as a promising solution. Developed as part of the doctoral thesis of López-Peña Fernández (2014) at the Pontifical University of Comillas (Madrid), under the BP Chair of Energy and Sustainability and the Technological Research Institute, the MASTER offers a valuable approach to energy planning analysis in the context of sustainability.

## *3.2 OBJECTIVES OF THE MASTER MODEL*

The MASTER model aims to maximize social welfare by optimizing investment and operational costs while representing the functioning of the energy system. It strikes a balance between simplicity and precision, providing reliable and easily interpretable results for decision-makers without imposing excessive computational burdens.

The MASTER model holds significant potential in the field of energy planning as it successfully achieves two main objectives:

1) Calculating the annual energy supply and resource distribution of a national energy system, considering social benefit and sustainability.
2) Presenting results in an easily interpretable manner, enabling stakeholders with limited technical background to derive value from the model.

On the one hand, the MASTER calculates the energy supply and resource distribution of a country while taking into account factors such as social benefit and sustainability. This calculation allows policymakers and energy planners to gain insights into the availability and allocation of energy resources, ensuring that the energy needs of the country are met while considering the broader social and environmental impacts.

On the other hand, the MASTER model excels in presenting its results in a manner that is easily interpretable. This aspect is particularly valuable as it enables stakeholders with limited technical backgrounds to derive value from the model. By providing clear and understandable outputs, such as visualizations or simplified reports, the model facilitates effective communication and decision-making among policymakers, regulators, and other stakeholders involved in energy planning processes.

## *3.3 DESCRIPTION OF THE MASTER.SO MODEL*

The MASTER.SO model is an integral component of the Model for Analysis of Sustainable Energy (MASTER), serving as a valuable tool for researchers and policymakers in the field of sustainable energy policy. Developed using the General Algebraic Modeling System (GAMS) and resolved through the CPLEX optimization solver, the MASTER.SO model is highly regarded for its precision and efficiency.

Operating on a static optimization approach, the MASTER.SO model focuses on a specific time period, typically a year. It functions as a bottom-up, partial equilibrium, linear programming model, taking into account various technical and policy constraints to provide an optimal solution that balances the external demand for energy services. The model's primary objective is to minimize the private and social costs associated with energy supply and CO2 emissions, offering an economic perspective on sustainable energy policy analysis.

A distinguishing feature of the MASTER.SO model is its extensive use of Sankey diagrams, which provide intuitive and comprehensive visual representations of energy flows within the system. These diagrams enable users to gain a better understanding of the energy system and its responses to different policy implications, facilitating the identification of potential bottlenecks and areas for improvement.

In addition to the Sankey diagrams, the MASTER.SO model generates a wide range of numerical outputs, including capacities, prices, costs, and other relevant indicators. These quantitative metrics, combined with the visual representations, provide a comprehensive understanding of the energy system, enabling informed policy decisions and trade-off analyses.

To ensure accuracy and validity, the MASTER.SO model relies on a robust database sourced from reliable and publicly available data. This ensures that the inputs used in the model are accurate and up-to-date, enhancing the reliability and validity of the model's outputs.

In brief, the MASTER.SO stands out among other models, such as MARKAL/TIMES, due to its unique ability to balance simplicity, reliability, and efficiency in analyzing and planning sustainable energy policies. With a strong focus on sustainability and transparency, this model places significant emphasis on evaluating the trade-offs and synergies of different policies, making it an invaluable resource for researchers and policymakers in the field. By combining advanced optimization techniques, visual representations, and extensive numerical outputs, the MASTER_SO model provides valuable insights for users from diverse technical backgrounds. Finally, its user-friendly design and comprehensive approach make it a powerful tool for understanding and addressing the complex challenges of sustainable energy planning.

## 3.4 TRANSFORMING THE MASTER.SO INTO AN OPEN-SOURCE FRAMEWORK

Despite the numerous advantages and features offered by the MASTER model, its reliance on proprietary software like GAMS poses a potential threat in the face of the increasing popularity of open-source solutions. The lack of replicability imposed by proprietary licenses restrains the creation of scientific knowledge and prevents the model from undergoing peer review, restricting the scientific community from revising, utilizing, and improving it.

As a result, it is crucial to migrate the MASTER model to an open-source and distributable framework. This transition will not only safeguard against potential obsolescence but also enhance its usability and accessibility to a broader audience. By embracing open-source solutions, the MASTER model can effectively adapt to the current trend and maintain its relevance in the field.

## 3.5 MOTIVATION FOR OPEN-SOURCING THE MASTER.SO

Open-source models have gained significant traction in recent years due to their ability to overcome limitations associated with proprietary software and promote a more inclusive and participatory approach to modelling. By making the MASTER model open source, it becomes accessible to a broader audience, encourages collaboration among stakeholders, fosters transparency in decision-making processes, and facilitates the development of innovative solutions to complex energy challenges. This section will explore the motivations behind converting the MASTER model to an open-source framework, highlighting its advantages and opportunities for researchers, policymakers, industry experts, and the public.

Table I summarizes the motivations behind the conversion of the MASTER model to open-source.

*Table I: Motivation for open-sourcing the MASTER model*

*Source: Own Elaboration*

| Section | Subcategory | Definition |
|---|---|---|
| Longevity and Maintenance | **Continuous Development and Updating** | Dynamic development and adaptation of the MASTER model to accommodate the constantly changing landscape of energy modelling research and policy requirements. |
| | **Community Maintenance and Support** | The integral role of a diverse community of developers and researchers in assuring continuous model maintenance, bug rectification, and incorporation of updates. |
| | **User Engagement and Ownership** | The cultivation of a sense of responsibility and proprietorship among users who actively participate in the maintenance and enhancement of the model. |
| Accessibility and Collaboration | **Interactive User Access** | The accessibility provided by open-source models for users to interact with, modify, and gain insights into the energy system. |
| | **Collaborative Knowledge Construction** | The collaborative nature of the open-source models, which encourages diverse perspectives and exchange of ideas. |
| | **Peer Review and Validation** | The opportunity brought by open-source models for critical evaluation, scrutiny, and validation of its design and implementation by experts and contributors in the field. |
| Transparency | **Model Evaluation and Scrutiny** | The ability of stakeholders to dive into the model's underlying assumptions and methodologies, fostering robust evaluation and reliability assessment. |
| | **Bias and Limitations Identification** | The opportunity provided by transparency to identify and address potential biases or limitations in the model. |
| | **Public Engagement** | The engagement with the broader public, promoting a sense of ownership and accountability. |

### 3.5.1 LONGEVITY AND MAINTENANCE

The field of energy modelling is characterized by its dynamic nature, with evolving research findings and policy requirements. As new data becomes available and new challenges arise, energy models must adapt and evolve to remain relevant and practical. By making the MASTER model open source, it can effectively respond to the changing landscape of energy modelling.

An open-source approach ensures that the MASTER model remains up-to-date and receives ongoing support and maintenance from a community of developers and researchers (see Niet et al., 2021). With a diverse group of contributors, the model can benefit from a wide range of expertise and perspectives, leading to continuous improvements and updates. This collaborative effort reduces the risk of the model becoming obsolete and enhances its longevity, providing long-term value to stakeholders.

The open-source nature of the MASTER model allows for the identification and resolution of issues promptly. The community can quickly identify and fix bugs and errors, ensuring the accuracy and reliability of the model's results. Additionally, as new research findings and methodologies emerge, the model can be easily updated and refined to incorporate the latest advancements in the field.

Furthermore, an open-source approach fosters a sense of ownership and responsibility among the community of users. With the ability to modify and customize the model, users are more likely to engage in its maintenance and improvement actively. This collective effort ensures that the model remains relevant and adaptable to the evolving needs of energy modelling.

### 3.5.2 ACCESIBILITY AND COLLABORATION

As an open-source framework, the MASTER model would promote accessibility, collaboration, and knowledge sharing among researchers, policymakers, and industry experts. This inclusive approach enables a broader audience to benefit from and contribute to the development of the model, fostering a collaborative environment for energy planning and policy analysis.

Open-source software ,allows users to access, use, and modify it according to their needs and requirements. This accessibility empowers stakeholders to actively engage with the model, gaining insights into the energy system and its implications for policy decisions. Researchers can explore different scenarios, policymakers can evaluate the impacts of proposed energy policies, and industry experts can assess the economic and operational consequences of strategic decisions.

The collaborative nature of open source further enhances the value of the MASTER model. By encouraging diverse perspectives and facilitating the exchange of ideas, open source fosters innovation and the development of best practices. Different stakeholders can contribute their expertise and insights, leading to a more comprehensive and robust energy planning analysis. This collaborative approach also helps address complex challenges in the energy sector by leveraging the collective knowledge and experience of a diverse group of individuals.

One significant advantage of open source is the ability to subject the model to peer review and validation. The transparency of the model's code and algorithms allows experts in the field to critically evaluate its design, implementation, and results. This peer review process enhances the credibility and trustworthiness of the MASTER model as it undergoes rigorous scrutiny and validation by the scientific community. The feedback and insights gained from peer review contribute to the continuous improvement and refinement of the model, ensuring its accuracy and reliability.

### 3.5.3 TRANSPARENCY

The conversion of the MASTER model into an open-source framework brings forth several motivations related to transparency and accountability. By open-sourcing the model, stakeholders gain the opportunity to delve deeper into the model's underlying assumptions and methodologies by examining the code and documentation. This transparency empowers users to evaluate the model's reliability and suitability for specific applications. Additionally, it allows stakeholders to verify and validate the calculations and results generated by the model. With access to the model's inner workings, stakeholders can replicate the analysis, compare outputs with their own estimations or alternative models, and ensure that decisions based on the model are grounded in robust research.

Transparency in the MASTER model enables stakeholders to identify and address potential biases or limitations. Users can locate any inherent biases in the model's design or data sources by examining the code and assumptions. This transparency empowers stakeholders to address these biases and work towards a more balanced and accurate representation of the energy system. Furthermore, transparency facilitates the identification of limitations in the model, such as simplifications or missing variables, which can be addressed through ongoing development and refinement.

Open-sourcing the MASTER model also fosters engagement with the broader public. By making the model's code and documentation accessible, the public gains insights into the energy planning and policy analysis process. This transparency allows for public scrutiny and understanding of the model's implications, fostering a sense of ownership and accountability in decision-making processes. Engaging the public in discussions about the model's assumptions and results promotes transparency and ensures that decisions are made with the broader public interest in mind.

## *3.6 USING PYTHON FOR OPEN-SOURCING THE MASTER.SO*

Converting the MASTER model from GAMS to an open-source framework involves two critical components: selecting a programming language and choosing suitable dependencies and libraries. In the process of open-sourcing the MASTER model into the openMASTER model, Python was chosen as the programming language, and the Pyomo optimization modelling framework was adopted. This section will dive into the motivations behind these choices and the advantages they bring to the conversion process.

### 3.6.1 MOTIVATION FOR SELECTING PYTHON AS THE PROGRAMMING LANGUAGE

The selection of Python as the programming language for the conversion process is driven by several factors. Python is widely recognized for its versatility, readability, and extensive library ecosystem. Its clean and intuitive syntax makes it easy to understand and write code, facilitating the translation of complex mathematical models into a computer-readable format. Additionally, Python's extensive library ecosystem provides access to many tools and functionalities beyond optimization modellings, such as data analysis, machine learning, and visualization. This integration allows for incorporating advanced analytical techniques and enhances the model's capabilities.

### 3.6.2 MOTIVATION FOR CHOOSING PYOMO AS THE OPTIMIZATION MODELLING FRAMEWORK

In addition to Python, adopting the Pyomo optimization modelling framework further enhances the conversion process. Pyomo is a powerful and flexible framework specifically designed for optimization modelling (see Bynum et al., 2021). It provides a robust platform for translating complex mathematical models into code, offering a range of modelling components and solvers. Pyomo's syntax is designed to be simple and expressive, allowing for the concise representation of optimization problems. Moreover, Pyomo supports the separation of model and data, enabling modularity and ease of maintenance. It also provides compatibility with various data formats, simplifying data integration into the model.

### 3.6.3 MOTIVATION FOR COMBINING PYTHON AND PYOMO

The choice to open-source the MASTER model and utilize Python with the Pyomo framework brings several advantages to the conversion process. Firstly, Python's popularity and extensive community support ensure a wealth of resources, documentation, and expertise available to developers. This support network facilitates the implementation and maintenance of the openMASTER model. Additionally, the open-source nature of Python and Pyomo promotes collaboration and knowledge sharing among researchers, policymakers, and industry experts. This collaborative approach fosters innovation, allows for the incorporation of diverse perspectives, and ensures the continuous improvement and refinement of the model.

In summary, converting the MASTER model to an open-source framework involves selecting Python as the programming language and adopting the Pyomo optimization modelling framework. Python's versatility, readability, and extensive library ecosystem, combined with Pyomo's robustness and flexibility, provide a solid foundation for the conversion process. The open-source nature of both Python and Pyomo promote collaboration, innovation, and continuous improvement, ensuring the development of a robust and accessible openMASTER model.

# Chapter 4. DEVELOPMENT OF THE OPENMASTER

## *4.1 MOTIVATION BEHIND THE OPENMASTER MODEL*

The openMASTER model aims to promote research in energy planning at all levels, from university students to established researchers and businesses in the sector. It seeks to involve professionals with varying levels of technical knowledge, from those with minimal programming and computing skills to expert modellers. The goal is to foster collaboration among agents from various disciplines, as each has something valuable to contribute.

The objective is to bring these tools closer to new communities that have not been previously considered part of the equation yet have significant value to offer with their different perspectives. The aim is to ensure that participation in the energy transition progress is not limited by extensive resources or advanced technical knowledge and to extract insights from different disciplines that have much to contribute to this field.

Furthermore, the objective is to move the model from the proprietary software in which it had been programmed, GAMS, into an open-source language that can be adapted to the requirements and needs of each individual or institution. This transformation allows for flexibility to achieve more personalized and creative solutions. By opening up the development process and allowing for user customization, the applications are not confined by the limitations imposed by the developers. This approach fosters a collaborative and inclusive environment where users can actively contribute to the evolution and enhancement of the model, resulting in a more dynamic and adaptable tool for research and analysis.

