openTEPES

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

Andrés Ramos
Andres.Ramos@comillas.edu
https://pascua.iit.comillas.edu/aramos/Ramos_CV.htm

1

Introduction

open TEPES

openTEPES

version 4.16.0

Navigation

Introduction
Electric System Input Data
Hydropower System Input Data
Hydrogen System Input Data
Heat System Input Data
Output Results
Mathematical Formulation
Research projects
Publications
Download & Installation
Contact Us

Quick search

Go

COMILLAS UNIVERSIDAD PONTIFICIA

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

"Simplicity and Transparency in Energy Systems Planning"

Read the Docs

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

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

The **openTEPES** model presents a decision support system for defining the integrated generation, storage, and transmission expansion plan (GEP+SEP+TEP) of a **large-scale electric system** at a tactical level (i.e., time horizons of 10-20 years), defined as a set of **generation, storage, and (electricity, hydrogen, and heat) networks dynamic investment decisions for multiple future years.**

It is integrated into the open energy system modelling platform, helping model Europe's energy system.

It has been used by the **Ministry for the Ecological Transition and the Demographic Challenge (MITECO)** to analyze the electricity sector in the latest Spanish National Energy and Climate Plan (NECP) 2023-2030 in June 2023.

Reference: A. Ramos, E. Quispe, S. Lumbreras "OpenTEPES: Open-source Transmission and Generation Expansion Planning" SoftwareX 18: June 2022 10.1016/j.softx.2022.101070

downloads 100k

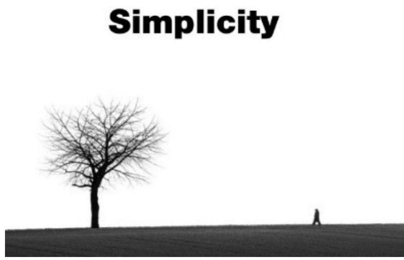
Index

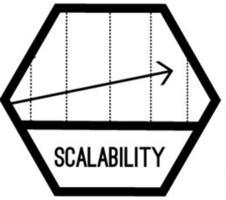
A. Ramos, E. Quispe, S. Lumbreras "OpenTEPES: Open-source Transmission and Generation Expansion Planning" SoftwareX 18: June 2022 10.1016/j.softx.2022.101070

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

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

Main Development Goals

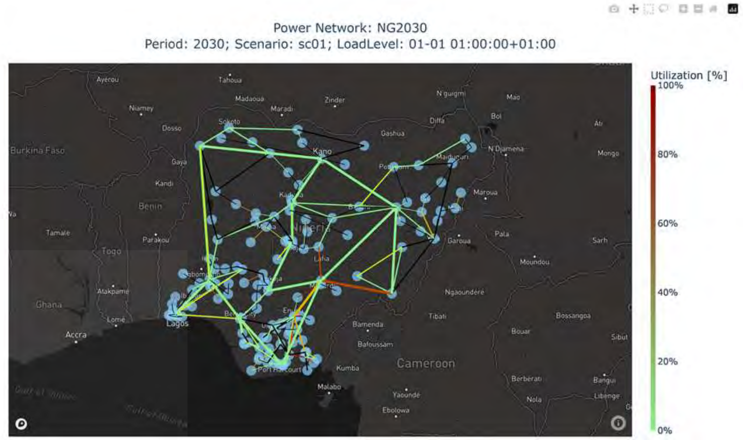




- Simplicity and transparency
- Code written to be read by humans
- Scalability: from small- to large-scale cases
- Strong orientation to computational efficiency:
  - In generating the optimization problem
    - Use of libraries (Pandas) for input data and data manipulation
  - Careful implementation for reducing solution time
    - Numerical stability. Scaling variables and constraints around 1
    - Tight and compact formulation of some constraints
- Developed in Python/Pyomo
- Input data and output results in text format (csv)

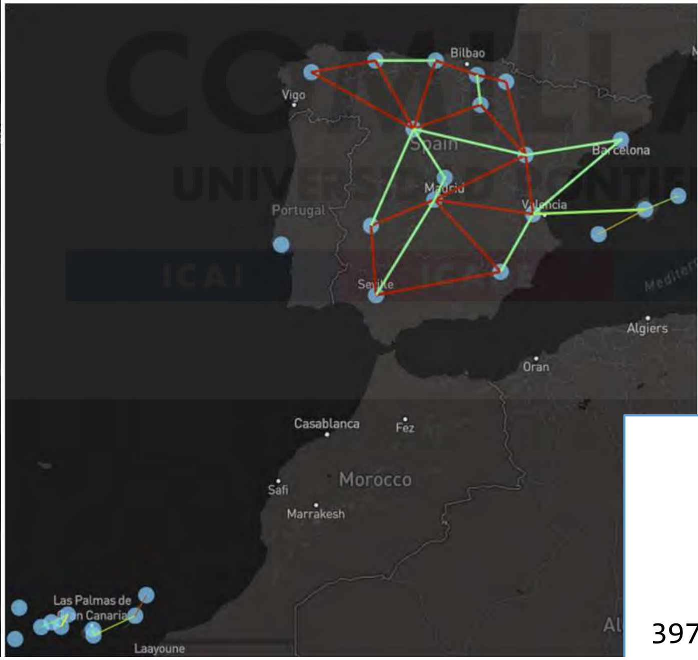
Some case studies

Nigeria NG2030



Europe TF2030

Spain ES2030



Case Spain SEP2030
2999548 rows, 3513436 columns, 11508142 nonzeros
Case Mainland Spain ES2030
5162243 rows, 6832942 columns, 21554828 nonzeros
Case Europe TF2030
39700167 rows, 34702184 columns and 123300396 nonzeros

