openTEPES

Simplicity and Transparency in Power Systems Planning

Andrés Ramos, Erik Álvarez

Repository hosted on GitHub

Documentation hosted by Read the Docs

1

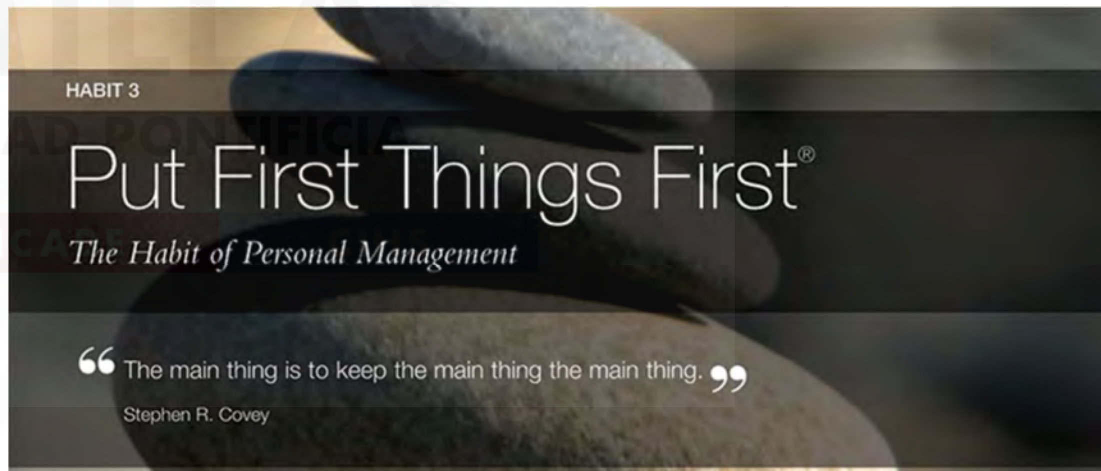
Introduction

1. Introduction
2. Modeling
3. Installation
4. Case studies
5. To be continued

Put First Things First

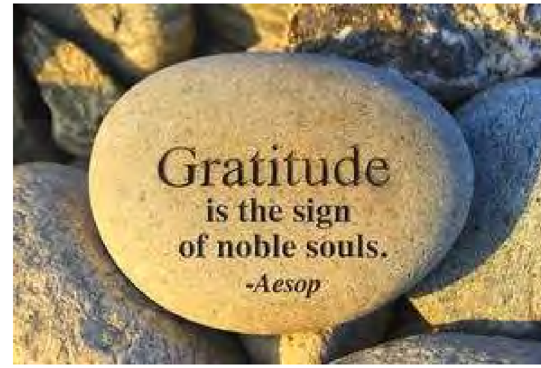
https://opentepes.readthedocs.io/en/latest/Download.html

Disclaimer:
This model is a work in progress and will be updated accordingly.



https://www.franklincovey.nl/resources-type/blog-2/habit-3-put-first-things-first/

Es de bien nacidos ser agradecidos (Spanish saying)



- Authors

Andrés Ramos

Erik Álvarez

Sara Lumbreras

open TEPES

"with the very valuable collaboration from David Domínguez (david.dominguez@comillas.edu) and Alejandro Rodríguez (argallego@comillas.edu), our local Python gurus"

Sponsored by: LOC, MRA, SLS, TGSR, ARG

GNU GENERAL PUBLIC LICENSE. Version 3 (GPLv3)

- The code can't become part of a closed-source commercial software product nor can be used for commercial purposes (only for research purposes)
- Any future changes and improvements to the code remain free and open

- Guarantee end users the freedom to run, study, share, and modify the software
- Any derivative work must be distributed under the same or equivalent license terms
- The licensee is allowed to charge a fee for this service or do this free of charge.
- Software under the GPL may be run for all purposes, including commercial purposes and even as a tool for creating proprietary software

GPLv3 Free Software

Free as in Freedom

Open Generation, Storage, and Transmission Operation and Expansion Planning Model with RES and ESS

openTEPES

version 4.3.7

Navigation

Introduction
Input Data
Output Results
Mathematical Formulation
Research projects
Publications
Download & Installation
Contact Us

Quick search

Go

openTEPES Documentation

Open Generation, Storage, and **T**ransmission Operation and **E**xpansion **P**lanning Model with RES and **ESS** (**openTEPES**)

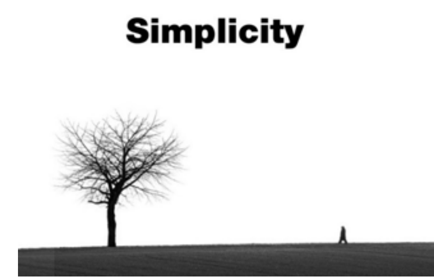
"Simplicity and Transparency in Power Systems Planning"

The **openTEPES** model has been developed at the Instituto de Investigación Tecnológica (IIT) of the Universidad Pontificia Comillas.

DOI: 10.24433/CO.8709849.v1

Index

v: latest



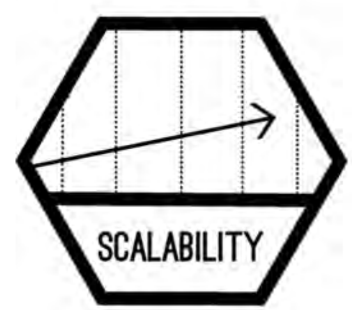
Main Development Goals

- Simplicity and transparency
- Code written to be read by humans
- Scalability: from small- to large-scale cases

- Chronological model with flexible duration of the time step (e.g., bi-hour, 3-hour, 4-hour time step), but also representative periods

- Strong orientation to efficiency:
  - In generating the optimization problem
    - Use of libraries (Pandas) for input data and data manipulation
  - Careful implementation for reducing solution time
    - Numerical stability. Scaling variables and constraints around 1
    - Tight and compact formulation of some constraints

```
Caso SEP2030
2999548 rows, 3513436 columns, 11508142 nonzeros
Case ES2030
5162243 rows, 6832942 columns, 21554828 nonzeros
```