## *4.2 DEFINING THE REQUIREMENTS OF THE OPENMASTER MODEL*

To achieve its objective of fostering an inclusive and collaborative approach to the energy transition, the openMASTER model must possess certain indispensable characteristics. These characteristics ensure that the model is accessible to a diverse range of participants, adaptable to different modelling needs, capable of integrating with other systems, and ultimately relevant and impactful in addressing real-world energy challenges. By embodying these qualities, the openMASTER model aims to empower a wide array of stakeholders to contribute to the development of innovative and effective solutions for a sustainable energy future.

The following sections will examine the essential characteristics that played a pivotal role in the design of the openMASTER model: accessibility, adaptability, interoperability, relevance, and impact. Subsequently, section 4.3 explores how these characteristics were effectively integrated into the model's framework.

### 4.2.1 ACCESIBILITY

Accessibility refers to the capacity of a model to provide easy and barrier-free access to its tools and resources. Open-source models must be designed in a way that allows a diverse range of users, regardless of their technical knowledge or experience, to utilize them effectively.

From a technical perspective, ensuring accessibility means that the model's interface and functionalities are intentionally designed to be easily understandable and usable by individuals with varying levels of technical proficiency. This user-friendly approach enables a broad spectrum of users to benefit from the tools and resources offered by the model, thereby facilitating the research and development process.

Furthermore, accessibility in terms of resources implies that the model is structured to minimize economic barriers to participation. By adopting an open-source framework, users are not burdened with the financial costs of accessing and utilizing the model's resources. This approach fosters a culture of experimentation and innovation, as users, including students and researchers, can freely engage with the application without the need to justify or recoup financial investments.

The advantages of ensuring accessibility within a model are manifold. It promotes inclusivity and diversity by enabling individuals of all abilities and backgrounds to contribute to research progress. Additionally, it encourages collaboration and knowledge exchange among a broader range of stakeholders, leading to more comprehensive and impactful outcomes. Overall, accessibility plays a vital role in democratizing research and ensuring that the benefits of models are accessible to a broader audience.

### 4.2.2 ADAPTABILITY

Adaptability represents the inherent flexibility of a model to meet the specific needs and requirements of each user or institution. This concept is particularly significant in the context of a rapidly changing world and the transition to clean energy.

From a technical perspective, adaptability allows users to modify and expand the source code of a model, enabling customization to fit specific contexts and challenges. This flexibility aligns with the dynamic nature of today's energy world, where new technologies and energy vectors continuously emerge, shaping the energy sector. The ability to integrate new functions and capabilities ensures that the model remains up-to-date and capable of incorporating emerging advancements.

From a resource standpoint, adaptability refers to a model's ability to function in diverse operational and technical environments. This characteristic is essential in today's interconnected world, where collaboration and knowledge exchange among stakeholders are crucial for addressing global challenges. The adaptability of a model allows it to be utilized by a wide range of actors, accommodating different data sources, computational resources, and user requirements.

### 4.2.3 RELEVANCE AND REAL-WORLD IMPACT

Relevance refers to the ability to effectively address and respond to the present-day needs and challenges in the energy sector. The relevance of energy models is determined by their applicability to real-world problems, their capacity to enhance understanding and yield solutions in energy transition, and their potential to bring about significant and impactful changes.

The urgency of transitioning to more sustainable forms of energy is being recognized more than ever due to the challenges of climate change, resource depletion, and increasing energy demand. This urgency needs models and tools that are innovative, effective, and adaptable in tackling these emerging and complex issues.

Furthermore, the relevance of these models stems from their capacity to inform evidence-based decision-making, guide policy development, and facilitate the adoption of sustainable energy practices at both the individual and societal levels.

### 4.2.4 INTEROPERABILITY

Interoperability refers to the ability of diverse models, algorithms, and software systems to interact with each other effectively. It plays a crucial role in computational research and software development by facilitating communication and data exchange between different elements in the digital domain. Model interoperability enables effective collaboration and understanding across different teams and systems, regardless of their original design or implementation. This understanding promotes alignment and smooth operation in diverse environments, enabling the collaboration of different methodologies and driving the continuous pursuit of knowledge and innovation. The concept of interoperability can be separated into two distinct stages within a project lifecycle: the development and production phases.

#### *4.2.4.1 Development Interoperability*

Development interoperability involves the integration of key elements and practices that facilitate collaboration and efficient development processes during the construction of software or models. It involves fostering collaboration among developers while maintaining an organized and systematic approach to development. By incorporating interoperability, developers can smoothly work together, share resources, and exchange information, ensuring a cohesive and streamlined development process.

The main considerations for achieving development interoperability are the following:

- *Collaboration* enables multiple researchers to work together seamlessly without task or code overlap. This is facilitated through effective teamwork, clear communication channels, and collaborative tools. By emphasizing collaboration, researchers can leverage their collective expertise to enhance productivity and minimize the risk of human error. Transparency is also enhanced, ensuring that all team members have visibility into the progress and outcomes of the collaborative efforts.
- *Version control systems*, such as Git, play a vital role in software development by effectively managing different versions of source code. These tools enable multiple developers to collaborate simultaneously without overwriting each other's changes. They also allow for easy reverting to previous code versions and facilitate testing and experimentation through the creation of separate branches for specific features or bug fixes.
- *Virtual environments* allow developers to isolate their workspace, ensuring the use of specific dependencies and library versions without conflicts with other parts of the system. This is particularly important when integrating libraries or modules written in different languages, as interoperability requires effectively integrating these libraries into the codebase. By creating virtual environments, developers can maintain controlled and self-contained environments for their projects, enabling efficient dependency management and seamless integration of external resources. This practice enhances the stability and reliability of the software development process, promoting a cohesive and functional codebase.
- *Issue tracking systems*, such as Jira and GitHub Issues, provide a centralized platform for tracking bugs and feature requests. They promote transparency and collaboration by ensuring that every team member is aware of ongoing tasks and priorities, facilitating effective communication and coordination.

*Table II: A summary of the main elements for development interoperability*

*Source: Own Elaboration*

| Element | Description | Examples |
|---|---|---|
| Collaboration | • Enabling multiple researchers to work together seamlessly without task or code overlap.<br>• Promoting effective teamwork, clear communication channels, and collaborative tools. | Establishing regular team meetings, using communication tools like Slack or Microsoft Teams, organizing code review sessions. |
| Version Control | • Managing different versions of source code.<br>• Reverting to previous code versions.<br>• Creating separate branches for specific features or bug fixes. | Git, GitHub or Bitbucket. |
| Virtual Environments | • Creating isolated workspaces with specific dependencies and library versions.<br>• Ensuring controlled environments and efficient dependency management.<br>• Efficient integration of external resources. | Python virtual environments (virtualenv, Anaconda), containerization technologies like Docker. |
| Issue Tracking | • Providing centralized platforms for tracking bugs and feature requests.<br>• Enhancing transparency, communication, and coordination among team members. | Jira, GitHub Issues, Trello. |

#### *4.2.4.2 Production Interoperability*

Production interoperability is defined as the capability of a model or software to effectively communicate, exchange data, and operate seamlessly with other systems or models in a live environment during the production phase. It encompasses various key components that enable smooth integration and interaction between different systems or models. The goal of production interoperability is to ensure that the model or software can function harmoniously with other systems, enabling efficient data exchange and collaboration. The main considerations for optimal production interoperability are:

- *Standardized data formats*, such as JSON, XML, and CSV, are essential for achieving production interoperability as they enable efficient data exchange between different systems. Adhering to these standardized formats ensures compatibility and facilitates integration with other systems.

- *Modularity* is another key aspect of production interoperability. By designing the system in a modular manner, specific components can be modified or replaced wi thout impacting the overall functionality. This promotes flexibility, adaptability, and the ability to integrate with new technologies or requirements.
- *Backward compatibility* is crucial for ensuring smooth operation in production environments. It ensures that newer versions of the software or model can still work with older data formats, software, and systems, facilitating a seamless transition and minimizing disruptions during updates.
- *Validation and testing* are essential in the production environment to verify that the software or model interacts as intended with other systems. Thorough testing and validation processes help identify and resolve compatibility issues or errors, ensuring smooth operation in real-world scenarios.

*Table III: Main considerations for production interoperability*

*Source: Own Elaboration*

| Element | Description | Examples |
|---|---|---|
| Standardized Data Formats | • Standardized data formats to facilitate efficient data exchange between systems.<br>• Ensuring data compatibility and integration. | Using common and extended data formats such as JSON, XML or CSV. |
| Modularity | • Designing the system in a modular manner to enable the interaction of several parts.<br>• Promoting flexibility, adaptability and ease of modification or replacement of components. | Component-Based Development: Designing a software model with modular components to achieve focused functionality, promote code reusability, and simplify integration of new features or modules. |
| Backward Compatibility | • Ensuring newer versions of the software or model can work with older data formats, software, and systems.<br>• Facilitating smooth operation during updates or interaction with legacy systems. | |
| Validation and Testing | • Conducting thorough testing and validation processes to ensure software or model interacts as intended with other systems.<br>• Identifying and resolving compatibility issues or errors for smooth operation in real-world scenarios. | Integration testing, interoperability testing, compatibility testing. |

## *4.3 FEATURES OF THE OPENMASTER MODEL*

In order to implement all the characteristics discussed in the previous section, the openMASTER model incorporates several features that can be divided into four categories:

1) Working environment and version control
2) Input and output data modules
3) Scenario management
4) Visualization and analysis of results

These categories encompass various functionalities and tools that enable users to effectively work within the openMASTER model and leverage its capabilities for energy optimization and analysis. The following section will delve into each category, highlighting the key features and their significance in supporting the openMASTER model's objectives.

### 4.3.1 WORKING ENVIRONMENT AND VERSION CONTROL

#### *4.3.1.1 Introduction to the working environment*

In the development of the open-source model, it was important to allow for multiple researchers to work in parallel. Additionally, due to the complexity of modelling an energy system with multiple variables and conditions, it is common for errors or changes to occur along the way. For this reason, the creation of a working environment with version control was deemed essential. To achieve this, the working environment required the following factors:

- Access to a change history and backups of previous versions.
- Synchronization of information among multiple users.
- Prevention of conflicts between changes made by different users.
- Support for simultaneous work by multiple researchers.

#### *4.3.1.2 Setting up the working environment*

For the working environment with version control, a Git server was set up on a local repository at the Universidad Pontificia de Comillas. Access to this server was done through a private VPN provided by the University to ensure the integrity of files and security against potential adversaries who could damage or steal the code.

- When interacting with Git servers, there are several interfaces available in the market such as GitLab, SourceTree and GitKraken. However, GitLab was the one chosen for the following reasons:
- GitLab is a user-friendly platform that simplifies the interaction with Git repositories. It offers an intuitive interface, clear documentation, and easy navigation, catering to both novice and experienced users.
- Additionally, GitLab provides a comprehensive set of features, including issue tracking, continuous integration/continuous deployment (CI/CD), and code review capabilities. These features create a robust development ecosystem, facilitating seamless collaboration and efficient project management.
- Moreover, GitLab benefits from a strong and active community of users and contributors, resulting in regular updates, bug fixes, and the introduction of new features. The extensive community support and documentation provided by GitLab ensure that users have the necessary resources to effectively utilize the platform.
- Ultimately, GitLab is the chosen interface hosted in the University's IIT server at the disposal of researchers.

#### *4.3.1.3 The virtual environment*

To ensure software compatibility among researchers, it was necessary to standardize the Python version and libraries used. This ensured that information loss was minimized and that changes were adapted based on the functions and considerations of a specific language version. To achieve this, researchers agreed to utilize virtual environments on their respective computers, utilizing a shared file (requirements.txt) uploaded to the Git repository. This file contained the versions of each required library, enabling collaborators to be notified and replicate any updates, additions, or deletions.

Virtual environments played a pivotal role in the project, enabling the team to effectively isolate and manage project-specific dependencies and configurations within a controlled environment. This approach ensured reproducibility and flexibility, empowering the team to experiment with different approaches. Moreover, virtual environments streamlined the process of maintenance and updates, freeing the team to concentrate on enhancing their energy optimization models without the worry of system dependency conflicts.

### 4.3.2 INPUT AND OUTPUT DATA MODULES

#### *4.3.2.1 Introduction to the input and output data modules*

In the realm of energy optimization models, the development of input and output data modules holds significant importance in guaranteeing interoperability, accessibility, and adaptability. These modules serve as the vital link between the energy optimization model and the data sources, facilitating the transmission of input data and the generation of output results. This section dives into the design of the input and ouput data modules implemented in the openMASTER model.

#### *4.3.2.2 File formats and processing*

The design of the data input and output system aimed to create a user-friendly and versatile solution that could be utilized by individuals with varying levels of technical expertise. To achieve this, the system was designed to be compatible with both generic and extended file formats, ensuring that data could be easily imported and exported. Specifically, two file formats were chosen: CSV and Excel. Although CSV is the primary format for the input and output of the model, Excel offers developers a convenient and organized means of modifying the sets and parameters. However, it is not essential for the functioning of the model. These formats were selected due to their widespread usage and compatibility with a wide range of software applications.

By utilizing these file formats, the system ensured that the results could be interpreted without the need for specialized tools or software. This is particularly beneficial in environments where not all users can access or be familiar with more advanced data management tools. The ability to visualize and analyze the data directly from these commonly used file formats eliminates the need for additional technical knowledge, such as SQL.

Furthermore, the design of the data processing in Python followed a modular approach. This means that the data processing was divided into separate blocks or modules, allowing for easy modification or customization of specific components without impacting the system's overall functionality. This modular design facilitates flexibility and adaptability and promotes code reusability, enabling the development of different services by combining existing code in various ways.