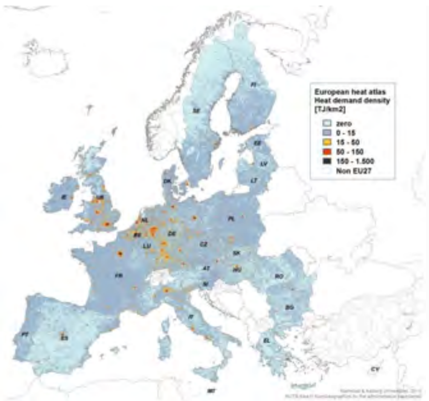
2

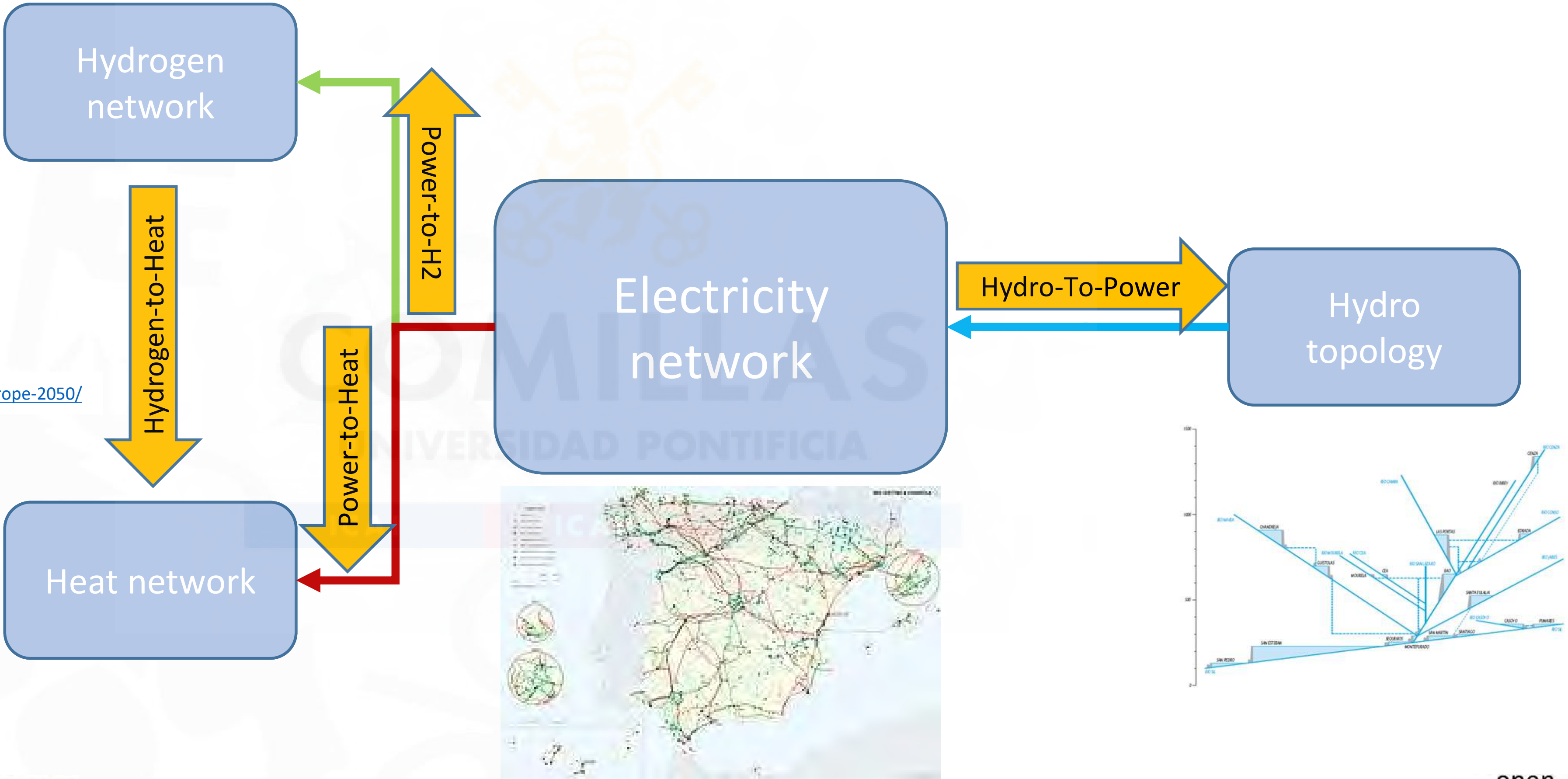
Modeling

Electricity/hydrogen/heat/water networks
Multi-energy carriers. Sector coupling

https://ehb.eu/

https://www.energyplan.eu/heat-roadmap-europe-2050/





Modeling options

Generation investment
- Binary generation investment decisions
- Binary generation retirement decisions
- Binary reservoir expansion decisions

Network investment
- Binary electric network expansion decisions
- Binary hydrogen network expansion decisions
- Binary heat network expansion decisions