2

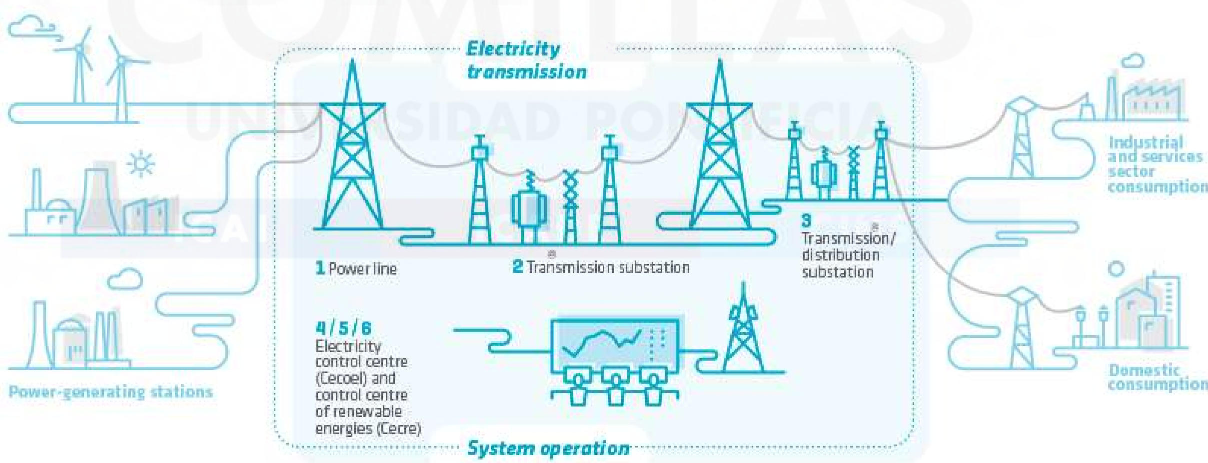
Modeling

Modeling Overview

- Built according to a bottom-up paradigm.
- It applies optimization to find the optimal generation, storage, and transmission expansion plan (GEP+SEP+TEP).
- Uses Mixed-Integer Linear Programming (runs on GUROBI, GLPK, or CBC) to solve the problem.
  - [Benders decomposition available for solving large-scale problems]

Main modeling features (i)

- Generation, storage, and transmission operation and expansion planning (GEP+SEP+TEP)
- Network constrained unit commitment (NCUC)
- DC power flow (DCPF) with ohmic losses
  - [ACPF also available]



Main modeling features (ii)

- Energy Storage Systems (ESS), e.g., hydro power plants, open- and closed-loop pumped-hydro storage, battery, EV, DSM, solar thermal
- Pumped-hydro storage (PHS) or batteries operate shifting energy between different timeframes and represent a small modification of the operation variable cost
  - Unit-based modelling of ESS

Generation, Storage, and Transmission Expansion (GEP+SEP+TEP)

- Determines the investment or retirement plans of new assets for supplying the forecasted demand at minimum cost.
- Minimum adequacy reserve margin [p.u.]
- The candidate generator, ESS, and lines are pre-defined by the user.
  - Candidate lines can be HVDC or HVAC circuits.
  - [Candidate discovery allows to propose automatically new transmission candidates].
- Provides an investment plan while considering system operation. It incorporates a Unit Commitment and schedules the operation of medium- and short-term storage (i.e., pumped-hydro storage, batteries).

Dealing with uncertainty

- Several stochastic parameters that can influence the optimal expansion expansion decisions are considered.
- The operation scenarios are associated to renewable energy sources, electricity demand, and natural hydro inflows

Demand and operating reserves

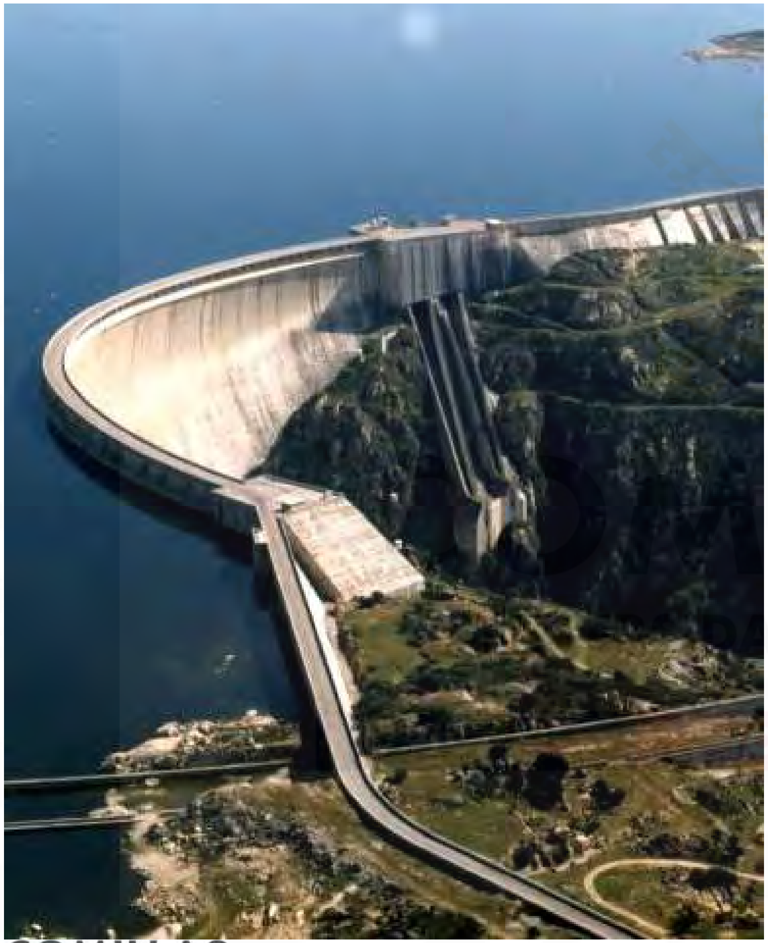
- Balance of generation and demand [GW]
- Upward and downward operating reserves (aFRR, mFRR, RR) [GW] provided by controllable generators (CCGT, storage hydro) and ESS (pumped-hydro storage, batteries), including activation of these reserves [GWh]
- Reserve activation: a proportion (e.g., 25-30 %) of the power provided as operating reserves which is asked to be deployed as energy

S. Huclin et al. "*Exploring the roles of storage technologies in the Spanish electric system with high share of renewable energy*" Energy Reports (accepted)

Thermal subsystem

- Maximum and minimum output of the second block of a committed unit (all except the VRES units) [p.u.]
- Total output of a committed unit [GW]
- Logical relation between commitment, startup and shutdown status of a committed unit [p.u.]
- Maximum ramp up and ramp down for the second block of a thermal unit [p.u.]
- Minimum up time and down time of a thermal unit [h]

Hydro and storage subsystems



- Power plants: hydro, open-loop pumped-hydro storage (PHS) aggregated in management units, closed-loop PHS treated individually, and system battery storage
- ESS energy inventory (only for load levels multiple of 24, or 168 h depending on the ESS type) [GWh]
- Energy outflows to represent H2 production or km for EV
- Total charge of an ESS unit [GW]
- Maximum and minimum charge of an ESS [p.u.]
- Incompatibility between charge and discharge of an ESS [p.u.]