#### *4.3.2.3 Data types*

In the context of an optimization model, it is possible to distinguish the following three types of data:

- *Sets (or indices)* represent groups or categories of related elements in the optimization problem. For instance, in an energy optimization model, sets might be defined as "hours of the day", "types of energy sources", or "nodes of an electric network". Sets provide an organizational structure for the data and help define the relationships among them.
- *Parameters* are constant values used in the optimization model to represent specific features of the system. These values are known prior to solving the problem and might include data like energy demand, production costs, equipment efficiency, and technical constraints, among others. Parameters provide information to the model and assist it in making optimal decisions.
- *Variables* are the unknowns of the optimization model, i.e., the quantities the model seeks to determine to achieve the optimal solution. These variables represent decisions, such as the amount of energy generated by each source or the load level at

each node of the electric network. Variables are subject to constraints and are defined based on the problem's sets and parameters.

Sets and parameters inform the model, whereas variables are the unknowns to be optimized. The relationship among them is established via the constraints of the optimization problem, which symbolizes how sets and parameters interact in real-world scenarios. These constraints, which may include mathematical equations, inequalities, logical conditions, and other mathematical expressions, define the rules and limitations that govern the behaviour of the optimization model. They ensure that the decisions made by the model align with the given sets and parameters, leading to an optimal solution. However, the definition of these constraints, which are inherent to the model's formulation, is beyond the scope of this section.

#### 4.3.2.3.1 Data types example in an energy optimization model

Consider the following scenario:

*"The objective is to optimize the generation of electric power in a network that comprises three types of energy sources: solar, wind, and thermal. The goal is to determine the optimal allocation of energy generation from each source for every hour of the day. This allocation aims to minimize the total generation costs while adhering to the maximum capacities of each energy source and meeting the energy demand required at each hour. The generation capacities, associated costs, and energy demand at each hour are known. The primary objective is to maximize efficiency and minimize costs in this electric power network by finding the optimal allocation of energy generation".*

*Table IV presents the formulation of the optimization model for the defined scenario, showcasing the key components and their relationships.*

*Table IV: Example formulation of an energy optimization model*

*Source: Own Elaboration*

| | |
|---|---|
| ***Sets*** | |
| Energy Sources | (solar, wind, thermal) |
| Hours of the Day | (hour1, hour2, hour3, ...) |
| ***Parameters*** | |
| Generation Capacity per Source | solar_capacity, wind_capacity, thermal_capacity |
| Generation Costs per Source | solar_cost, wind_cost, thermal_cost |
| Energy Demand per Hour | demand_hour1, demand_hour2, demand_hour3, ... |
| ***Variables*** | |
| Amount of Energy Generated per Source per Hour | variable_solar_hour1, variable_solar_hour2, variable_solar_hour3, ... |
| | variable_wind_hour1, variable_wind_hour2, variable_wind_hour3, ... |
| | variable_thermal_hour1, variable_thermal_hour2, variable_thermal_hour3, ... |
| ***Constraints*** | |
| Maximum Generation Capacity per Source | variable_solar_hourX <= solar_capacity |
| | variable_wind_hourX <= wind_capacity |
| | variable_thermal_hourX <= thermal_capacity |
| Energy Demand Satisfaction | variable_solar_hour_X + variable_wind_hourX + variable_thermal_hourX >= demand_hourX |
| ***Objective Function*** | |
| Minimizing Total Generation Costs | total_cost = (variable_solar_hour1 x solar_cost) + (variable_wind_hour1 x wind_cost) + (variable_thermal_hour1 x thermal_cost) + ... |

The optimization model utilizes sets and parameters to establish constraints, such as the maximum generation capacity of each energy source and the energy demands at different times of the day. It then aims to optimize the variables by determining the amount of energy generated by each source in each hour, with the objective of minimizing costs or maximizing efficiency.

In summary, sets, parameters, and variables are the fundamental components used to construct an energy optimization model. Sets organize related data, parameters provide constant information, and variables represent the decisions to be optimized. In other words, sets and parameters represent the input of the model, while variables represent its outputs (results).

### *4.3.2.4 The input data module*

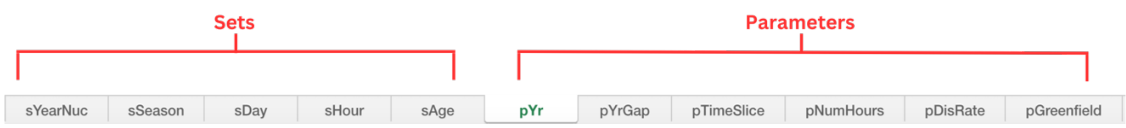
The previous example demonstrates that sets and parameters are the inputs of the model. components of a model. This section will now delve into the process of loading input data into the openMASTER model.

#### 4.3.2.4.1 Raw data representation

The initial data are stored across different tabs in an Excel spreadsheet. This format was chosen to consolidate all necessary data into a single file. In addition, it offers an easily editable interface in case data need to be adjusted. Furthermore, it provides an easily interpretable visual interface for a quick overview of the relationships between variables and the types of scenarios considered, without needing to delve into the technical details of the optimization model. The starting character on the name of the sheet indicates the type of data it contains: 's' for sets, 'p' for parameters, and 'v' for variables (see Figure II).

*Figure II: Nomenclature of Sets and Parameters*

*Source: Own Elaboration*




Thus, each type of data table has a different format. For instance, sets are usually lists of possible index types. However, variables and parameters can be tables with a multitude of formats depending on the indices they rely on. For example, a parameter depending on both technology and time will have a more complex format than one solely depending on technology. Figure III depicts the structure of a set and illustrates the structural distinction between two parameters.

*Figure III: Example of a set and two parameters*

*Souce: Own Elaboration*

Set

| sYear |
|---|
| y2020 |
| y2025 |
| y2030 |
| y2035 |
| y2040 |
| y2045 |
| y2050 |

Parameter With a Single Set

| sYear | pEmiCO2Cap |
|---|---|
| y2020 | 255 |
| y2025 | 177,5 |
| y2030 | 100 |
| y2035 | 82,25 |
| y2040 | 64,5 |
| y2045 | 46,75 |
| y2050 | 29 |

Parameter with Multiple Sets

| sCE/sYear | y2020 | y2025 | y2030 | y2035 | y2040 | y2045 | y2050 |
|---|---|---|---|---|---|---|---|
| sCENUCLEAR | 4800 | 4800 | 4800 | 4800 | 4800 | 4800 | 4800 |
| sCEIMCOTRA | 1450 | 1450 | 1450 | 1450 | 1450 | 1450 | 1450 |
| sCEIMCOIGCC | 1950 | 1950 | 1950 | 1950 | 1950 | 1950 | 1950 |
| sCEIMCOSCPC | 1650 | 1650 | 1650 | 1650 | 1650 | 1650 | 1650 |
| sCEIMCOSCCCS | 3400 | 3400 | 3400 | 3400 | 3400 | 3400 | 3400 |
| sCECCGTTRA | 550 | 550 | 550 | 550 | 550 | 550 | 550 |
| sCECCGTCCS | 1750 | 1750 | 1750 | 1750 | 1750 | 1750 | 1750 |

In summary, the use of an Excel spreadsheet for data storage offers a unified, flexible, and easily manageable data representation solution. It eases the tracking of the relationships between variables, parameters, and sets, and facilitates understanding the structure of the underlying optimization model. The naming convention helps to identify the type of data stored in each tab, providing a user-friendly interface for users to interact with the model.

#### 4.3.2.4.2 Overview of the data loading process

The Python model employs a two-step data loading process, transitioning from Excel to CSV and then from CSV to Pyomo. This approach enhances modularity and facilitates future modifications to the data format. By separating the data loading into two stages, changes to one section do not impact others, promoting efficiency and ease of implementation.

Loading data from a CSV is faster, and the initial step does not need to be repeated for every data load unless new data is created. This design allows for potential changes or expansion in the data structure or format, increasing the model's versatility and adaptability. The efficiency of CSV file processing further optimizes the model's performance, particularly when handling large data loads or frequent data updates.

#### 4.3.2.4.3 Data loading pipeline

Given the visual nature of Excel tables containing the sets and parameters, programming languages cannot directly interpret them. Therefore, a system was developed to identify and process different types of tables automatically. However, to ensure interpretability, the system allows for the inclusion of descriptions or additional information alongside the data tables introducing additional complexity to the data pipeline design (see Figure IV). The data-loading pipeline is composed of the following steps:

1) Identifying the data type (sets or parameters) based on the sheet name.
2) Defining the boundaries of the data table within each Excel sheet (see the ~BOUNDS~ indicators in Figure IV).
3) Identifying the table format and correctly processing it based on its typology.
4) Converting the input data into CSV format for subsequent processing by the Python program.

Separating the initial data from the model's input data makes it possible to continue loading data (CSV) into the model while updating or modifying the input data. This modular design allows for selecting specific functions based on specific needs, streamlining the data updating process and enhancing the flexibility and robustness of the model. This approach also enables separate and parallel workflows for data preparation and model computation, further improving the overall efficiency and effectiveness of the system.

*Figure IV: Excel data sheet with supplementary information*

*Source: Own Elaboration*

Parameter: PE Cost
Unit: [€ per MWh]

ATENTION: THIS TABLE IS **FORMULATED**. CHANGES SHOULD BE DONE AT THE **FORECASTING TABLE** (IN YELLOW)

pPECost

| | sPE/sYear | y2020 | y2025 | y2030 | y2035 | y2040 | y2045 | y2050 | y2055 | y2060 | y2065 | y2070 | y2075 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ~BOUNDS~ | | | | | | | | | | | | | | ~BOUNDS~ |
| | sPENUCLE | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | 2,88 | |
| | sPEIMPCO | 10 | 9 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | |
| | sPENAGAS | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | 18,4 | |
| | sPELNGAS | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 | |
| | sPECROIL | 40 | 40 | 40 | 37,5 | 35 | 32,5 | 30 | 30 | 30 | 30 | 30 | 30 | |
| | sPEHYDRR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEHYDRC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEMNHY | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEWINON | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEWINOF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPESOLPV | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPESOLTE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPESOLTH | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | sPEBIOMEC | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | |
| | sPEBIOMAW | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | |
| | sPEBIOMFW | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | |
| | sPESWAST | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | |
| | sPEBIOETHPI | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | 54 | |
| | sPEBIODIEPI | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | |
| | sPEBIOGAS | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | 104 | |
| ~BOUNDS~ | sPEHUMANE | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | 175 | ~BOUNDS~ |

**Interpol Rule: lineal interpolation between known forecasting values**
Initial and final values (in green) are compulsory
Formula for interpolated values needs to be adjusted in case new values (rows) are included

FORECASTING TABLE

| sPE/sYear | 2020 | 2030 | 2050 | 2075 |
|---|---|---|---|---|
| sPENUCLE | 2,88 | 2,88 | 2,88 | 2,88 |
| sPEIMPCO | 10 | 8 | 8 | 8 |
| sPENAGAS | 18,4 | 18,4 | 18,4 | 18,4 |
| sPELNGAS | 37 | 37 | 37 | 37 |
| sPECROIL | 40 | 40 | 30 | 30 |
| sPEHYDRR | 0 | 0 | 0 | 0 |
| sPEHYDRC | 0 | 0 | 0 | 0 |
| sPEMNHY | 0 | 0 | 0 | 0 |
| sPEWINON | 0 | 0 | 0 | 0 |
| sPEWINOF | 0 | 0 | 0 | 0 |
| sPESOLPV | 0 | 0 | 0 | 0 |
| sPESOLTE | 0 | 0 | 0 | 0 |
| sPESOLTH | 0 | 0 | 0 | 0 |
| sPEBIOMEC | 21 | 21 | 21 | 21 |
| sPEBIOMAW | 17 | 17 | 17 | 17 |
| sPEBIOMFW | 8 | 8 | 8 | 8 |
| sPESWAST | 21 | 21 | 21 | 21 |
| sPEBIOETHPI | 54 | 54 | 54 | 54 |
| sPEBIODIEPI | 46 | 46 | 46 | 46 |
| sPEBIOGAS | 104 | 104 | 104 | 104 |
| sPEHUMANE | 175 | 175 | 175 | 175 |

The researchers manually set indicators, denoted as "BOUNDS," when storing the raw data in the Excel file. These indicators serve as unique identifiers, allowing the model's data load pipeline to determine the boundaries of the table. This capability not only permits the inclusion of additional information within the Excel sheet, as discussed previously, but also facilitates precise control over the specific portion of data introduced into the model. This level of control is particularly valuable when dealing with different scenarios. Figure IV provides a clear example of this behaviour, illustrating how the BOUNDS indicators enable the model to identify and process the desired data accurately.

#### 4.3.2.4.4 How Python interprets the Excel table format

To facilitate Python's understanding of the data arrangement in tables, an "INDEX" sheet is included in the Excel file (see Figure V). This sheet provides information about the dimensions or structure of the data, as indices can be found in either rows or columns, similar to pivot tables. The "INDEX" sheet specifies the number of indices that are presented in rows ('DIM_ROW') and the number of indices (sets) that appear in columns ('DIM_COL'). This information is also loaded into a separate CSV file, allowing Python to access it without repeating the loading function.