Generation operation
- Binary generation operation decisions
- Up/down ramp constraints
- Up/down time constraints

Electric network operation
- Single node
- Binary transmission switching decisions
- Network losses

Modeling overview

Source: EPRI

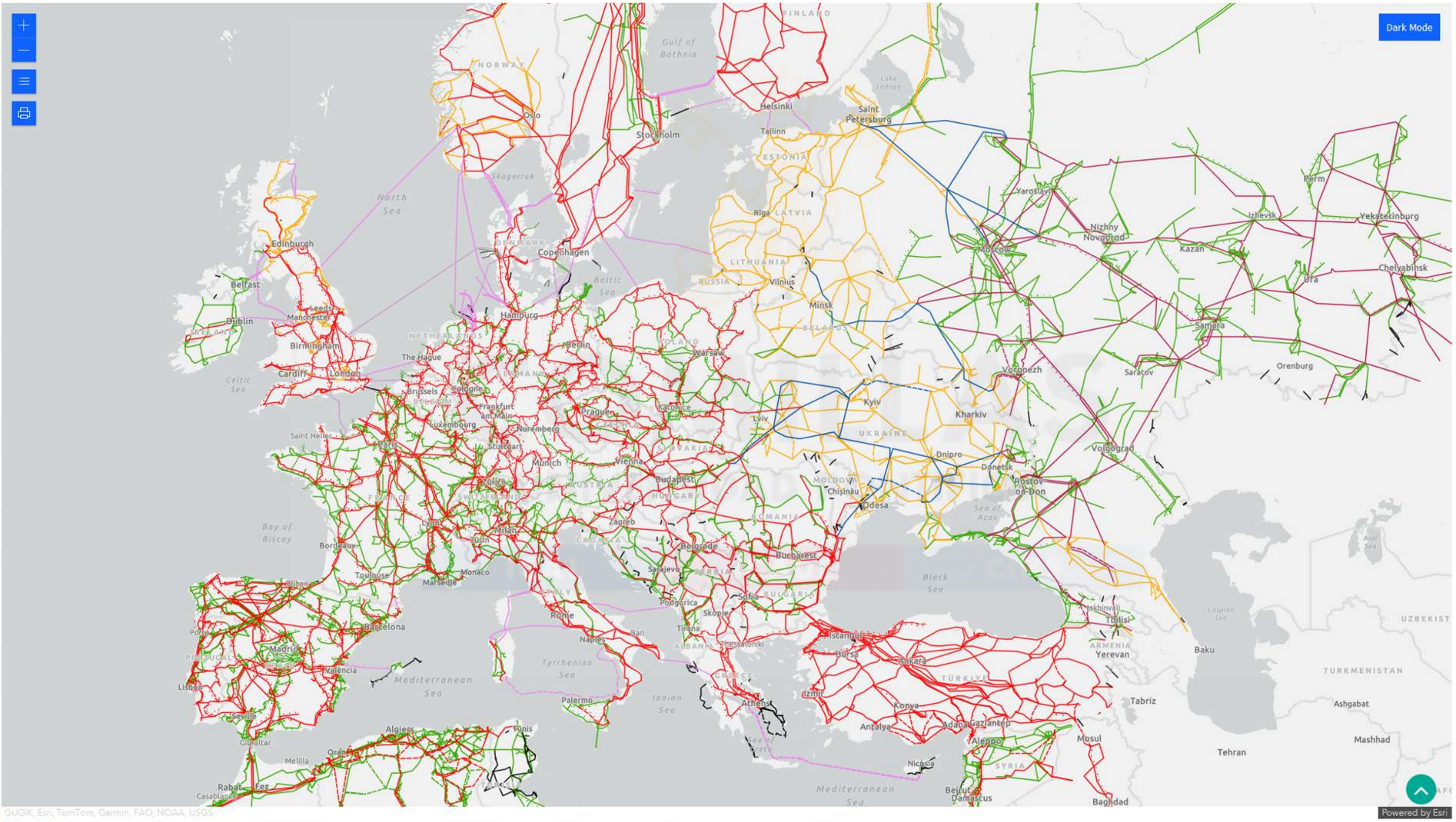
- Built according to a bottom-up paradig
- Find the optimal generation, storage, and transmission resource planning (IRP, GEP+SEP+TEP).
- Provides an optimal investment plan while considering system operation to minimize the total cost
- Time domain
  - Multiyear (dynamic, perfect foresight) with 8736 hours/year or representative stages
  - Flexible duration of the time step (e.g., bi-hour, 3-hour, 4-hour time step)
- It uses mixed-integer linear programming (runs on GUROBI, GLPK, or CBC) to solve the problem.