Variable renewable energy (VRE)

- Power plants: solar PV, onshore wind, biomass, cogeneration, run-of-the-river hydro
- Maximum and minimum hourly variable generation

Mathematical formulation

https://opentepes.readthedocs.io/en/latest/MathematicalFormulation.html

- Variables
  - Generation and transmission expansion
  - Commitment and operation (thermal, ESS, VRE)
  - Operating reserves
  - Stored energy
  - Flows, voltage angles, losses
- Constraints
  - Expansion
    - ✓ Commitment decision bounded by investment decision for candidate committed units
    - ✓ Output and consumption bounded by investment decision for candidate ESS
  - Generation
    - ✓ Balance of generation and demand at each node with ohmic losses
    - ✓ Upward and downward operating reserves
    - ✓ ESS energy inventory
    - ✓ Maximum and minimum output of the second block of a committed unit
    - ✓ Total output of a committed unit
    - ✓ Logical relation between commitment, startup and shutdown status of committed unit
    - ✓ Maximum ramp up and ramp down for the second block of a thermal unit
    - ✓ Minimum up time and down time of thermal unit
  - Network
    - ✓ Transfer capacity in candidate transmission lines
    - ✓ DC Power flow for existing and candidate AC-type lines (Kirchhoff's second law)
    - ✓ Half ohmic losses are linearly approximated as a function of the flow

Objective function: minimization of total (investment and operation) cost for the scope of the model

Generation, storage and network investment cost [M€]

$$\sum_g CFG_g icg_g + \sum_{ijc} CFT_{ijc} ict_{ijc}$$

Generation operation cost [M€]

$$\sum_{\omega png} [P_\omega DUR_n (CV_g gp_{\omega png} + CF_g uc_{\omega png}) + CSU_g su_{\omega png} + CSD_g sd_{\omega png}] + \\ + \sum_{\omega pni} P_\omega DUR_n CENS ens_{\omega pni}$$

Constraints

Relation between commitment and investment decision on candidate committed units (all except the RES units) [p.u.]

$$uc_{\omega png} \leq icg_g \quad \forall \omega png, g \in CG$$

Relation between output/consumption and investment decision on candidate ESS [p.u.]

$$\frac{gp_{\omega png}}{\overline{GP}_g} \leq icg_g \quad \forall \omega png, g \in CE$$

$$\frac{gc_{\omega png}}{\overline{GC}_g} \leq icg_g \quad \forall \omega png, g \in CE$$

1. Introduction
2. Modeling
3. Installation
4. Case studies
5. To be continued

3

Installation

Installation

Easy-way (Python Package)

1. Miniconda. Choose the 64-bit installer if possible.

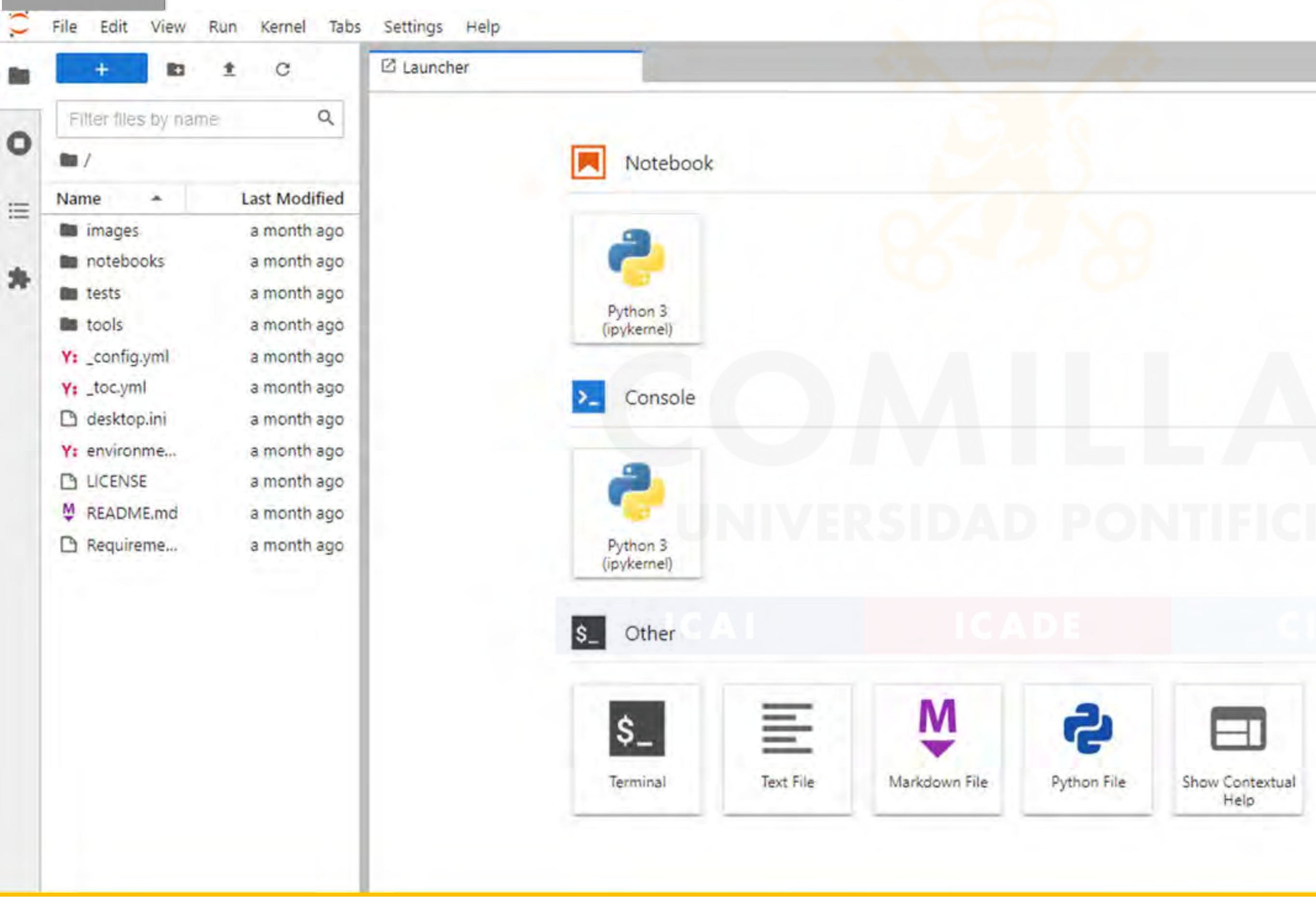
2. Packages and Solver:
    1. Launch a new command prompt (Windows: Win+R, type "cmd", Enter)
    2. Install openTEPES via pip by
       pip install openTEPES
    3. Install the solver

Hard-way (Clone or download)

1. Clone the openTEPES repository.
    1. Launch the command prompt (Windows: Win+R, type "cmd", Enter), or the Anaconda prompt
    2. Set up the path by
       cd "C:\Users\<username>\...\openTEPES"
       (Note that the path is where the repository was cloned.)
    3. Install openTEPES via pip by pip install.
2. Download from the website (ReadTheDocs), and install as if this has been cloned.