*Figure V: Sample of the "INDEX" Excel sheet*

*Source: Own Elaboration*

| TYPE | GROUP | NAME | DIM_ROW | DIM_COL | UNITS | DESCRIPTION |
|---|---|---|---|---|---|---|
| Set | Set | sPE | 1 | 0 | - | Primary Energy Commodities |
| Set | Subset | sPE_Nuc | 1 | 0 | - | Nuclear Primary Energy Commodities |
| Set | Relational Set | sQCEPriIN | 2 | 0 | - | Relational set: Input PE to Primary CE |
| Set | Relational Set | sQCESecIN | 2 | 0 | - | Relational set: Input TE to Secondary CE |
| Set | Relational Set | sQCEStoIN | 2 | 0 | - | Relational set: Input TE to Storage CE |
| Set | Relational Set | sQCEPriOUT | 2 | 0 | - | Relational set: Primary CE to Output TE |
| Set | Relational Set | sQCESecOUT | 2 | 0 | - | Relational set: Secondary CE to Output TE |
| Set | Relational Set | sQCEStoOUT | 2 | 0 | - | Relational set: Storage CE to Output TE |
| Set | Relational Set | sQSTInTE | 2 | 0 | - | Relational set: Input TE to ST |
| Set | Relational Set | sQSTInRM | 3 | 0 | - | Relational set: Input RM to ST |
| Set | Relational Set | sQSTOUT | 2 | 0 | - | Relational set: ST to Output ES |
| Set | Relational Set | sQSTOUT_max | 2 | 0 | - | Relational set: ST to Output ES - maximum power to production |
| Set | Relational Set | sQESSD | 2 | 0 | - | Relational set: ES to Output SD |
| Set | Relational Set | sQSDMD | 2 | 0 | - | Relational set: SD to Output MD |
| Parameter | SysSettings | pYr | 1 | 0 | [years] | Year numbers |
| Parameter | SysSettings | pYrGap | 0 | 0 | [years] | Year gap |
| Parameter | SysSettings | pTimeSlice | 2 | 1 | [%] | Time slice load factor |

When loading data into the model, the program follows a structured approach. It first generates the INDEX, which outlines the arrangement of the data. Then, based on the defined indices and parameters during the modelling process, the data is loaded into the model. This systematic approach ensures efficient data processing, minimizes potential errors, and enhances the model's adaptability to different data layouts.

#### 4.3.2.4.5 Loading data from CSV files

Finally, the CSV files contain the stored information for each of the indices and parameters. A separate CSV is generated for each data table, named after the particular set or parameter.

Additionally, by utilizing the information found in the INDEX, the data can be loaded directly with Python.

Figure VI provides an example of the arrangement of one of the parameters within its corresponding CSV file, displaying the dependent indices and its value. The interpretation of indices and the data type is obtained by reading the mentioned INDEX sheet.

*Figure VI: CSV file containing a parameter's data*

*Source: Own Elaboration*

```
sPE,sYear,pPECost
sPENUCLE,y2020,2.88
sPEIMPCO,y2020,10.0
sPENAGAS,y2020,18.4
sPELNGAS,y2020,37.0
sPECROIL,y2020,40.0
sPEHYDRR,y2020,0.0
sPEHYDRC,y2020,0.0
```

### *4.3.2.5 The output data module*

In the data loading process of the model, the main data types involved are sets and parameters. However, in the data output, the focus shifts to variables. As mentioned earlier, variables are the unknowns to be determined during the optimization process, and they are only available once the model has been fully executed. In the data output, we can distinguish two branches:

1) The model's data output for storage purposes
2) The loading of the stored data for subsequent visualization.

The loading of variables is treated as output data since they represent the results of the model, which will be used in subsequent sections for result visualization and analysis.

#### 4.3.2.5.1 Storage of the model's output data

The output data of the model was defined to mirror the input data pipeline but in reverse.

As previously mentioned, the information regarding the indices of the parameters is stored in the “INDEX” Excel sheet. Similarly, for the output variables, this information is obtained from the "Output" sheet in Excel (see Figure VII). However, the presentation of this information differs in the latter case. Each column with the 'DIM_' prefix orderly indicates the indices that compose the variable. Specifically, 'DIM_ROW' denotes the row indices, while 'DIM_COL' denotes the column indices. Python utilizes this information to comprehend the dimensions, as defined earlier, and the indices upon which a specific variable relies. Additionally, the “Output” sheet contains information about the name and description of the current scenario, employed for scenario management (see section 4.3.3). Once this information is obtained, the following steps are executed:

1) Firstly, after executing the model, the objective is to associate each variable with its indices and store them in separate Python data tables containing the information for each variable. To maintain unified information, all these tables are stored in a Python dictionary, where the key is the variable name, and the values are the dataframes with the information for each variable. This format facilitates subsequent representation and visualization.
2) Simultaneously to storing the variables in separate data tables, this information is exported in CSV format, eliminating the need to re-run the model to operate, obtain values, and represen the data.
3) Finally, similarly than input data, to maintain a more visual and interpretable view, the CSV files containing the variables are converted to a common Excel format where all the results are consolidated (see Figures VII and VIII). It is worth noting that the size of the output variable tables is often much larger than that of the input sets and parameters. Therefore, when dealing with large variables, it may be necessary to reduce their complexity before visualizing them in Excel or similar tools. This can be achieved by simplifying the temporal detail or employing other techniques to condense the data. By doing so, the visualization process becomes more manageable and allows for clearer insights to be derived from the data.

*Figure VII: Sample of the "Output" Excel sheet*

*Source: Own Elaboration*

| NAME | DIM_1 | DIM_2 | DIM_3 | DIM_4 | DIM_5 | DIM_6 | DIM_7 | DIM_8 | DIM_ROW | DIM_COL |
|---|---|---|---|---|---|---|---|---|---|---|
| vSysCost | | | | | | | | | 0 | 0 |
| vOpVarom | sYear | | | | | | | | 0 | 1 |
| vTotalCost | sYear | | | | | | | | 0 | 1 |
| vInvCostCE | sCE | sYear | | | | | | | 1 | 1 |
| vInvCostST | sST | sYear | | | | | | | 1 | 1 |
| vOpCost | sYear | | | | | | | | 0 | 1 |
| vQPEDom | sPE | sYear | sSeason | sDay | sHour | | | | 1 | 4 |
| vQPEImp | sPE | sYear | sSeason | sDay | sHour | | | | 1 | 4 |
| vQCEPriIN | sPE | sCE | sYear | sSeason | sDay | sHour | | | 2 | 4 |
| vQCEPriOUT | sCE | sTE | sYear | sSeason | sDay | sHour | | | 2 | 4 |
| vQCESecIN | sTE | sCE | sYear | sSeason | sDay | sHour | | | 2 | 4 |
| vQCESecOUT | sCE | sTE | sYear | sSeason | sDay | sHour | | | 2 | 4 |
| vQCEStoIN | sTE | sCE | sYear | sSeason | sDay | sHour | | | 2 | 4 |
| vQCEStoOUT | sCE | sTE | sYear | sSeason | sDay | sHour | | | 2 | 4 |
| vCEStoLevel | sCE | sYear | sSeason | sDay | sHour | | | | 1 | 4 |

| | |
|---|---|
| Scenario name: | Sc001 |
| Scenario description: | Escenario de prueb |

*Figure VIII: Example of a model's output variable in Excel*

*Source: Own Elaboration*

| sSD_Ind / sYear | y2020 | y2025 | y2030 | y2035 | y2040 | y2045 | y2050 |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| sSD_DSIND_IAL | 0,79 | 0,87 | 0,95 | 0,9575 | 0,965 | 0,9725 | 0,98 |
| sSD_DSIND_IIS | 15,11 | 15,575 | 16,04 | 16,255 | 16,47 | 16,685 | 16,9 |

#### 4.3.2.5.2 Loading variables from CSV files

Once the model has been executed and the results have been stored, it is not necessary to rerun the computation unless there have been changes in the input data. In order to effectively utilize and prepare the data for future representation and visualization, it was essential to design a model for loading data from CSV files. This approach ensures that the data can be easily accessed and interpreted without the need for code execution, making it more user-friendly for individuals with less technical expertise.

To maintain consistency with the model's previous data output system and avoid the need to reload the results upon model execution, the load format was designed as a Python dictionary, similar to the structure used in the previous section. This allows for a seamless integration of the loaded data with the existing output pipeline.

To retrieve the model's output data, a script was developed to automatically iterate over each output file named after the variable it represents. The information from each file is then stored in the dictionary for future use. This modular input and output data system not only enhances accessibility and adaptability but also streamlines the workflow in managing and visualizing the model's outputs.

Overall, this approach provides an efficient and user-friendly solution for handling and analyzing the model's output data while accommodating potential changes in the input data.

### 4.3.3 SCENARIO MANAGEMENT

#### *4.3.3.1 Importance of Scenario Management*

Scenario management involves simulating and analyzing various conditions and possibilities in energy planning. It is not simply a mathematical process but rather involves fundamental human decision-making behind the objectives and constraints of the model. While the model's results are the outcome of precise mathematical calculations, it is important to recognize that the constraints and the objective function to be optimized are strategic decisions made by experts and stakeholders to give meaning and relevance to the model.

The constraints in the optimization model reflect human decisions regarding factors such as generation capacity, technical limitations, and resource availability. These decisions are essential to ensure that the model accurately represents the real-world energy system and captures practical considerations.

Similarly, the optimization objective is determined by human choices based on priorities and desired outcomes. These decisions are influenced by policies, strategies, and goals set by energy planning authorities.

On the other hand, scenario management involves the selection and definition of different possible situations and conditions for evaluation and comparison. This choice is based on an understanding of the potential challenges, opportunities, and changes that the energy system may face and aims to analyze the implications and consequences of different courses of action.

Some examples of typical scenarios include:

- *Low Emissions Scenario:* This scenario focuses on minimizing greenhouse gas emissions and promoting a transition to cleaner and renewable energy sources. It allows for the evaluation of the impact of emission reduction policies and technologies and the development of strategies to meet climate objectives.

- *Economic Cost Minimization Scenario:* This scenario aims to minimize the economic costs associated with energy generation and distribution. It helps identify optimal combinations of energy sources, technologies, and operational strategies that provide a cost-effective solution to meet energy demand.
- *Social Welfare Maximization Scenario:* This scenario seeks to maximize social welfare and considers aspects such as equity in access to energy, sustainable economic development, and improvement in quality of life. It allows for the evaluation of how energy planning decisions can positively impact communities and ensure a fair and equitable distribution of benefits.

#### *4.3.3.2 Scenario management in the openMASTER model*

In order to enhance the relevance of the model and adapt it to current needs, it was essential to develop a system that allows for the straightforward storage of different scenarios within the same model.

To achieve this, a folder system was implemented, where after each execution, both the code and the input and output data are stored. This approach ensures persistence and version control in the face of code changes, such as modifications to the objective function or the utilization of different data sources, enabling comparisons from the perspective of different resources or existing technologies.

Furthermore, the creation of the first scenario also generated a historical record which keeps track of the description and characteristics of each scenario. This organizational structure allows easy access to any available scenarios at any given time.

The management of scenarios also highlights the advantage of designing the input and output systems in a modular and independent manner. This allows for the loading of data from any scenario for visualization purposes by simply changing the file path, while the remaining steps remain unchanged. This modular design ensures flexibility and ease of use in exploring and analyzing the data associated with different scenarios.

*Figure IX: Scenario history log*

*Source: Own Elaboration*

```
scenarios > scenarios_index.csv
1    ScenarioID,Scenario name,Scenario description
2    Sc001_14_05_2023-16_58_17,Sc001,Social Welfare Scenario
3    Sc002_15_05_2023-18_51_39,Sc002,Low Emissions Scenario
```

Figure IX presents a partial display of the historical records of the scenarios. It is important to observe that each scenario is assigned a distinct identifier, which is composed of the scenario name and the timestamp of the record. This unique identifier is employed to unambiguously label the various scenario files.

### 4.3.4 VISUALIZATION AND ANALYSIS OF RESULTS

One of the main objectives of the openMASTER model is to develop an application that is relevant and applicable to address the current requirements of energy planning. To achieve this, the model offers four main visualization utilities:

1) ***Data representation with Excel:*** The openMASTER model allows for the export and representation of results data using Excel spreadsheets. This facilitates the analysis and visualization of energy planning-related data.
2) ***Chart templates:*** The model provides predefined chart templates that enable the creation of clear and compelling visualizations of energy data. These templates make it easier to interpret the results and communicate the information to different audiences.
3) ***Report Graphing Tool:*** openMASTER includes a chart generation feature that allows for the creation of custom charts for reports and presentations. This tool provides a visual interface that allows modifying the formal and visual appearance of the graphs to enhance the usability of the data for different types of users.

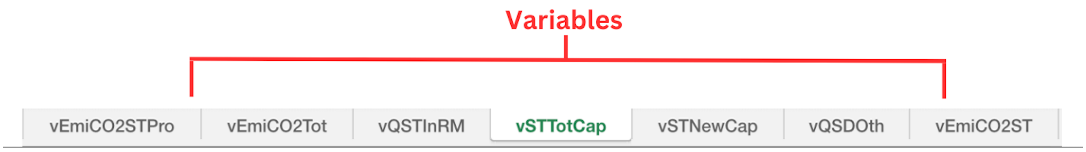
4) ***Plotly dashboard integration:*** openMASTER includes a Plotly dashboard that offers a unified view of energy data visualizations. The interactive capabilities of Plotly allow users to quickly compare and analyze results from different years and scenarios. This dynamic interface facilitates in-depth analysis by allowing users to easily manipulate data and make comparisons.

### *4.3.4.1 Representation with Excel*

Similarly, to the input data, the output data results are exported to an Excel file through a dedicated code module. Each sheet within the Excel file represents a distinct variable, denoted by the prefix 'v' (see Figure X).

*Figure X: Nomenclature of variables*

*Source: Own Elaboration*




Furthermore, Figure XI serves as an exemplification of how a variable is represented in its corresponding Excel sheet.