GUROBI OPTIMIZATION

COMILLAS UNIVERSIDAD PONTIFICIA ICAI ICADE CIHS

open TEPES

Geographical representation



Node

Electrical node

Zone

NUTS2, NUTS3

Area

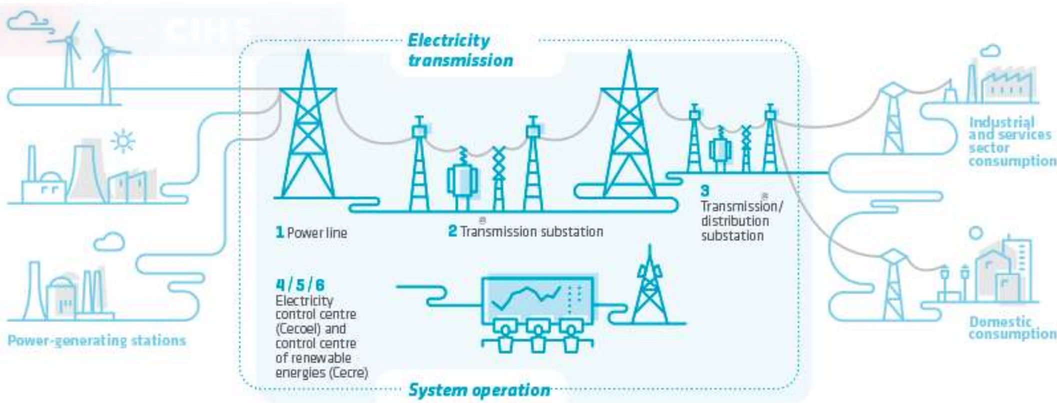
Country

Region

CSW, CSE, CCS

Main modeling features (i)

- DC power flow (DCPF) with/without ohmic losses
- Network-constrained unit commitment (NCUC)
- Operation scheduling of medium- and short-term storage (i.e., pumped-hydro storage, batteries).



Main modeling features (ii)

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

Main modeling features (iii)

- Minimum adequacy reserve margin [p.u.]

- Minimum synchronous must-run power (inertia) [s]

- Maximum system carbon emissions [tCO2]

- Minimum system RES energy (Renewable Portfolio Standard RPS) [GWh]

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

- Determines the investment/retirement plans of new assets for supplying the forecasted demand at minimum total cost.
- User pre-defined candidate generators, ESS, and transmission lines.
  - Candidate lines can be HVDC or HVAC circuits.

Dealing with uncertainty

- Several stochastic parameters that can influence the optimal expansion decisions are considered.
- The operation scenarios are associated with:
  - Natural hydro inflows
  - Renewable energy sources
  - Electricity demand



Demand and operating reserves

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

S. Huclin et al. "*Exploring the roles of storage technologies in the Spanish electric system with high share of renewable energy*" Energy Reports 8:4041-4057, November 2022. 10.1016/j.egyr.2022.03.032

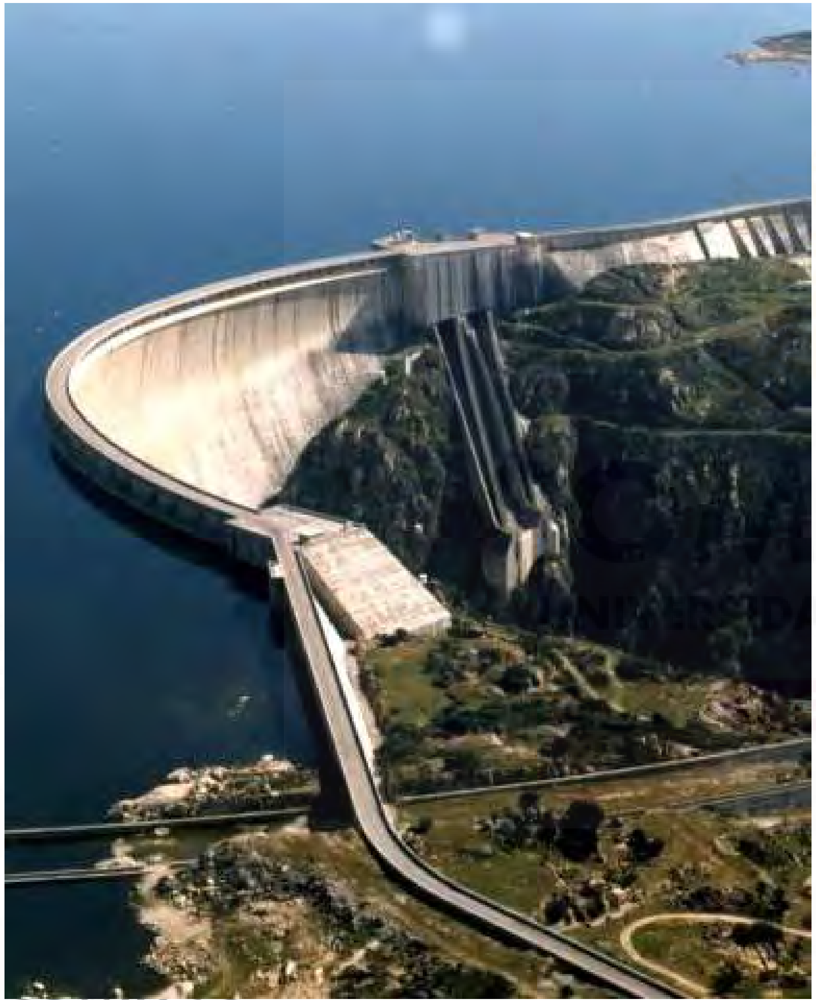
Thermal subsystem

- Minimum output and 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 down for the second block of a thermal unit [MW/h]
- Minimum up and down time of a thermal unit [h]
- Min/max unit energy generation for a time scope (weekly, monthly, yearly)
- No load, variable, operating reserve, and startup costs.