Interactive Tutorial: thanks to…

https://mybinder.org/v2/gh/IIT-EnergySystemModels/openTEPES-tutorial/HEAD



- Path: notebooks\"…. .ipynb"
- Notebooks:
  - 00-index.ipynb
  - 01-openTEPES-Demo.ipynb
    - 1.2. Quick-run
    - 1.3 Running Step by Step
  - 02-Time-Step.ipynb
  - 03-Stages.ipynb
  - 04-Execution-Modes.ipynb
    - Economic Dispatch
    - Unit Commitment
    - Transmission Expansion Planning
    - Generation Expansion (or Retirement) Planning
    - Optimal Transmission Switching
- Study cases:
  - 9n
  - 9n_ByStages
  - sSEP
  - RTS24

4

Case Studies

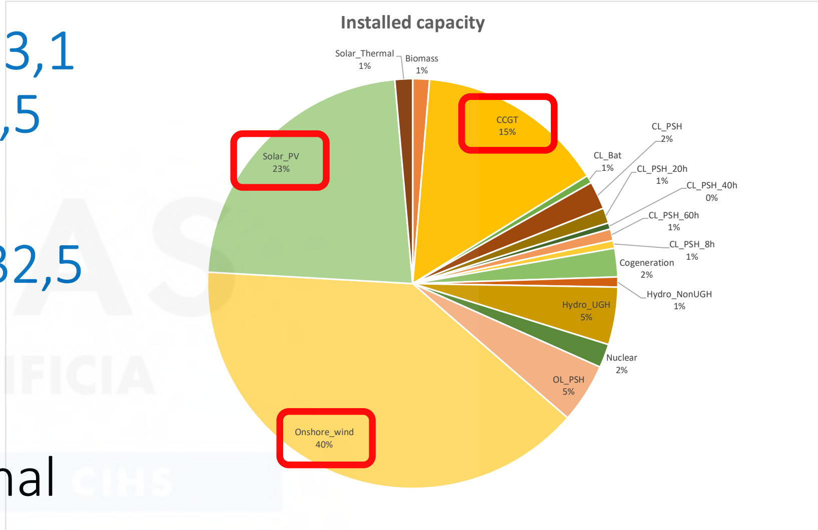
Research projects

WHY…? WHAT FOR…?

- Impact of the electric vehicle in the electricity markets in 2030, developed for Repsol. November 2021 - February 2022.
  - It aims at analyzing the impact on the electricity markets of the mainland Spanish system of the high penetration of electric vehicles in a 2030 scenario.
- European Climate and Energy Modelling Forum (ECEMF), developed for the European Commission. May 2021 - December 2024.
  - It aims at providing the knowledge to inform the development of future energy and climate policies at national and European levels. In support of this aim, ECEMF proposes a range of activities to achieve five objectives and meet the four challenges set out in the call text. ECEMF's programme of events and novel IT-based communications channel will enable researchers to identify and co-develop the most pressing policy-relevant research questions with a range of stakeholders to meet ambitious European energy and climate policy goals, in particular the European Green Deal and the transformation to a climate neutral society.
- Assessment of the storage needs for the Spanish electric system in a horizon 2020-2050 with large share of renewables, developed for the Instituto para la Diversificación y Ahorro de la Energía (IDAE). January 2021 - March 2022.
  - It aims at assessing, from a technical and economic point of view, the daily, weekly and seasonal storage needs for the Spanish electricity system in the 2020-2050 horizon.
- FlexEner. New 100% renewable, flexible and robust energy system for the integration of new technologies in generation, networks and demand - Scenarios, developed for Iberdrola under Misiones CDTI 2019 program (MIG-20201002). October 2020 - December 2023.
  - It aims at investigating new technologies and simulation models in the field of renewable generation, storage systems and flexible demand management and operation of the distribution network. A 100% renewable and decarbonised energy mix is sought, effectively integrated into the electrical system of the future in a flexible, efficient and safe way.
- Improving energy system modelling tools and capacity, developed for the European Commission. October 2020 - June 2022.
  - It aims at improving the description of the Spanish energy system in model TIMES-SINERGIA, from the technologies considered or a higher time resolution to the detailed modeling of the power sector, such as the inclusion of transmission constraints.
- MODESC – Platform of innovative models for speeding the energy transition towards a decarbonized economy, developed for the Ministry of Science and Innovation under Retos Colaboración 2019 program (RTC2019-007315-3). September 2020 - December 2023.
  - It aims at developing of a global platform that integrates innovative energy simulation and impact assessment models that allow speeding the decarbonization of the electricity system including the electrification of the energy demand.
- Open ENergy TRansition ANalyses for a low-carbon Economy (openENTRANCE), developed for the European Union. May 2019 - April 2023
  - It aims at developing, using and disseminating an open, transparent and integrated modelling platform for assessing low-carbon transition pathways in Europe.
- Analysis of the expansion and operation of the Spanish electricity system for a 2030-2050 time horizon, developed for Iberdrola. January 2019 - December 2021.
  - It aims at evaluating the potential and role that each generation, storage and consumption technology can play in the future mix of the Spanish electricity system.