*Figure XI: Variable representation with Excel*

*Source: Own Elaboration*

| sST / sYear | sVin / sYear | y2020 | y2025 | y2030 | y2035 | y2040 | y2045 | y2050 |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| sST_DSIND_IAL | y2005 | 0,000165 | 0,000182 | 0,000198 | 0,000197 | 0,000198 | 0,000203 | 0,000194 |
| sST_DSIND_IAL | y2006 | 0,000163 | 0,000179 | 0,000195 | 0,000197 | 0,000198 | 0,0002 | 0,000202 |
| sST_DSIND_IAL | y2007 | 0,000165 | 0,000182 | 0,000198 | 0,0002 | 0,000201 | 0,0002 | 0,000205 |
| sST_DSIND_IAL | y2008 | 0,000148 | 0,000182 | 0,000198 | 0,000197 | 0,000198 | 0,000182 | 0,000205 |
| sST_DSIND_IAL | y2009 | 0,000165 | 0,000182 | 0,000198 | 0,0002 | 0,000201 | 0,000192 | 0,000202 |
| sST_DSIND_IAL | y2010 | 0,000165 | 0,000182 | 0,000195 | 0,0002 | 0,000199 | 0,000192 | 0,000205 |
| sST_DSIND_IAL | y2011 | 0,000162 | 0,000179 | 0,000198 | 0,0002 | 0,000201 | 0,0002 | 0,000183 |
| sST_DSIND_IAL | y2012 | 0,000165 | 0,000179 | 0,000198 | 0,0002 | 0,000201 | 0,000203 | 0,000205 |
| sST_DSIND_IAL | y2013 | 0,000165 | 0,000182 | 0,000198 | 0,0002 | 0,000198 | 0,000203 | 0,000205 |
| sST_DSIND_IAL | y2014 | 0,000165 | 0,000182 | 0,000198 | 0,0002 | 0,000201 | 0,000203 | 0,000205 |
| sST_DSIND_IAL | y2015 | 0,000165 | 0,000179 | 0,000188 | 0,000197 | 0,000201 | 0,000203 | 0,000205 |
| sST_DSIND_IAL | y2016 | 0,000165 | 0,000172 | 0,000198 | 0,0002 | 0,000201 | 0,0002 | 0,000205 |
| sST_DSIND_IAL | y2017 | 0,000165 | 0,000182 | 0,000198 | 0,0002 | 0,000201 | 0,000203 | 0,000205 |
| sST_DSIND_IAL | y2018 | 0,000162 | 0,000182 | 0,000195 | 0,0002 | 0,000201 | 0,000203 | 0,000205 |
| sST_DSIND_IAL | y2019 | 0,000165 | 0,000182 | 0,000198 | 0,0002 | 0,000201 | 0,0002 | 0,000205 |
| sST_DSIND_IAL | y2020 | 0,000165 | 0,000182 | 0,000198 | 0,0002 | 0,000201 | 0,000203 | 0,000205 |
| sST_DSIND_IAL | y2025 | | 0,000182 | 0,000198 | 0,0002 | 0,000201 | 0,000203 | 0,000202 |
| sST_DSIND_IAL | y2030 | | | 0,000198 | 0,0002 | 0,000201 | 0,000203 | 0,000194 |
| sST_DSIND_IAL | y2035 | | | | 0,000197 | 0,000198 | 0,000203 | 0,000194 |
| sST_DSIND_IAL | y2040 | | | | | 0,000201 | 0,000203 | 0,000202 |
| sST_DSIND_IAL | y2045 | | | | | | 0,000203 | 0,000205 |
| sST_DSIND_IAL | y2050 | | | | | | | 0,000205 |
| sST_DSIND_IIS | y2005 | 0,003153 | 0,00325 | 0,003347 | 0,003392 | 0,003437 | 0,003482 | 0,003343 |
| sST_DSIND_IIS | y2006 | 0,003153 | 0,00325 | 0,003347 | 0,003392 | 0,003437 | 0,003482 | 0,003527 |
| sST_DSIND_IIS | y2007 | 0,003153 | 0,00325 | 0,003347 | 0,003392 | 0,003437 | 0,003301 | 0,003501 |
| sST_DSIND_IIS | y2008 | 0,003153 | 0,00325 | 0,003347 | 0,003392 | 0,003437 | 0,003432 | 0,003527 |
| sST_DSIND_IIS | y2009 | 0,003153 | 0,00325 | 0,003347 | 0,003392 | 0,003258 | 0,003482 | 0,003527 |
| sST_DSIND_IIS | y2010 | 0,003153 | 0,00325 | 0,003299 | 0,003392 | 0,003437 | 0,003482 | 0,003476 |
| sST_DSIND_IIS | y2011 | 0,003153 | 0,00325 | 0,003347 | 0,003343 | 0,003437 | 0,003432 | 0,003527 |
| sST_DSIND_IIS | y2012 | 0,003153 | 0,00325 | 0,003347 | 0,003392 | 0,003437 | 0,003482 | 0,003476 |
| sST_DSIND_IIS | y2013 | 0,002989 | 0,00291 | 0,003347 | 0,003392 | 0,003437 | 0,003301 | 2,55E-05 |
| sST_DSIND_IIS | y2014 | 0,003153 | 0,00325 | 1,67E-09 | 0,003392 | 0,001375 | 0,003482 | 0,00139 |
| sST_DSIND_IIS | y2015 | 0,001261 | 0,00291 | 0,002997 | 0,001215 | 0,003258 | 0,003482 | 0,00139 |

#### 4.3.4.1.1 Motivation behind using Excel

Using Excel to represent the results of the openMASTER model offers several benefits. Firstly, Excel provides a familiar and widely-used platform for data analysis and visualization, making it accessible to many users involved in energy planning and decision-making.

By inputting the results of the energy optimization model into Excel, users can easily organize and format the data to create clear and concise visual representations. This allows for a better understanding of the optimized energy system, including the allocation of energy resources, the efficiency of different components, and the system's overall performance.

Excel's charting capabilities enable users to create various charts, such as stacked bar charts or line charts, to visualize the optimized energy flows, energy generation, or energy consumption patterns. These visual representations provide valuable insights into the impact of the optimization model, allowing stakeholders to identify areas of improvement, assess the effectiveness of energy-saving measures, and make informed decisions to enhance energy efficiency and sustainability.

Furthermore, Excel's data analysis features, such as formulas and pivot tables, enable users to perform further calculations and analysis on the optimized energy data. This allows for an in-depth examination of key performance indicators, cost-benefit analysis, and scenario modelling to evaluate the economic and environmental impacts of different energy optimization strategies.

#### 4.3.4.1.2 Purpose and limitations of Excel representation

Due to the limitations in the maximum number of rows and columns in an Excel file, visualizing variables that depend on numerous datasets and parameters may pose challenges in achieving a user-friendly representation of the data. However, as the data is also available in CSV format, more complex visualization solutions can still be utilized without encountering issues.

Moreover, Excel may not be the most suitable tool for interactive or dynamic visualizations, as it needs more support for real-time updates or interactive exploration of the results. Additionally, Excel's capabilities for advanced statistical analysis or modelling may be limited compared to specialized software or programming languages, which can restrict the ability to perform sophisticated statistical analyses or conduct further modelling based on the optimization results.

Nevertheless, the openMASTER model does not intend to rely solely on Excel to provide these advanced features. The availability of the data in CSV format allows external tools such as Python or R to achieve more advanced visual representations. However, considering the accessibility and versatility that Excel provides and the fact that the data scales should not pose a significant problem for most tables, Excel remains a suitable choice for a preliminary visualization of the results within the openMASTER model.

Furthermore, these limitations can be viewed as a trade-off for the benefit of offering accessibility in visualizing the results to users with varying levels of technical knowledge. Given that the available space in Excel is generally more than sufficient for most tables, it still serves as a practical and user-friendly option for representing the results of the openMASTER model.

#### *4.3.4.2 Chart templates*

In order to facilitate data representation for users unfamiliar with the Python development environment, a series of advanced templates were pre-programmed to allow for easy visualization of the data, as well as some of the most relevant and standard energy result graphics.

By replacing the data and making simple changes such as the title, axis labels, or units, advanced representations of future executions can be quickly obtained without the need for advanced technical knowledge. The pre-programmed graphics include:

1) Sankey diagram
2) Bar chart and stacked bar chart
3) Area chart and stacked bar chart
4) Sectors diagram
5) Evolutionary line

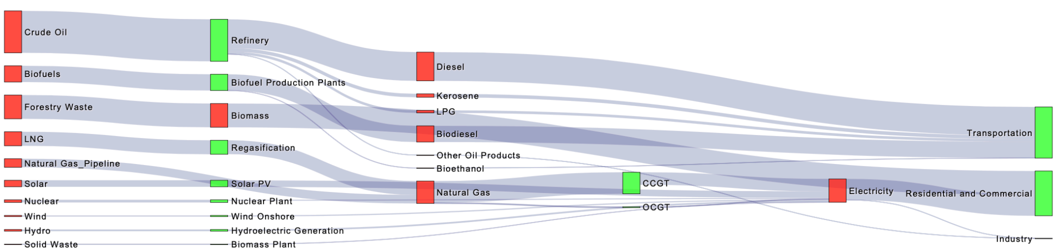
#### 4.3.4.2.1 Sankey diagram

The Sankey diagram is a visual representation that illustrates the flow or energy quantities between different components or categories (nodes) within an energy system. It consists of nodes, which represent the entities, and links, which represent the flow between the nodes. The width of the links corresponds to the magnitude or proportion of the flow being represented. The Sankey diagram is a valuable tool for visualizing energy balance, showcasing system efficiency, identifying energy losses or leaks, and understanding the contribution of each component to the overall energy flow. This diagram provides a comprehensive and intuitive representation of the energy dynamics within a system.

For example, Figure XII showcases the various energy sources (solar, wind, hydro, etc.) and their flow into the electrical grid, illustrating the distribution of energy generated by each source, their intermediate transformations and their final utilization across different sectors, including residential, industrial, and transportation.

*Figure XII: Example of a Sankey diagram*

*Source: Own Elaboration*



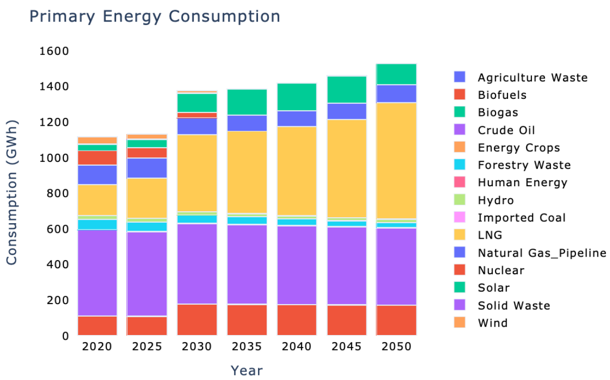
#### 4.3.4.2.2 Bar chart and stacked bar chart

The bar charts represent the magnitude of a variable across different categories or time periods using rectangular bars. Each bar represents the quantity or value corresponding to each category. The Bar Chart displays individual values for each category, while the Stacked Bar Chart accumulates the values of previous categories as it progresses. These charts are useful for quickly comparing and visualizing differences in magnitudes and trends among different categories or time periods.

For example, Figure XIII presents a comparative analysis of the consumption of various primary energy sources over the years. This analysis enables the examination of the magnitude of current consumption, the trends in energy consumption over time, and the projection of future consumption for upcoming years. By visually representing the data, this figure facilitates the identification of patterns, shifts, and potential future scenarios in energy consumption.

*Figure XIII: Example of a stacked bar chart*

*Source: Own Elaboration*



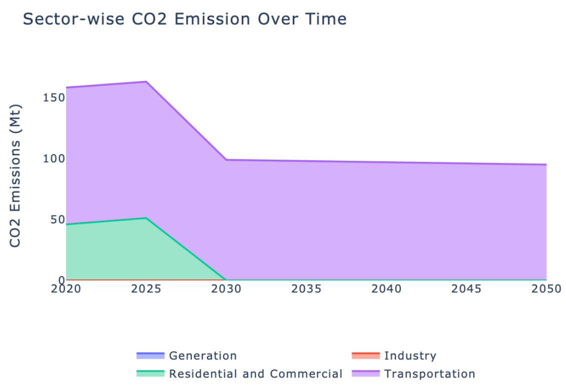

#### 4.3.4.2.3 Area chart and stacked area chart

These graphics represent the distribution and evolution of a variable over time or across different categories using coloured areas. Each area represents the magnitude of the variable in a specific category or time period. The Area Chart illustrates how the variable changes in each category or moment, while the Stacked Area Chart displays the accumulation of the variable as it progresses. These diagrams are valuable for visualizing patterns, trends, and changes in the variable over time or across different categories.

For example, Figure XIV presents a visual representation of the CO2 emissions across different sectors. This information, when analyzed in conjunction with other charts such as generation or consumption charts, can provide valuable insights into the efficiency improvements within energy systems and the progress made in transitioning towards cleaner energy sources.

*Figure XIV: Example of an area chart*

*Source: Own Elaboration*



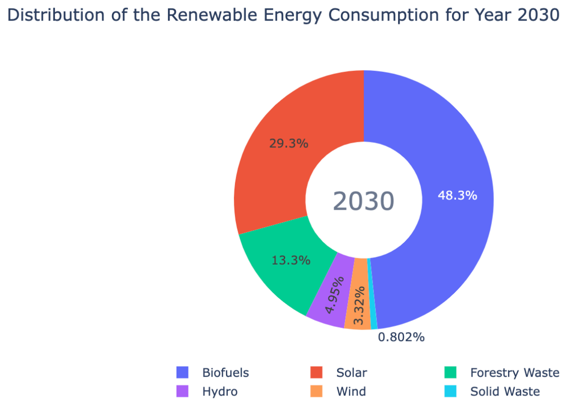

#### 4.3.4.2.4 Sectors diagram

Also known as a pie chart, this diagram represents the proportion of different categories within a whole using circular sectors. Each sector represents the relative proportion of a category compared to others. The Pie Chart is a useful tool for visualizing the contribution or participation of each category in a dataset and facilitates the comparison of proportions.

For example, Figure XV presents a comparative analysis of the consumption of various renewable energy sources. This chart serves as a valuable tool for assessing the relative significance of each energy source within the energy grid and identifying areas that require further development.