Variable renewable energy (VRE)

- Solar PV, on- and off-shore wind, biomass, cogeneration, run-of-the-river hydro, biogas
- Minimum and maximum hourly variable generation

Hydro and storage subsystems



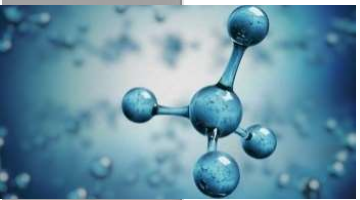
- Hydro, open- and closed-loop pumped-hydro storage (PHS), PHS treated individually, and system battery storage
- EV (dumb charging, smart charging, and V2G)
- ESS energy inventory [GWh] [hm^3]
- Energy outflows to represent H2 production or km for EV
- Total charge of an ESS unit [GW]
- Minimum and maximum charge of an ESS [p.u.]
- Incompatibility between charge and discharge of an ESS [p.u.]
- Maximum ramp up and down [MW/h]
- Minimum and maximum hourly storage [GWh]

Hydro cascade basins

Tajo

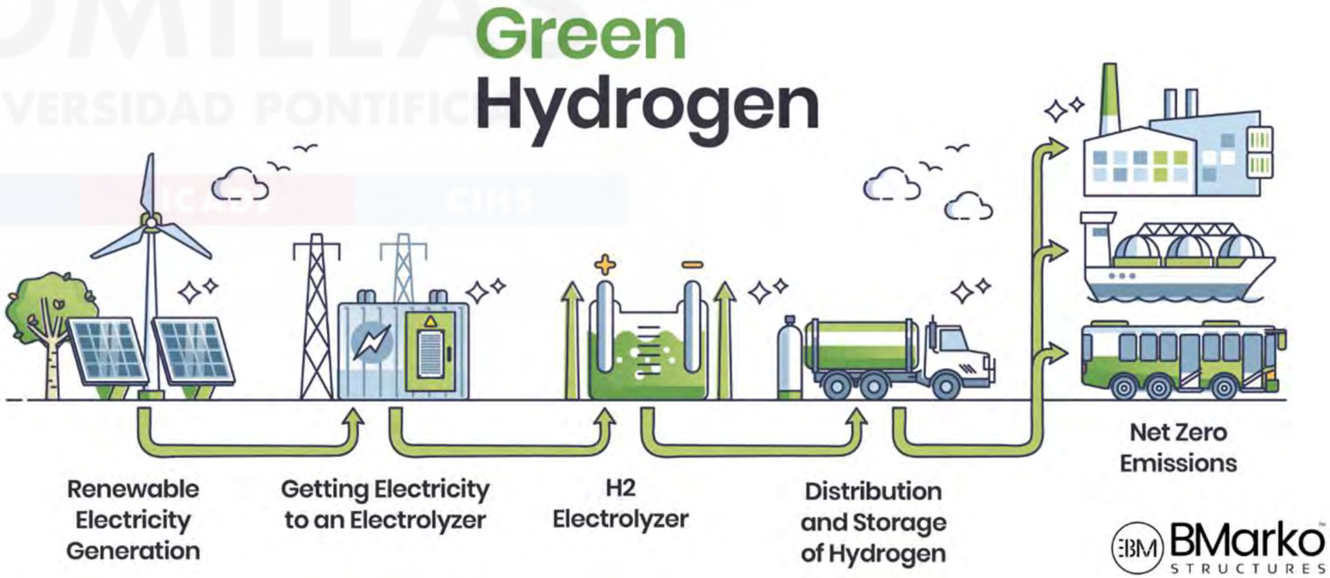
Source: Iberdrola

Hydrogen energy carrier

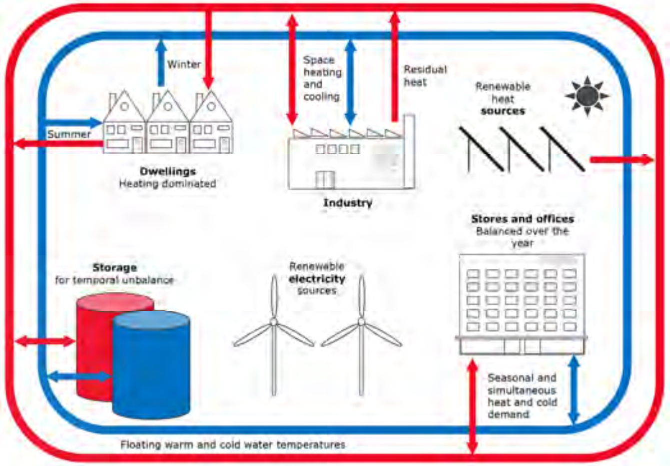


- Hydrogen demand
- Hydrogen network
- Electrolyzer (consumes electricity to produce hydrogen)

https://bmarkostructures.com/blog/what-are-hydrogen-electrolyzers/



Heat energy carrier



- Heat demand
- Heat network
- Heat pump, electrical heater (consumes electricity to produce heat)
- CHP. Cogeneration (produces electricity and heat simultaneously)
- Fuel heater, boiler (consumes fuel to produce heat)
  - Hydrogen heater can be used as a fuel (connecting both carriers)

Electric, hydro, hydrogen, and heat systems input data

https://opentepes.readthedocs.io/en/latest/InputData.html#hydro-system-input-data

Electric System Input Data

All the input files must be located in a folder with the name of the case study.