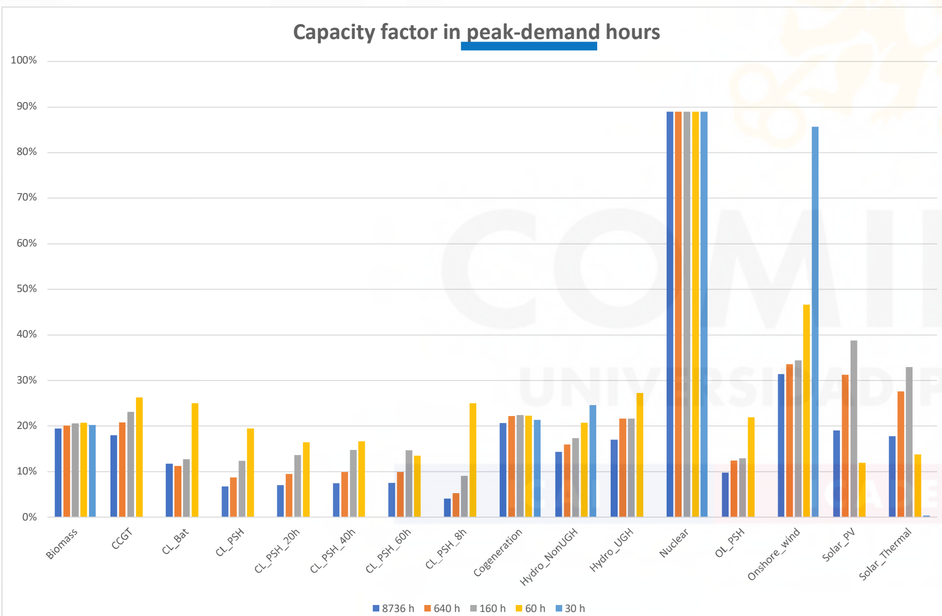
Mainland Spain 2030

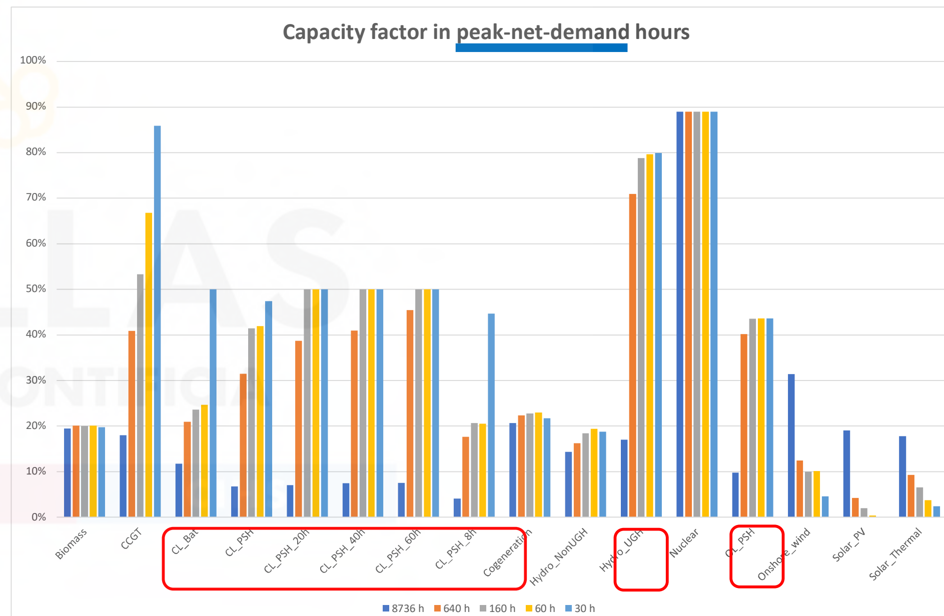
- 10-year Integrated National Energy and Climate Plan (NECP)
- Installed capacity: 137 GW
- Half of the nuclear units phased out (3,1 GW), no coal units, existing CCGT (24,5 GW)
- Significant investments on solar PV (32,5 GW) and onshore wind (38,2 GW)
- Existing storage hydro and pumped-hydro storage (16,5 GW) and additional pumped-hydro storage (3,5 GW)
- Batteries forced to be installed (2,5 GW)



Firmness/Electric Load Carrying Capability (ELCC)

Capacity factors of the different technologies at peak hours of demand and net demand

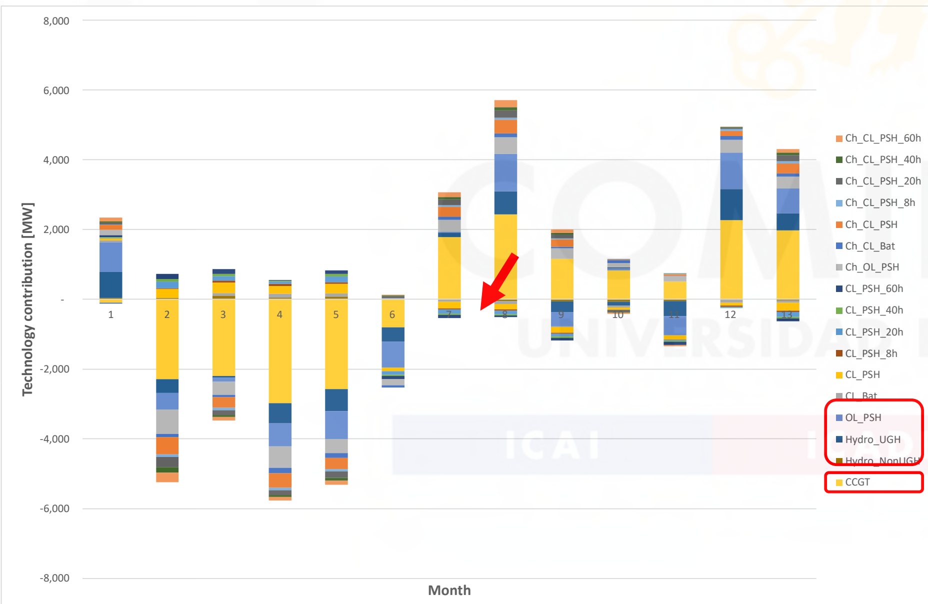


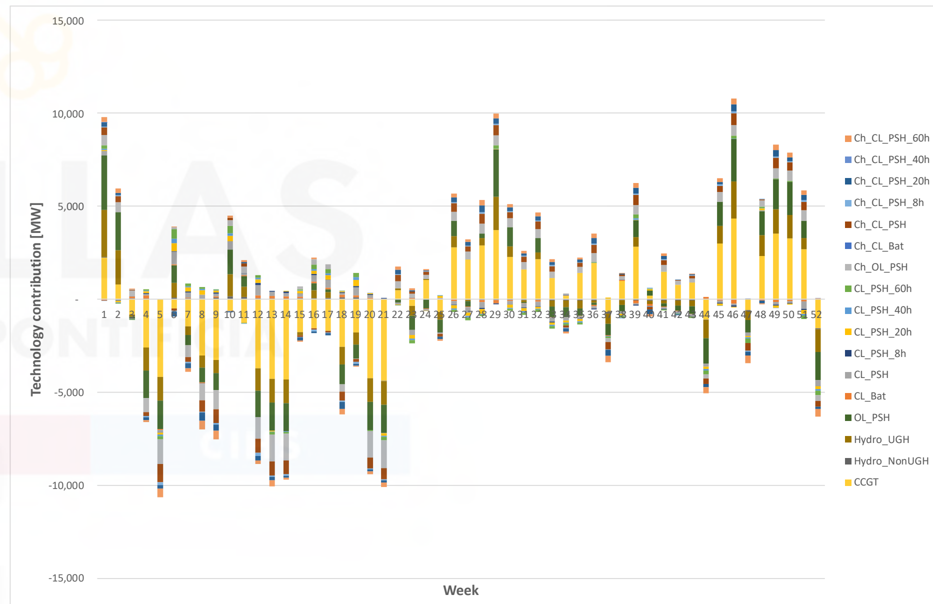


S. Huclin et al. "*Exploring the roles of storage technologies in the Spanish electric system with high share of renewable energy*" Energy Reports (accepted)