*Figure XV: Example of a sector diagram*

*Source: Own Elaboration*



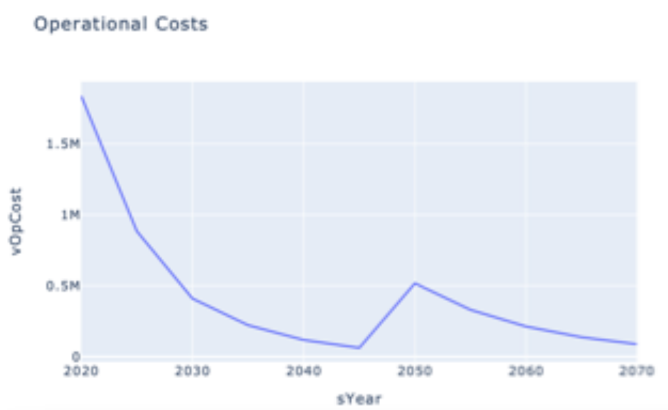

#### 4.3.4.2.5 Evolutionary line

This graph illustrates the temporal evolution of a variable, depicting its changes over time or at different moments using a line that connects the data points. The evolutionary line enables the visualization of trends, changes, and patterns in the variable as time progresses. It serves as a valuable tool for identifying shifts and conducting time series analysis.

For example, Figure XVI presents the evolution of operational costs over the years, providing a clear depiction of the cost trends and future projections in response to changing environments, particularly with the transition towards a more sustainable world.

*Figure XVI: Example of an evolutionary line*

*Source: Own Elaboration*



### *4.3.4.3 Report Graphing Tool*

#### 4.3.4.3.1 Motivation behind the Report Graphing Tool

Throughout the thesis, one of the primary objectives has been to make the model accessible to various user profiles and facilitate the interpretation and impact of the obtained results.

With this goal in mind and to facilitate the utilization of the data for different reports, articles, and presentations, a graphical interface software was developed. This software provides users with a user-friendly interface where they can easily load data through a dropdown menu and modify various aesthetic and formatting elements of the graph. This customization feature allows users to adapt the charts to their specific needs and simplifies the usage of the model's graphs.

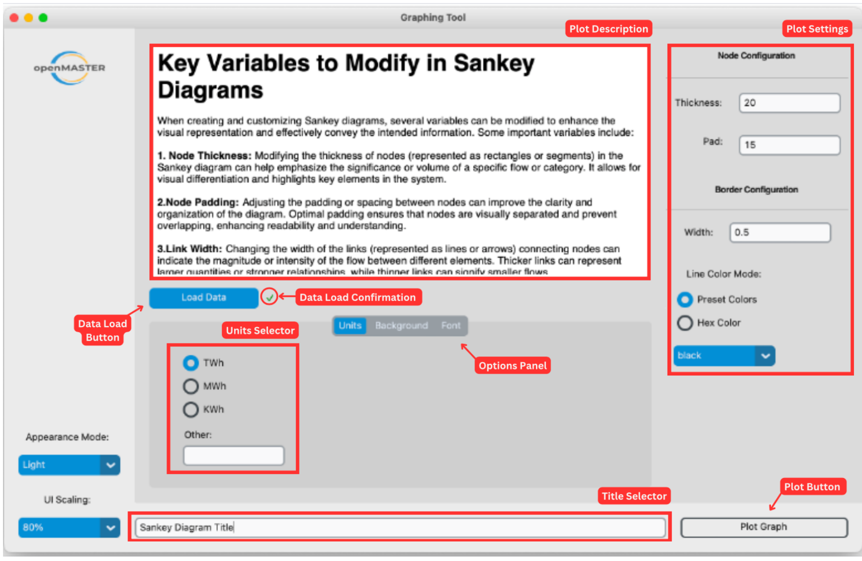
The development of this software is based on the premise that economists, journalists, or professionals from other disciplines may not necessarily know how to execute a program in Python. However, they possess valuable expertise in providing insights, visibility, and interpreting the results. Therefore, it is essential to ensure that these user profiles can easily and optimally utilize the data in the most straightforward manner possible.

#### 4.3.4.3.2 Overview of the Report Graphing Tool

The Report Graphing Tool is a versatile tool that can be applied to all the graphs discussed in the previous section. While there may be slight variations due to differences in typology, Figures XVII and XVIII are excellent demonstrations of the plotting app's capabilities, as the overall structure is shared among all the graphs.

*Figure XVII: Visual interface of the Report Graphing Tool (I)*

*Source: Own Elaboration*




## Plot Description Panel

The Plot Description section provides instructions, observations, or important information that researchers consider relevant when sharing the application. This information can be modified through a Markdown file provided with the app, allowing for easy customization.

## Data Loading

The visual interface simplifies the data loading process by utilizing the default file manager system of the user's computer. For Sankey diagrams, which are more complex, the data is loaded in JSON format, while for other types of graphs, the data is loaded via CSV. A green tick appears next to the loading button to indicate successful data loading.

## Plot Settings Panel

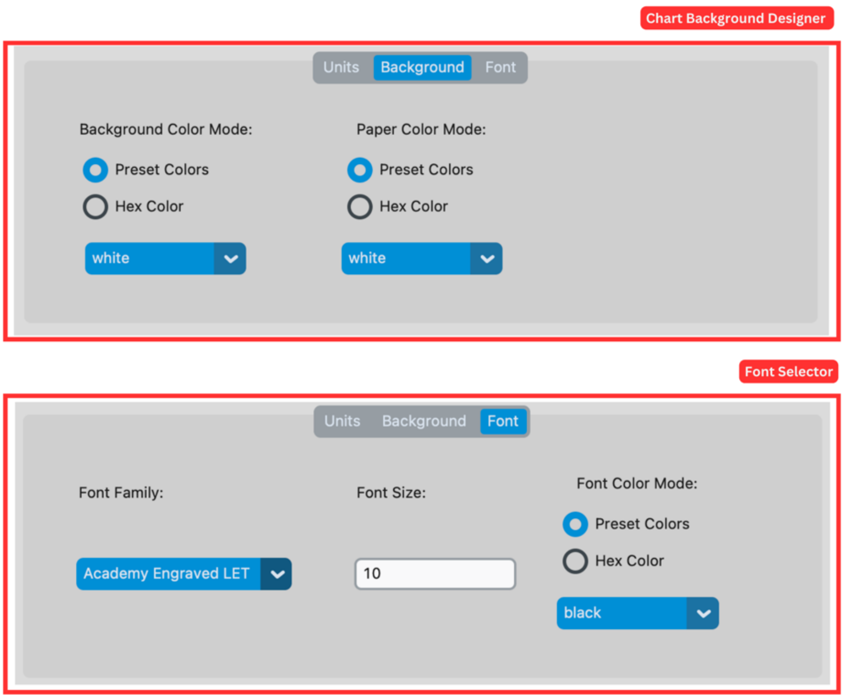
To accommodate different plot sizes and requirements, the interface includes a graphical settings section that allows for customization of the plot's shape and aesthetic aspects. This section is specific to each type of plot and is not common across all graph types.

**Title and Units Selection**

Additionally, it is crucial to have the ability to modify the title and units of the chart, as these formal aspects are essential in every representation.

*Figure XVIII: Visual interface of the Report Graphing Tool (II)*

*Source: Own Elaboration*




**Formal Customization**

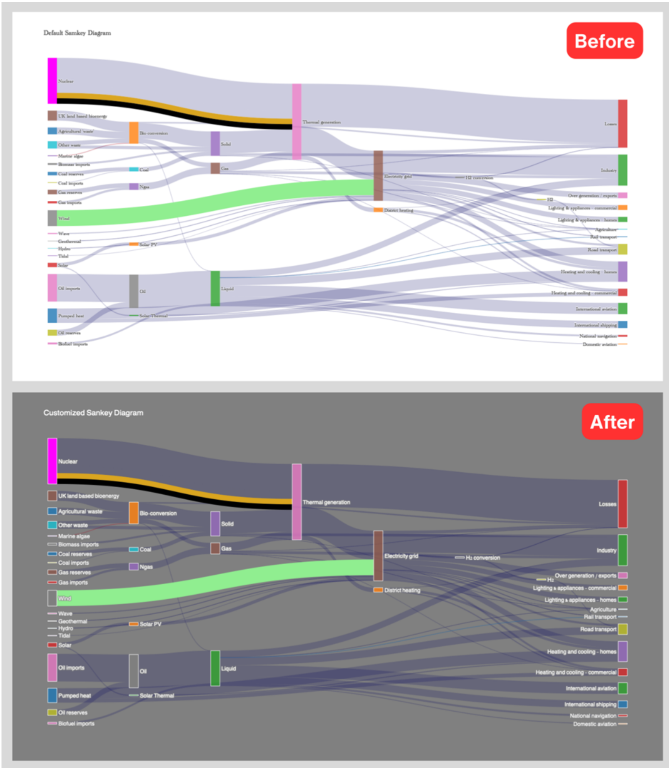
Lastly, as emphasized throughout the paper, it is important to adapt the graphs to the specific visualization needs of different users, such as researchers, journalists, or economists. Therefore, a significant portion of the application is dedicated to customizing the plot according to the user's formal requirements, including options to change colors, modify the background, and adapt fonts to suit the specific document or report being created. See Figure XVIII.

#### 4.3.4.3.3 Example usage of the Report Graphing Tool

Figure XIX exemplifies the capabilities of the Report Graph Generator, showcasing its ability to easily and efficiently make simple formal changes to adapt to specific required formats or appearances.

*Figure XIX: Example usage of the Report Graphing Tool on a Sankey Diagram*

*Soruce: Own Elaboration*




By providing users with a user-friendly interface to customize the formal aspects of the charts, the Report Graph Generator empowers users to tailor the visual representation to their specific needs and preferences. This flexibility ensures that the generated graphs align with the desired format or appearance, making them more impactful and suitable for various applications, such as research papers, reports, or presentations. The emphasis on relevance, adaptability, and accessibility underscores the commitment to providing a versatile and user-centric tool for effective data visualization and communication.

#### *4.3.4.4 Plotly dashboard integration*

##### 4.3.4.4.1 Motivation behind the Plotly dashboard integration

The integration of the Plotly dashboard into the openMASTER model was driven by the need for a more interactive and comprehensive visualization tool in energy planning. As energy planning involves complex datasets and multidimensional scenarios, there is a demand for a tool that can provide a panoramic and detailed view of this data.

The Plotly dashboard is well-known for its dynamic and highly customizable nature, allowing users to dive deep into datasets and uncover insights that may be hidden in traditional static charts. By enabling users to visualize multiple years and scenarios simultaneously, the integration of Plotly facilitates robust comparisons and trend analyses.

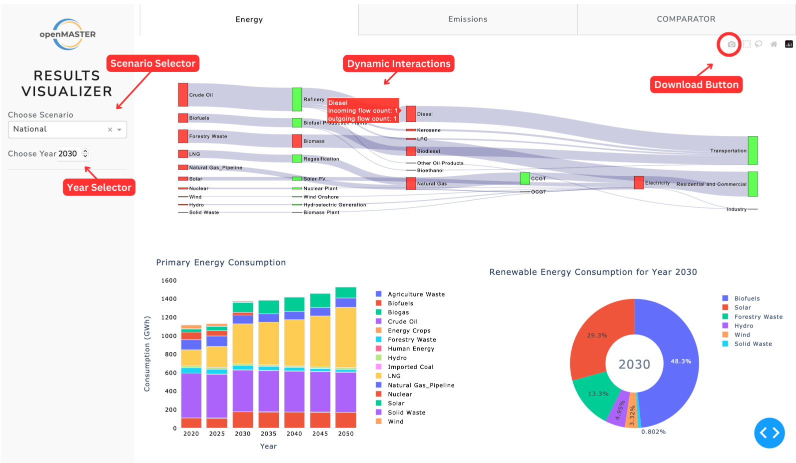
Furthermore, the interactive features of the Plotly dashboard promote user engagement, enabling stakeholders to actively interact with their data, a feature often lacking in conventional data analysis and visualization tools. The user-friendly interface and adaptability of the Plotly dashboard cater to the diverse needs of energy planners and policymakers, enhancing the overall utility of the openMASTER model.

##### 4.3.4.4.2 Overview of the Plotly dashboard integration

Figure XX provides a comprehensive overview of the Plotly dashboard integrated into the openMASTER model. This dashboard is an essential component of the openMASTER toolset, offering an intuitive and interactive interface. It enables users to explore complex energy planning data across various scenarios and timeframes with ease. The figure showcases the dynamic manipulation and comparison of data visualizations, empowering users to generate actionable insights. It highlights key functionalities of the dashboard, including the ability to customize chart types, zoom in on specific time periods, and switch between different scenarios. These features enhance the user's analytical capabilities and facilitate a deeper understanding of the data.

*Figure XX: Plotly dashboard integration*

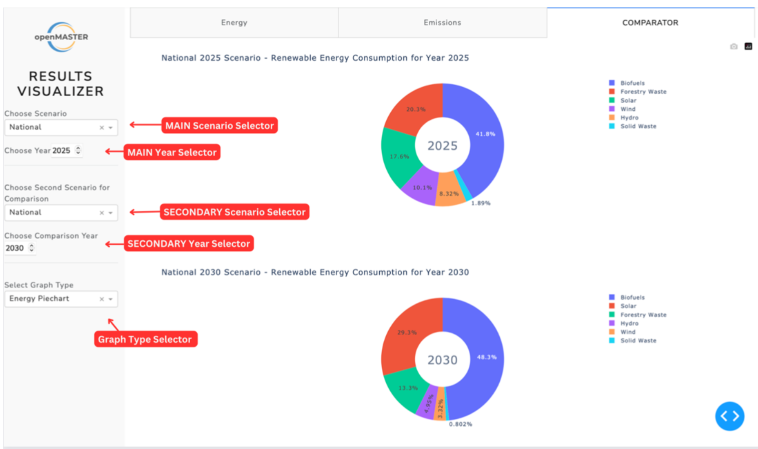
*Soruce: Own Elaboration*




Additionally, integrating a Plotly dashboard in the openMASTER model facilitates the selection and comparison of various scenarios, periods, and graph types, promoting a user-friendly comprehension of the data. Figure XXI emphasizes the significance of the "COMPARATOR" tab, which empowers users to compare data from different scenarios within the same time period and track the evolution of a single scenario across multiple time periods. This adaptability offers valuable insights for strategic decision-making and policy assessment in the energy planning domain, enhancing the overall effectiveness of the tool.