Acronyms

Acronym	Description
AC	Alternating Current
aFRR	Automatic Frequency Restoration Reserve
AWE	Alkaline Water Electrolyzer (consumes electricity to produce hydrogen)
BESS	Battery Energy Storage System
FHU	Fuel Heating Unit (Fuel to Heat: consumes any fuel other than hydrogen to produce heat)
CC	Capacity Credit
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power. Cogeneration (produces electricity and heat simultaneously)
DC	Direct Current
DCPF	DC Power Flow
DR	Demand Response
DSM	Demand-Side Management
DSR	Demand-Side Response
EHU	Electrical Heating Unit (Power to Heat: consumes electricity to produce heat)
EFOR	Equivalent Forced Outage Rate
ELZ	Electrolyzer (Power to Hydrogen: consumes electricity to produce hydrogen)
ENS	Energy Not Served
ENTSO-E	European Network of Transmission System Operators for Electricity
ESS	Energy Storage System
EV	Electric Vehicle
mFRR	Manual Frequency Restoration Reserve
H2	Hydrogen
HHU	Hydrogen Heating unit (Hydrogen to Heat: consumes hydrogen to produce heat)
HNS	Hydrogen Not Served
HP	Heat Pump (power to heat: consumes electricity to produce heat)
HTNS	Heat Not Served
NTC	Net Transfer Capacity
OCGT	Open Cycle Gas Turbine
PHS	Pumped-Hydro Storage
PNS	Power Not Served
PV	Photovoltaics
RES	Renewable Energy Source
TTC	Total Transfer Capacity
VOLL	Value of Lost Load

Output results

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

open TEPES

openTEPES

version 4.16.0

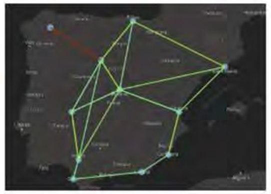
Navigation

Quick search

Go

Output Results

Some maps of the electricity transmission network and the energy share of different technologies is plotted.



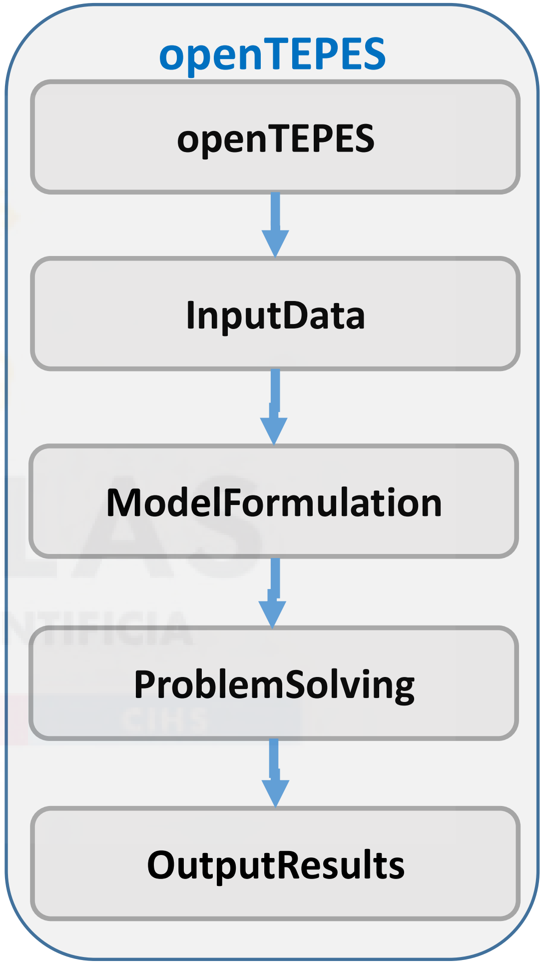
https://opentepes.readthedocs.io/en/latest/_images/oT_Plot_MapNetwork_ES2030.png

v: latest

Output results

- Investment: (generation, storage, hydro reservoirs, electric lines, hydrogen pipelines, and heat pipes) investment decisions
- Operation: unit commitment, startup, and shutdown of non-renewable units, unit output and aggregation by technologies (thermal, storage hydro, pumped-hydro storage, RES), RES curtailment, electric line, hydrogen pipeline, and heat pipe flows, line ohmic losses, node voltage angles, upward and downward operating reserves, ESS inventory levels, hydro reservoir volumes, power, hydrogen, and heat not served
- Emissions: CO2 emissions by unit
- Marginal: Locational Short-Run Marginal Costs (LSRMC), stored energy value, water volume value
- Economic: investment, operation, emission, and reliability costs and revenues from operation and operating reserves
- Flexibility: flexibility provided by demand, by the different generation and consumption technologies, and by power not served

openTEPES structure



3

Case Studies

Installation

Easy-way (Python Package)

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

https://docs.conda.io/projects/miniconda/en/latest/

2. Packages and Solver:
    1. Launch a new Anaconda command prompt
    2. Install openTEPES via pip by

```
pip install openTEPES
```

    3. Install the solver

Run in an Anaconda prompt

If installed with pip

(located in C:\ProgramData\miniconda3\Scripts)
(located in C:\ProgramData\anaconda3\Scripts)

```
openTEPES_main.exe
```