Flexibility

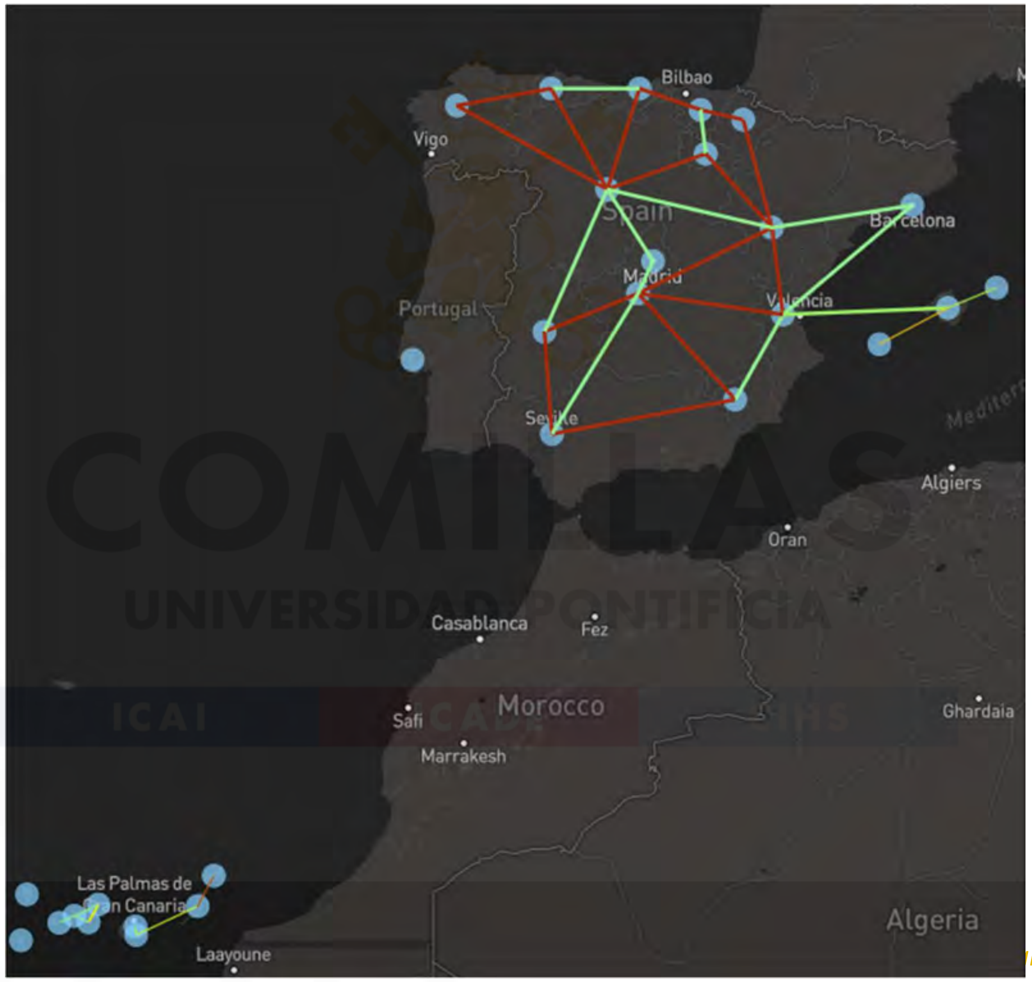
Technology contribution to the monthly/weekly variation of the net demand (difference between the value and its mean)



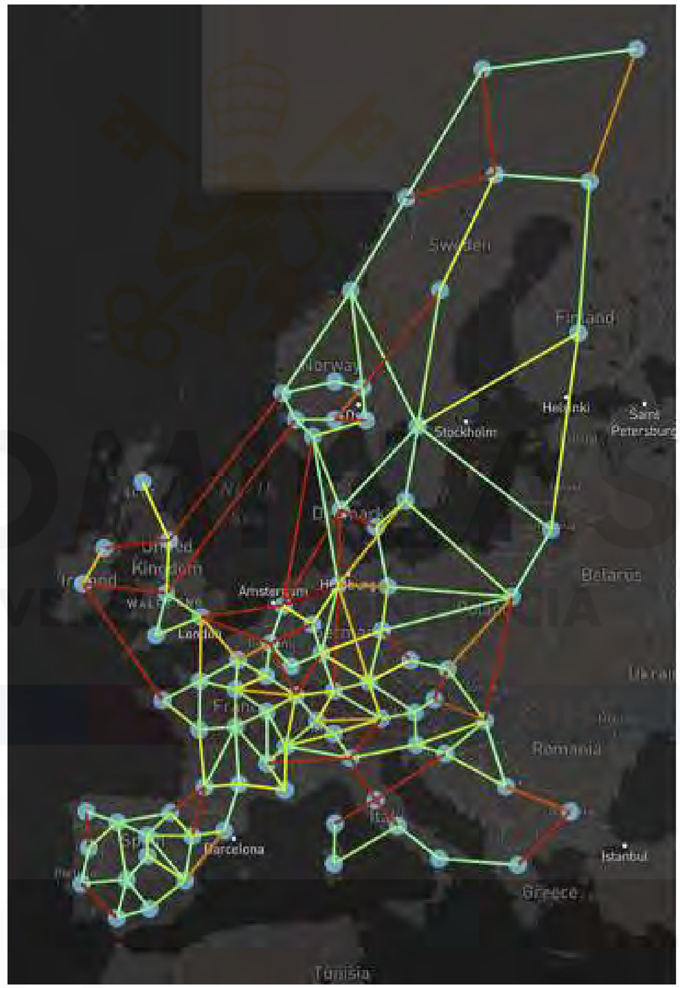


A. Ramos "Assessing the operational flexibility provided by energy storage systems. The Spanish system in 2030" IEA Wind Task 25 Spring 2021 meeting. April 2021

Spain 2030


Bilbao
Vigo
Spain
Barcelona
Madrid
Portugal
Valencia
Seville
Algiers
Oran
Casablanca
Fez
Morocco
Safi
Marrakesh
Ghardaia
Las Palmas de
Gran Canaria
Laayoune
Algeria