*Figure XXI: Plotly dashboard "COMPARATOR" tab*

*Source: Own elaboration*



# Chapter 5. CASE STUDY: PNIEC VS. OPENMASTER

## *5.1 INTRODUCTION TO THE NATIONAL INTEGRATED ENERGY AND CLIMATE PLAN (PNIEC)*

The National Integrated Energy and Climate Plan (NECP, PNIEC in Spanish) is a political and strategic framework established by the Spanish Government to meet its greenhouse gas emissions reduction targets and transition to a low-carbon economy. The plan is submitted to the European Commission as part of Spain's commitments under the European Green Deal (Directorate-General for Communication (European Commission), 2021). The PNIEC outlines specific measures and policies to be implemented in various sectors, such as energy, transport, industry, and agriculture, to achieve these objectives. It also includes targets for renewable energy deployment, energy efficiency improvements, and the phasing out of fossil fuels. The PNIEC serves as a roadmap for Spain's energy and climate policies, guiding the country towards a sustainable and decarbonized future.

### 5.1.1 OBJECTIVES OF THE PNIEC

The objectives of the PNIEC are multifaceted and encompass various aspects of reducing greenhouse gas emissions and the transition towards a sustainable economy. One of the primary objectives is to achieve a 23% reduction in emissions by 2030 compared to 1990 levels. This reduction target aligns with Spain's commitment to the Paris Agreement and demonstrates the country's dedication to combatting climate change.

To achieve this reduction, the PNIEC focuses on several key strategies. One of the main strategies is the promotion of renewable energy sources. The plan sets a target of 42% renewable energy in final energy consumption by 2030. This includes increasing the deployment of wind, solar, and other renewable energy technologies to replace fossil fuel-based energy generation.

Another important objective is improving energy efficiency. The PNIEC aims for a 39.5% improvement in energy efficiency by 2030. This involves implementing measures to reduce energy consumption in various sectors, such as buildings, transportation, and industry. By enhancing energy efficiency, Spain can reduce its overall energy demand and subsequently lower greenhouse gas emissions.

Furthermore, the PNIEC emphasizes the need to phase out the use of fossil fuels and promote the electrification of various sectors. This includes transitioning to electric vehicles, increasing the electrification of heating and cooling systems, and promoting the use of electric power in industrial processes. By reducing reliance on fossil fuels, Spain can significantly decrease its carbon footprint and contribute to global efforts to mitigate climate change.

### 5.1.2 USE CASES OF AN OPEN-SOURCE ENERGY MODEL IN THE CONTEXT OF THE PNIEC

In this context, open-source models are a valuable tool in promoting collaboration among various stakeholders to achieve the National Integrated Energy and Climate Plan (PNIEC) objectives. These models can be utilized by a range of actors, including government institutions, NGOs, private companies, researchers, and individual citizens, to inform and guide their actions in relation to the energy transition. Government institutions can employ these models to develop effective energy policies, while NGOs can explore different transition strategies to influence public opinion and the policy-making process. Private companies can benefit from a better understanding of the energy landscape to adapt to new regulations and seize opportunities, while researchers can utilize these models to study the energy system and the transition to cleaner energy sources.

Individual citizens can also use these models to comprehend the impact of their personal choices on the energy transition. Additionally, educational institutions, media outlets, and technology developers can leverage these models to promote energy literacy, inform the public, and anticipate future infrastructure needs and technological advancements in the energy sector. In summary, open-source models facilitate collaboration and the achievement of the goals of the PNIEC by engaging diverse stakeholders in the transition towards a low-carbon economy.

### 5.1.3 EXAMPLES OF HOW DIFFERENT ACTORS CAN ADAPT AND USE OPEN-SOURCE MODELS FOR THEIR OWN PURPOSES

Researchers and policymakers are the main beneficiaries of open-source models. However, there are other collectives that lack the expertise to construct or operate complex energy models. Therefore, offering these groups a user-friendly tool for generating reports is highly valuable.

For instance:

- A regional government can customize the model to include region-specific data and use it to develop regional-level energy transition strategies.
- A private company in the energy sector can adapt the model to understand how different policies or technological changes can impact their business and use this information to develop sustainable business strategies.
- Furthermore, media outlets could use the model to create interactive visualizations that allow readers to explore different energy transition scenarios and their implications.
- Schools and universities could adapt the model to incorporate educational activities, enabling students to experiment with different energy transition scenarios and understand their impact.
- While these are just a few examples, open-source models offer many opportunities to engage the population and facilitate the transition towards a sustainable economy by bringing the energy transition objectives closer to the public.

While these are just a few examples, open-source models offer many opportunities to engage the population and facilitate the transition towards a sustainable economy by bringing the energy transition objectives closer to the public.

### 5.1.4 How open-source models can assist achieving the objectives of the PNIEC

Ultimately, open-source models offer a significant tool to help achieve the objectives of the National Integrated Energy and Climate Plan (PNIEC). By providing a detailed and quantified view of the energy system and potential transition pathways, the model aids in identifying optimal and sustainable strategies for the energy transition. Furthermore, it can highlight barriers and facilitators for the energy transition, enabling actors to direct their efforts more effectively.

Additionally, by making information about the energy transition accessible and understandable for all, the model can cultivate greater awareness and citizen engagement. It can also reduce uncertainty and risk associated with the energy transition by providing data-driven projections and allowing actors to experiment with different scenarios and strategies, which can attract investments in clean energy and expedite its implementation. Lastly, by fostering collaboration and the exchange of ideas, the open-source model can help generate innovative and practical solutions to the challenges of the energy transition.

## *5.2 Utilizing the openMASTER model in a real-world scenario*

The present section aims to showcase how different stakeholders in society can benefit from open-source models to actively contribute to the future of the country's energy sector. Specifically, it explores the adaptability of the openMASTER model in addressing a specific energy context related to the PNIEC. To this purpose, the section conceptualizes the scenario at hand and demonstrates the model's capabilities in providing valuable insights for its analysis.

### 5.2.1 SCENARIO DEFINITION

The proposed scenario focuses on a research group, such as the BP Chair for a Sustainable Net Zero at the Institute of Technological Research (IIT, in Spanish) of the Universidad Pontificia Comillas, which aims to develop climate change scenarios and policy recommendations.

This scenario is focused on comprehending the effects of the energy transition on the demand in residential, commercial, services, and transportation sectors. To achieve the sectoral emission targets of the PNIEC, this scenario examines these sectors through the lens of energy demand. The research group can utilize the open-source model to simulate different energy transition scenarios, understanding how these will impact the demand in each sector and exploring strategies such as implementing energy efficiency technologies, electrifying transportation fleets, or integrating renewable energy sources. These strategies can contribute to formulating well-informed recommendations to enhance the transition of the country towards a greener and sustainable economy.

### 5.2.2 SOLVING THE SCENARIO WITH OPENMASTER

In this context, it is particularly important to provide visualizations and data representations that are not only by regulators but also by non-experts in the energy sector, including investors who finance the operations of the Chair. This section exemplifies how the openMASTER model helps overcome these challenges and highlights the significance of the selected visualizations in facilitating an accessible understanding of the energy system.

#### *5.2.2.1 Sankey diagram: understanding the Spanish energy system*

##### 5.2.2.1.1 The need for understanding the Spanish energy system

To effectively plan and implement energy measures, it is crucial to have a comprehensive understanding of a country's energy system. This entails knowledge of available resources, generation capacities of different energy sources, capabilities of energy transformation technologies, and the sources of end-use demand. Equally important is understanding the infrastructure and interconnections that enable the fulfilment of this demand.

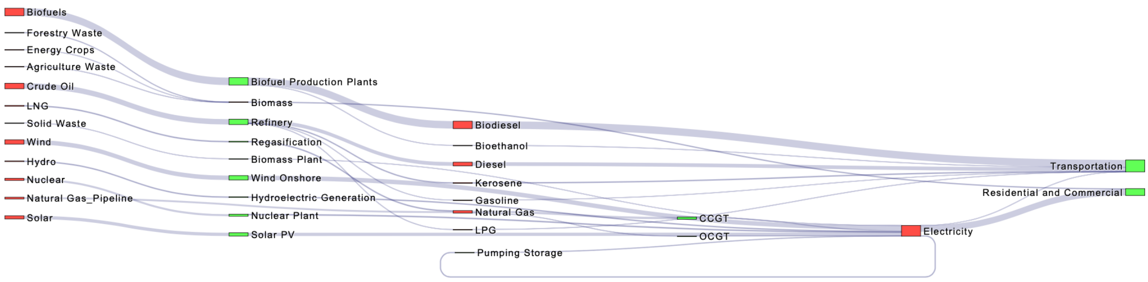
This understanding is vital because each country possesses a unique energy landscape shaped by its historical energy policies. For instance, France has heavily relied on nuclear energy, while Spain has prioritized the development of renewable technologies such as solar, wind, and hydroelectric power. Conversely, countries rich in fossil energy resources, like the United Arab Emirates, are major exporters of commodities like oil. On the other hand, some nations heavily depend on energy imports, as is the case with Spain's reliance on imported gas. Comprehending this infrastructure is essential for addressing limitations and designing appropriate solutions that align with a country's energy capabilities.

#### 5.2.2.1.2 How Sankey diagrams help understand the energy system

Sankey Diagrams are a valuable tool for gaining insights into energy flows, from primary sources to end-users, in a manner that is easily accessible and interpretable. These diagrams provide a clear representation of energy consumption patterns across different sectors, including residential, commercial, services, and transportation. By utilizing Sankey diagrams, the research group can obtain a comprehensive overview of the energy landscape, identify areas of high consumption, and pinpoint opportunities for efficiency improvements or transitions to cleaner energy sources. Comparing Sankey diagrams from different scenarios or time periods allows for a deeper understanding of changes in energy usage and efficiency. For example, comparing diagrams from different years can reveal shifts in energy consumption patterns, changes in primary energy sources, or advancements in energy efficiency.

*Figure XXII: Case Study - Representation of the Spanish Energetic Landscape for 2025*

*Source: Own Elaboration*




From Figure XXII, researchers gain valuable insights into the projected energy landscape for 2025. It is evident that fossil fuels, such as crude oil and natural gas, continue to dominate the energy mix. However, there is a notable increase in the contribution of biofuels, wind, and solar energies as primary sources of generation. This observation highlights the shifting paradigm in the energy sector and prompts researchers to consider investment in renewable sources. By embracing renewable energy technologies at an early stage, the country can benefit from advantages such as cost savings, reduced environmental impact, and enhanced sustainability. However, it is important for the research group to assess its limitations in the energy transition process. For instance, in the transportation sector, there may be fewer options for alternative energy sources, as many of them still rely on fossil fuels. On the other hand, in the commercial sector, there may be more flexibility in adopting renewable energy solutions.

### *5.2.2.2 Energy consumption: from primary energy to the end-user*

#### 5.2.2.2.1 The need for understanding the energy consumption patterns

Furthermore, it is also important to comprehend both the primary energy consumption patterns and the division of end-user consumption by sector. The analysis of primary energy consumption patterns provides insights into the initial sources of energy utilized, encompassing fossil fuels such as coal, gas, and oil, as well as renewable sources like wind, solar, and hydroelectric power. By gaining an understanding of these patterns, researchers can assess the current environmental impact of sectoral operations and determine the necessary adjustments to align with the sectoral emission targets outlined in the PNIEC.

Simultaneously, examining the energy consumption of end-users across different sectors, including residential, commercial, services, and transportation, allows to identify areas with the highest energy usage. This knowledge facilitates the development of targeted strategies to reduce energy consumption and emissions in the most impactful sectors.

#### 5.2.2.2.2 How bar and area charts help understand the consumption patterns

Area charts are effective tools for illustrating the primary energy consumption patterns of each sector, displaying the quantities of different energy sources consumed, such as natural gas, coal, nuclear, hydro, wind, or solar. By presenting this data in a clear and comparative format, area charts facilitate the identification of the most heavily relied upon energy sources and highlight opportunities for increasing the utilization of renewable sources. On the other hand, bar charts offer a visual representation of end-user energy consumption categorized by sector. By plotting the energy consumption of each sector over time, bar charts enable the research group to observe the evolution of energy use in residential, commercial, services, and transportation sectors. This analysis can reveal trends, such as sectors experiencing increasing or decreasing energy consumption, and inform strategies for emission reduction.

*Figure XXIII: Case Study - Accumulated primary energy consumption in Spain*

*Source: Own Elaboration*

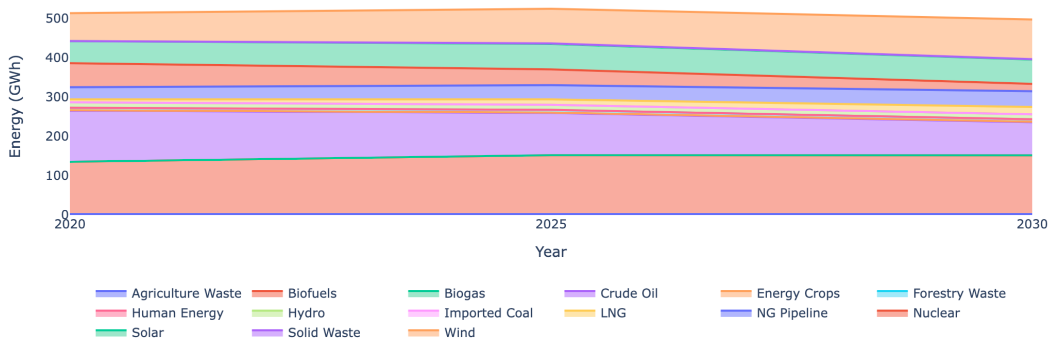
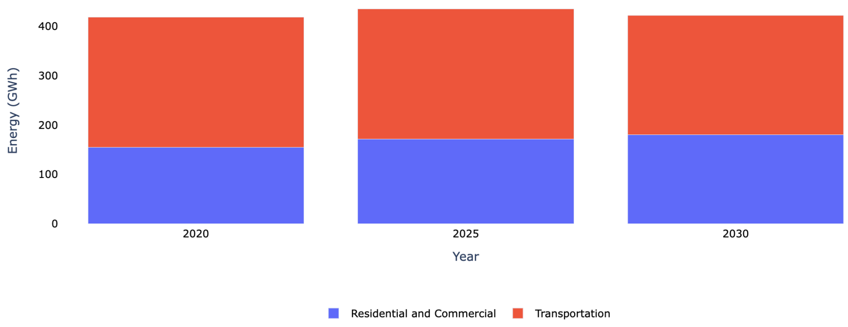


*Figure XXIV: Case Study - Final energy consumption in Spain*

*Source: Own Elaboration*




Figures XXIII and XXIV provide valuable insights into the dominant energy sources for the residential, commercial, and transportation sectors in Spain. The data reveals that biofuels, wind energy, and crude oil play significant roles in these sectors. Additionally, the figures demonstrate the feasibility of reducing energy consumption and the expected increase in popularity of renewable sources. For companies operating in the transportation sector, understanding the prominence of biofuels and crude oil can inform decisions regarding fuel choices for their fleet. On the other hand, companies in the residential or commercial sectors can draw inspiration from the importance of wind energy to develop strategies for integrating renewable sources into their operations or services. Furthermore, the feasibility of reducing energy consumption and the anticipated rise in popularity of renewable sources are crucial trends for companies to consider.