Select

- Directory
- Case
- Solver
- Results
- Log information

Installing Gurobi

- Install gurobi from an Anaconda prompt (run as Administrator or not)
  `conda install -c gurobi gurobi`
- Register for a free Gurobi account as an academic and log in
  https://portal.gurobi.com/iam/register/
- Request for a free academic license: Named-User Academic
  https://portal.gurobi.com/iam/licenses/request/?type=academic
- You will get something like this
  `grbgetkey ae36ac20-16e6-acd2-f242-4da6e765fa0a`
- Create a cmd prompt and go to the Python folder
  `C:\ProgramData\miniconda3` or `C:\ProgramData\anaconda3`
- Use `grbgetkey ae36ac20-16e6-acd2-f242-4da6e765fa0a`
- You will get a `gurobi.lic` text file with the license linked to your username and PC name
- Copy the license into the Python folder

C:\ProgramData\miniconda3
C:\ProgramData\anaconda3

Research projects

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

- Electricity Market Modelling, developed for **Repsol**. November 2023 - April 2024. L. Olmos, A. Ramos, S. Gómez Sánchez
- Day-ahead market price simulation tool (HESIME), developed for the **Ministry of Science and Innovation/State Research Agency** (10.13039/501100011033) under the program **Public-Private Partnerships** with **NextGenerationEU/PRTR** funds (CPP2022-009809). April 2023 - March 2026. L. Olmos, A. Ramos, S. Gómez Sánchez
- Open Modelling Toolbox for development of long-term pathways for the energy system in Africa (OpenMod4Africa), developed for the **European Union**. July 2023 - June 2026. L. Olmos, S. Lumbreras, A. Ramos, M.A.E. Elabbas
- Highly-efficient and flexible integration of biomass and renewable hydrogen for low-cost combined heat and power generation to the energy system (Bio-FlexGen), developed for the **European Union**. September 2021 - August 2024. J.P. Chaves, A. Ramos, J.F. Gutierrez
- Analysis of the role of pumped-hydro storage power plants in the Spanish NECP 2030, developed for **Iberdrola**. July 2023 - October 2023. A. Ramos, P. Linares, J.P. Chaves, M. Rivier, T. Gómez
- Support in the preparation of the application to the call on innovative energy storage systems, developed for **Glide Energy**. June 2023 - October 2023. L. Rouco, A. Ramos, F.M. Echavarren, R. Cossent
- Analysis of the technical and economic benefits of solar thermal generation in the Spanish peninsular system, developed for **ProTermosolar**. March 2023. A. Ramos, L. Sigrist
- Hydro generation advanced systems: modeling, control, and optimized integration to the system (AVANHID), developed for the **Ministry of Science and Innovation/State Research Agency** (10.13039/501100011033) under the program **Public-Private Partnerships** with **NextGenerationEU/PRTR** funds (CPP2021-009114). December 2022 - November 2025. A. Ramos, J.M. Latorre, P. Dueñas, L. Rouco, L. Sigrist, I. Egido, J.D. Gómez Pérez, F. Labora
- Local markets for energy communities: designing efficient markets and assessing the integration from the electricity system perspective (OptiREC), developed for the **Ministry of Science and Innovation/State Research Agency** (10.13039/501100011033) under the program **Strategic projects oriented to the ecological transition and digital transition** with **NextGenerationEU/PRTR** funds (TED2021-131365B-C43). December 2022 - November 2024. A. Ramos, J.P. Chaves, J.M. Latorre, J. García, M. Troncia, S.A. Mansouri, O.M. Valarezo, M. Mohammed
- Delivering the next generation of open Integrated Assessment MOdels for Net-zero, sustainable Development (DIAMOND), developed for the **European Union**. October 2022 - August 2025. S. Lumbreras, L. Olmos, A. Ramos
- Application of the ENTSO-e cost-benefit analysis method to Aguayo II pumped-hydro storage, developed for **Repsol**. June 2022. A. Ramos, L. Olmos, L. Sigrist
- Application of the ENTSO-e cost-benefit analysis method to Los Guájares pumped-hydro storage, developed for **VM Energía**. May 2022 - June 2022. A. Ramos, L. Olmos, L. Sigrist
- Impact of the electric vehicle in the electricity markets in 2030, developed for **Repsol**. November 2021 - February 2022. A. Ramos, P. Frías, J.P. Chaves, P. Linares, J.J. Valentín
- European Climate and Energy Modelling Forum (ECEMF), developed for the **European Union**. May 2021 - December 2024. S. Lumbreras, A. Ramos, L. Olmos, C. Mateo, D. Santos Oliveira
- 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 - June 2022. A. Ramos, P. Linares, J.P. Chaves, J. García, S. Wogrin, J.J. Valentín
- 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. M. Rivier, T. Gómez, A. Sánchez, F. Martín, A. Ramos, J.P. Chaves, S. Gómez Sánchez, L. Herding, T. Freire
- Improving energy system modelling tools and capacity, developed for the **European Commission**. October 2020 - June 2022. S. Lumbreras, A. Ramos, P. Linares, D. Santos, M. Pérez-Bravo, A.F. Rodríguez Matas, J.C. Romero
- 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. T. Gómez, M. Rivier, J.P. Chaves, A. Ramos, P. Linares, F. Martín, L. Herding
- Open ENergy TRansition ANalyses for a low-carbon Economy (openENTRANCE), developed for the **European Union**. May 2019 - June 2023. L. Olmos, S. Lumbreras, A. Ramos, E. Alvarez
- Analysis of the expansion and operation of the Spanish electricity system for a 2030-2050 time horizon, developed for **Iberdrola**. January 2019 - December 2021. M. Rivier, T. Gómez, A. Sánchez, F. Martín, T. Freire, J.P. Chaves, T. Gerres, S. Huclin, A. Ramos