Europe TF2030

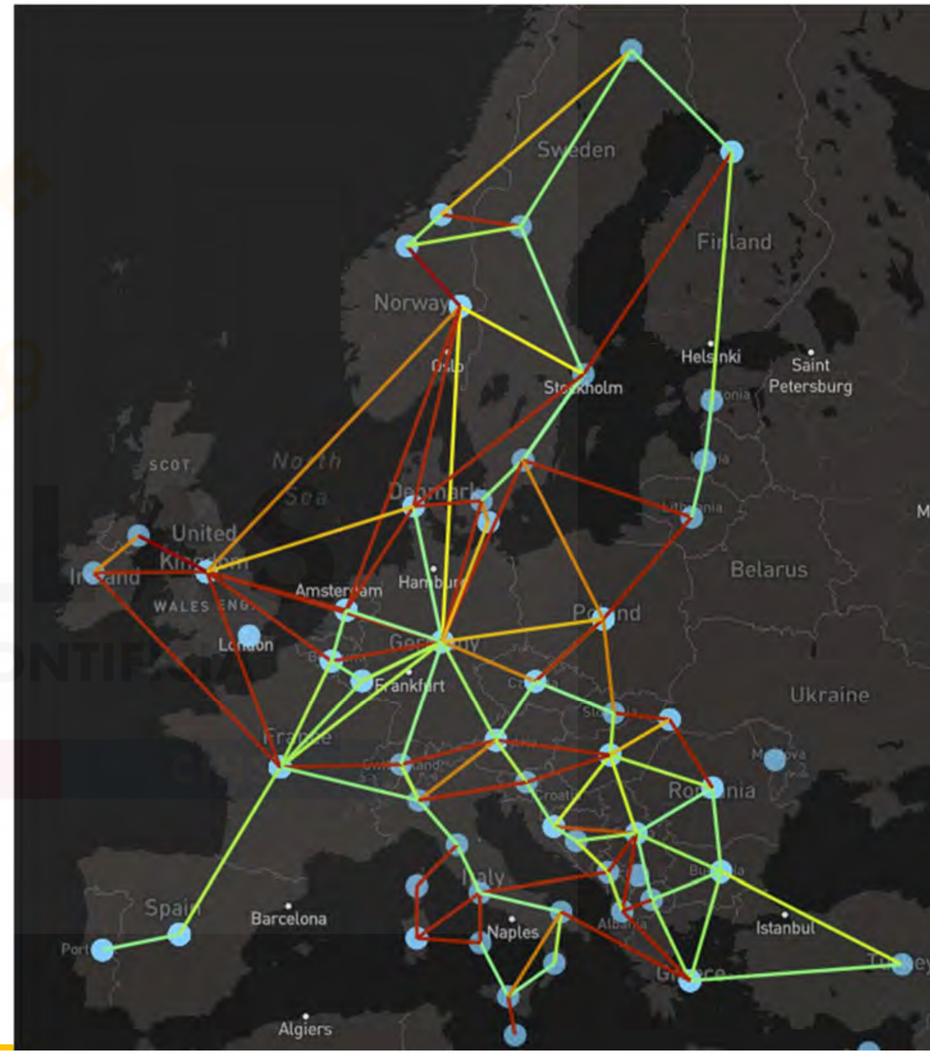


MAF (Mid Term Adequacy Forecast) 2030

(https://www.entsoe.eu/outlooks/maf/Pages/default.aspx)

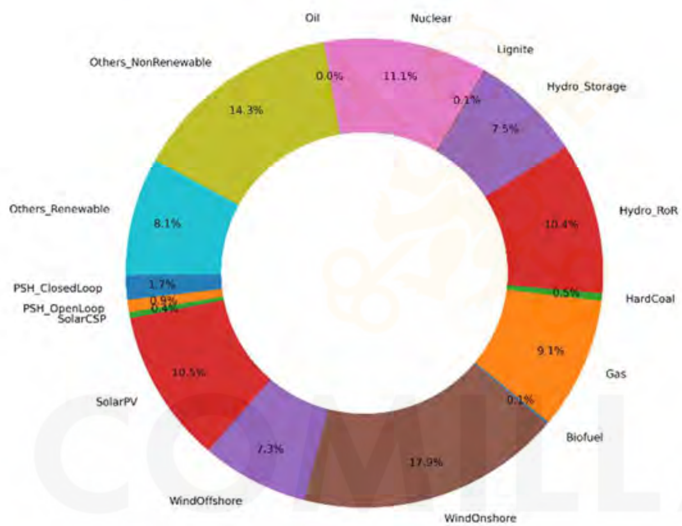
- How is the European system going to be in 2025 and 2030 from an adequacy point of view?