As societal and governmental pressure to reduce carbon emissions intensifies, companies that proactively work towards energy reduction and the integration of renewables are likely to gain a competitive edge. This shift towards renewables also presents new market opportunities for companies. For example, a transportation company may invest in electric or biofuel-powered vehicles, while a commercial entity might consider installing solar panels on their premises. By capitalizing on these opportunities, companies can position themselves as leaders in sustainability and potentially attract environmentally conscious customers.

### *5.2.2.3 Comparing renewable energy sources*

Understanding the distribution of renewable energy consumption and recognizing which types of renewable energy are more widespread in a country are essential for strategic business and regulatory planning. This information can serve as a guide for companies to make informed investment decisions, focusing on technologies that are already proven and supported within the country's infrastructure and regulatory framework. Additionally, it can also help regulators in formulating policies that incentivize companies to adopt more sustainable practices.

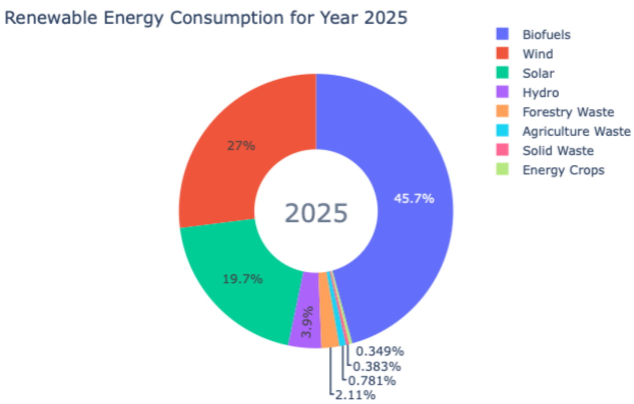
Moreover, understanding the local suitability of different renewable sources helps to make efficient and cost-effective decisions. If a type of renewable energy is more suitable for the local terrain and weather conditions, it is likely to be more efficient, reliable, and ultimately more cost-effective.

Additionally, aligning with the prevalent renewable energy technologies in the country can also strengthen the country's reputation as a sustainable and locally conscious nation. This can enhance its public image and potentially boost international relations.

#### 5.2.2.3.1 Visualizing the distribution of renewable energy consumption with sector diagrams

*Figure XXV: Case Study - Distribution of reenwable energy consumption for year 2025 in Spain*

*Source: Own Elaboration*



As seen in Figure XXV, Spain has a high penetration of solar and wind energy due to its favorable climate and terrain. Knowing this can help the company align its investment and implementation strategies with the most commonly used and supported renewable technologies in the country. If a company operates in the residential or commercial sector, it could consider investing in solar panels or wind turbines, given the existing infrastructure and regulatory support.

#### *5.2.2.4 Setting the eye on emissions*

While analyzing energy data is important, the ultimate key indicator lies in the measurement of greenhouse gas emissions. Emissions data serves as a crucial measure of the environmental impact and is closely linked to a nation's primary energy sources and consumption practices. By visualizing this data, researchers can identify areas with high emissions and implement appropriate strategies to reduce them.

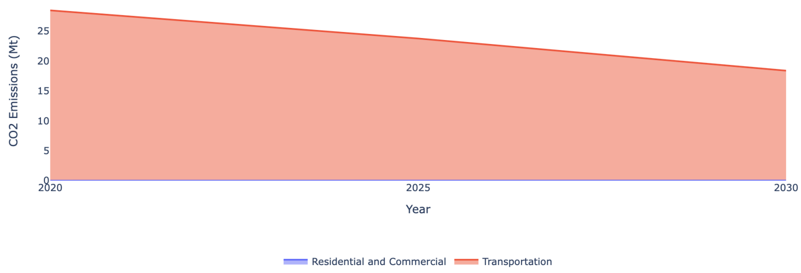
For instance, if residential and commercial sectors exhibit high emissions due to inefficient energy use, the research groups can formulate recommendations which prioritize enhancing energy efficiency in these areas. This could involve retrofitting buildings or offering more energy-efficient products and services.

From a compliance perspective, having a clear understanding of each sector's emissions profile enables it to meet local, regional, or national emission standards and regulations. As countries strive to meet their climate targets, future policies are likely to become more stringent. By adopting a proactive approach to managing and reducing emissions, the research group can position itself favorably for future regulatory changes.

Overall, prioritizing the measurement and reduction of greenhouse gas emissions not only contributes to environmental sustainability but also offers strategic advantages in terms of reputation, international political positioning, and compliance with evolving regulations.

*Figure XXVI: Case Study - Sectorwise CO2 emissions in Spain*

*Source: Own Elaboration*




Taking into account the findings presented in Figure XXVI, it becomes evident that the transportation sector is the primary contributor to emissions. Therefore, any initiative aimed at promoting cleaner and more sustainable transportation solutions can make a significant impact on achieving a sustainable future. These insights could guide regulators towards investments in cleaner transportation methods, such as electric vehicles, biofuels, or optimizing logistics to reduce travel distances and enhance efficiency.

Moreover, the chart provides a projection of a continuous decline in CO2 emissions as a result of the ongoing transition towards renewable energy sources. This visual representation is invaluable as it quantifies the effectiveness of green measures in reducing emissions. It serves as a motivating factor for industries to persist on the path of sustainability, reinforcing the notion that their efforts in adopting environmentally friendly practices are yielding tangible progress.

### 5.2.3 DISCUSSION OF THE AVAILABLE VISUALIZATIONS

The preceding section emphasizes the practical relevance of the selected visualization approach employed in the openMASTER model, highlighting its emphasis on providing energy modeling solutions that are tailored to real-world scenarios. The openMASTER model effectively utilizes comprehensive yet easily understandable visualizations to swiftly present a clear and holistic depiction of a country's energy landscape.

Moreover, these visualizations offer valuable insights that enable diverse stakeholders within a company or other interested parties to quickly grasp the fundamental dynamics of the energy sector. The simplicity of the visualizations does not compromise their value; instead, it enhances the accessibility of complex data, facilitating engagement in discussions surrounding energy transition among individuals with varying roles and levels of expertise. This inclusive characteristic of the openMASTER model is crucial, as it promotes broader participation and fosters collaboration in the pursuit of sustainable energy objectives.

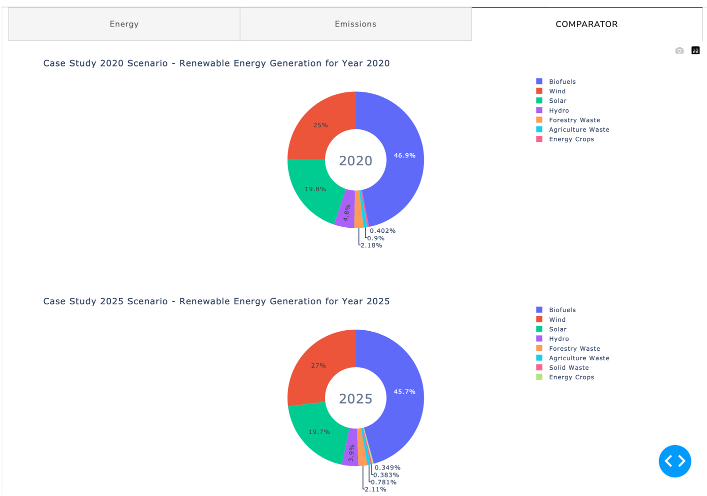
In instances where more advanced and specific visualizations are required, the model also provides the option to output results in CSV files, addressing the need for more detailed analysis.

### 5.2.4 UNLEASHING THE FULL POTENTIAL OF THE OPENMASTER MODEL

In addition to the provided graphing templates, the openMASTER model offers additional visualization solutions to maximize the utilization of data. Instead of being presented in separate charts, the Plotly dashboard integration enables the simultaneous display of all plots, making it an ideal tool for sharing model results in meetings with regulators or investor presentations. Moreover, the "COMPARATOR" tab within the Plotly dashboard facilitates the comparison of graphs from different scenarios or time periods. For instance, Figure XXVII illustrates the disparities in the distribution of renewable energy generation between 2020 and 2025.

*Figure XXVII: Case Study - Comparation of the primary energy consumption between 2020 and 2025*

*Source: Own Elaboration*



Finally, Figure XXVIII illustrates how a visualization could be represented using the Report Graphing Tool. By utilizing this tool, researchers can effectively communicate its commitment to environmental goals and enhance stakeholder understanding of its sustainability efforts.

*Figure XXVIII: Case Study - Publishing the results*

*Source:Own Elabortion*

# Chapter 6. CONCLUSIONS

*The present thesis highlights the significance of energy models in achieving the sustainable development goals set by the United Nations. It emphasizes that these goals are not solely the responsibility of governments and large companies, but require collective efforts from all members of society. To enable broader participation, the bachelor thesis focuses on open-source models and evaluates existing solutions, considering their advantages and limitations for different energy needs and objectives.*

*The study emphasizes the value of open-source models and proposes converting the MASTER model to open-source to enhance accessibility and foster collaboration within the community. This analysis establishes a framework for future projects, outlining a methodology based on version control to ensure the models' accessibility, adaptability, and interoperability.*

*The subsequent focus of the study is on the development of the openMASTER model, exploring its functionalities and presenting a practical and user-friendly approach to address a country's energy challenges. The thesis serves as a guide for future users, providing a visual understanding of the model's capabilities and how they can be applied to meet specific needs and contribute to society. The emphasis is on striking a balance between simplicity and providing a comprehensive overview of the energy context, including advanced analysis tools when necessary.*

*Finally, the case study relates the objectives of various stakeholders, particularly in the private sector, to align their business operations with the energy objectives of the National Integrated Energy and Climate Plan (PNIEC). This allows for the identification of possible business strategies that benefit both the companies, by gaining competitive advantages, and society, through investments in green technologies and a consciousness of the need to address environmental issues and climate change. Furthermore, several examples are provided to demonstrate how to maximize the practical use of the tools and visualizations that accompany the openMASTER model.*

*This work has significant implications for both the public and private sectors in terms of energy transition and planning. For the public sector, the openMASTER model offers an accessible and flexible tool for designing and evaluating energy policies. Policymakers can utilize the model to test and compare various decarbonization scenarios and strategies, enabling informed decision-making that contributes to sustainable development and zero emissions goals. The inclusion of multiple stakeholders in the energy planning process highlights the importance of inclusive and equitable decision-making, fostering collaboration and* *transparency in the public sector. The open-source approach also encourages societal participation and interdisciplinary collaboration, leading to innovative and effective solutions.*

*For the private sector, the openMASTER model can serve as a valuable tool for planning. Companies can leverage the model to optimize their operations, assess the impact of different energy transition strategies, and gain insights into potential risks and opportunities. The inclusive approach of this work underscores the significance of stakeholder collaboration and commitment, enabling companies to improve community relations and develop sustainable and socially responsible strategies.*

*In conclusion, this bachelor thesis emphasizes the importance of stakeholder collaboration and commitment in developing sustainable and socially responsible business strategies. It not only highlights the utility and applicability of openMASTER but also encourages its adoption and use in various contexts, facilitating energy transition and progress towards a more sustainable and environmentally friendly society.*

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# APPENDIX I: ALIGNMENT OF THE WORK WITH THE SDGS

The present work aligns with the following SDGs in the quest to create a sustainable and inclusive future:

***SDG 7: "Affordable and Clean Energy"***

The world population is continuously growing, and as a result, the demand for energy is also increasing. For this reason, a sustainable future must be accompanied by responsible management of energy resources, particularly fossil fuels, which are becoming increasingly limited.

In this context of transitioning towards a clean and sustainable economy capable of meeting the expected growth, the project is introduced as an energy planning tool that serves as a guide for regulators and stakeholders.

***SDG 9: "Industry, Innovation and Infrastructure"***

The efficient use of resources is a crucial element for the survival of the industry and technological progress. Thus, it can be argued that the future of industrialization relies on the pillars of innovation and sustainability.

Considering all of the above, the development of an open-source energy planning model is a significant initiative to facilitate the transition towards sustainability and make progress accessible to specialists and stakeholders worldwide. This way, everyone can contribute to the advancement of the industry, the creation of new jobs, and technological investment.

***SDG 11: "Sustainable Cities and Communities"***

Climate change is an ongoing global reality. Despite the reduction in greenhouse gas emissions in recent years due to the Covid-19 pandemic, it is expected that levels will increase again. Additionally, rapid urbanization of cities and the growth of activities contribute to a significant deterioration in air quality and resource accessibility.

In this context, the project emerges as an additional and effective tool for promoting a clean and sustainable economic recovery. It aims to optimize the distribution of energy resources to maximize social and environmental well-being.