- Like Reliability Assessment and Performance Analysis done by NERC in the USA

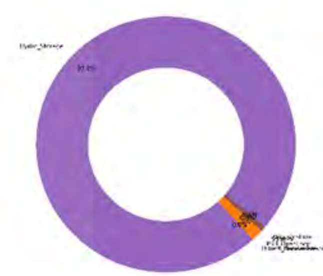


Energy generation mix

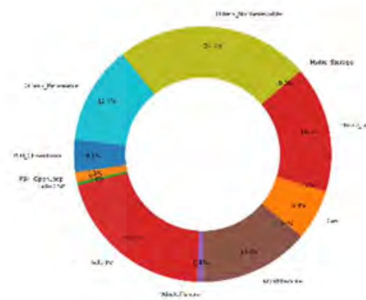
Europe



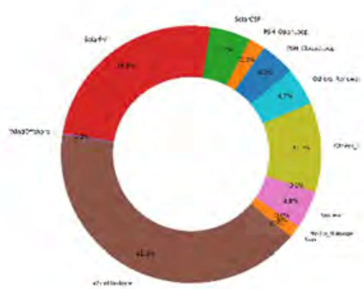
Norway



Italy



Spain

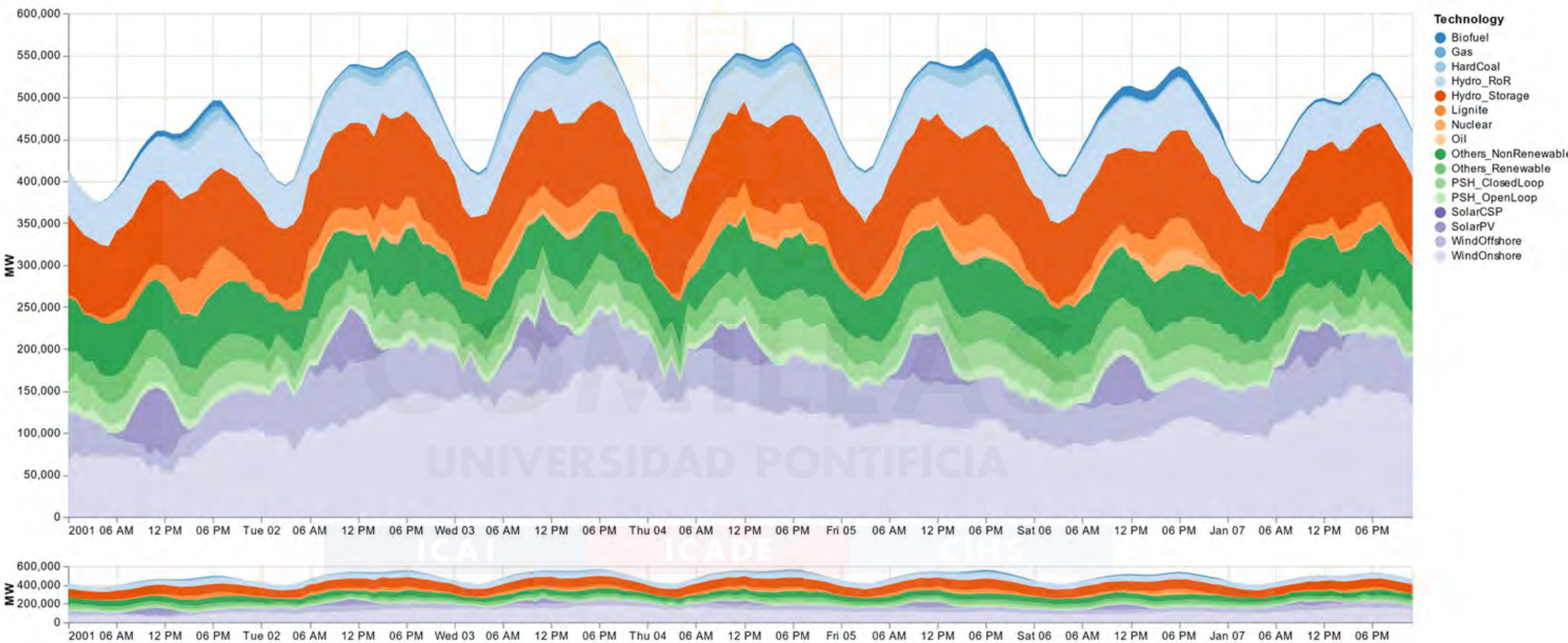


Germany

France

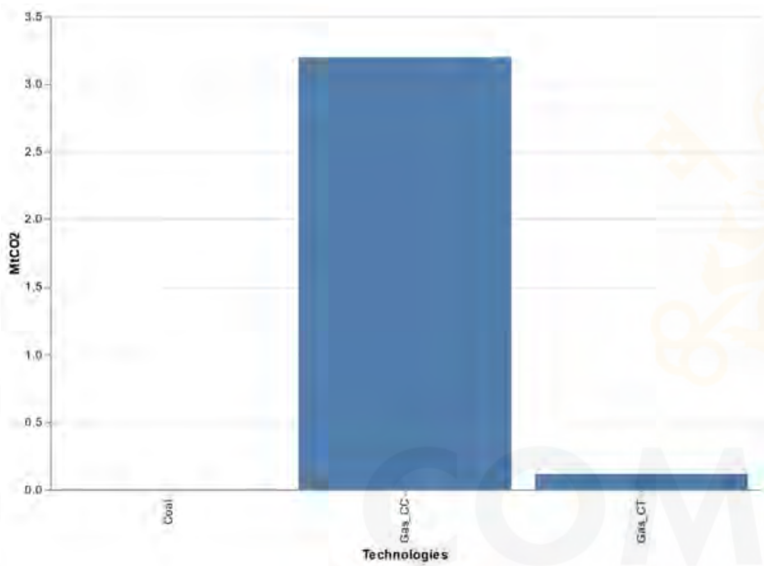
UK

Hourly Technology Output

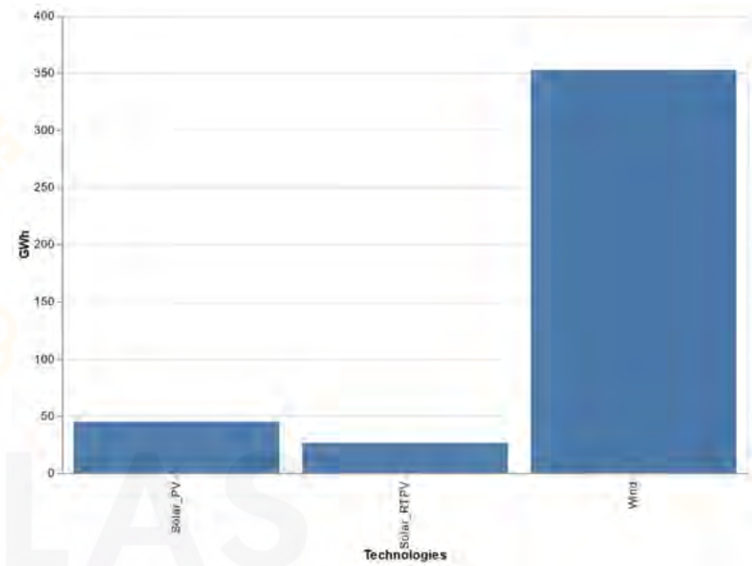


Other results

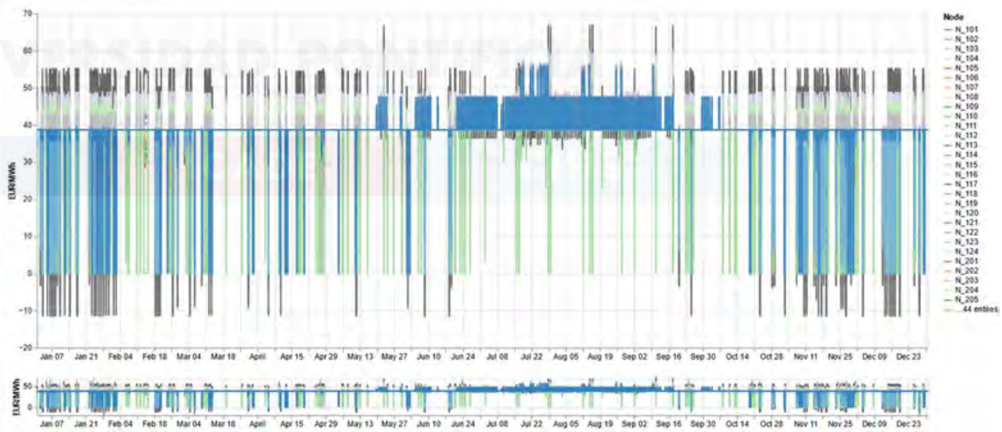
Emissions



Curtailment



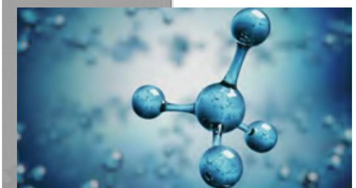
LSRMC



5

To Be Continued

Further developments



- Modeling
  - H2 modeling
  - Modeling hydro subsystems (cascaded reservoirs and volume magnitudes)
- Usage
  - Running the model in Jupyter Lab, as in Binder, not in your PC
  - APPSI (Auto-Persistent Pyomo Solver Interfaces)
    - Data management and parallel running of Monte Carlo scenarios
  - Pre-defined running modes:
    - Transmission network: single node, DC or AC load flow
    - Power generation: no expansion, w/wo unit commitment, operating reserves or CO2 emissions.

Thank you for your attention

DOI: https://doi.org/10.24433/CO.8709849.v1

https://opentepes.readthedocs.io/en/latest/index.html

A. Ramos, E. Alvarez, S. Lumbreras "*OpenTEPES: Open-source Transmission and Generation Expansion Planning*" SoftwareX (submitted)

GitHub - IIT-EnergySystemModels/openTEPES: Open Generation, Storage, and Transmission Operation and Expansion Planning Model with RES and ESS (openTEPES)

Andres.Ramos@comillas.edu