Studies conducted. Energy transition analysis (i)

- Linkage with energy system models (integrated assessment models) to refine the representation of the power sector (e.g., focused on the transmission network)
  - Analyze the 2030-2050 energy transition at the European scale and specifically the impact of the transmission lines in the long-term generation investment decisions

- National Energy and Climate Plan (NECP) 2030 for Spain
  - Exhaustive analysis of the 2030 scenarios of the Spanish electric system
  - Prospective analysis of the 2050 Spanish electric system

Studies conducted. Storage analysis (ii)

- Cost-benefit analysis (CBA) of candidate pumped-hydro storage units
  - Economic impact of new pumped-hydro storage units in the electric system
- Future ESS role (batteries vs. pumped-hydro storage vs. CSP)
  - Analysis of the competition between batteries (2 to 4 h storage), pumped-hydro storage units (8 to 60 h storage), and solar thermal (6 to 9 h storage)
- Penetration of EV and type of charge
  - Impact of the EV in the system operation and the charge type (dumb, smart, V2G)
- Impact of local energy communities on transmission investments with detailed representation of storage hydro in Norway and Spain

D. Santos-Oliveira, J. Lecarpentier, S. Lumbreras, L. Olmos, A. Ramos, M. Chammas, Th. Brouhard *The impact of EV penetration on the European Power System: the Tradeoffs in Storage*. Social Science Research Network 2024 10.2139/ssrn.4700642

Studies conducted. Security of supply (iii)

- Technologies providing firmness and flexibility to the system
  - How much is each technology contributing to the security of supply (electric load-carrying capability) at critical hours?

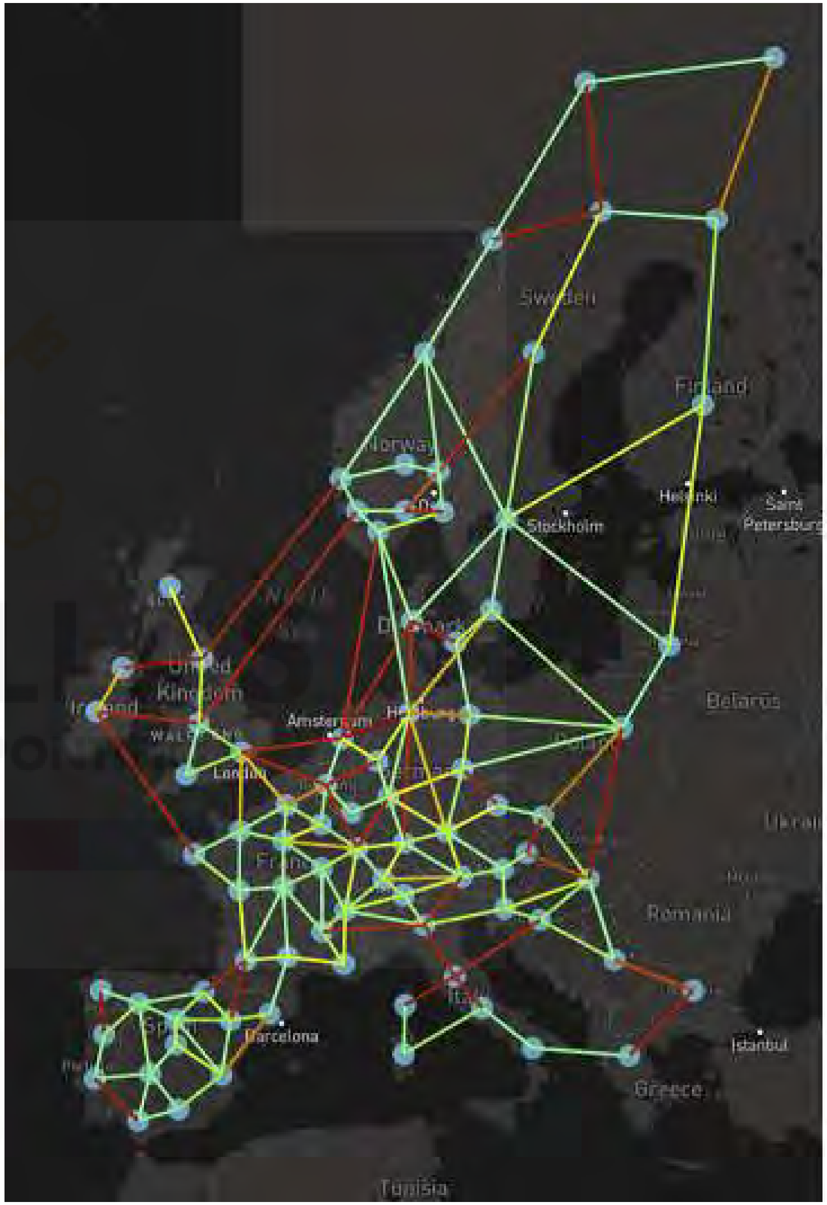
openENTRANCE - Impact of LECs on the power system functioning

- Open ENergy TRansition ANalyses for a low-carbon Economy (openENTRANCE), developed for the European Union. May 2019 - June 2023. L. Olmos, S. Lumbreras, A. Ramos, E. Alvarez
  - It aims to develop, use, and disseminate an open, transparent, and integrated modeling platform for assessing European low-carbon transition pathways.

Scope of the analysis

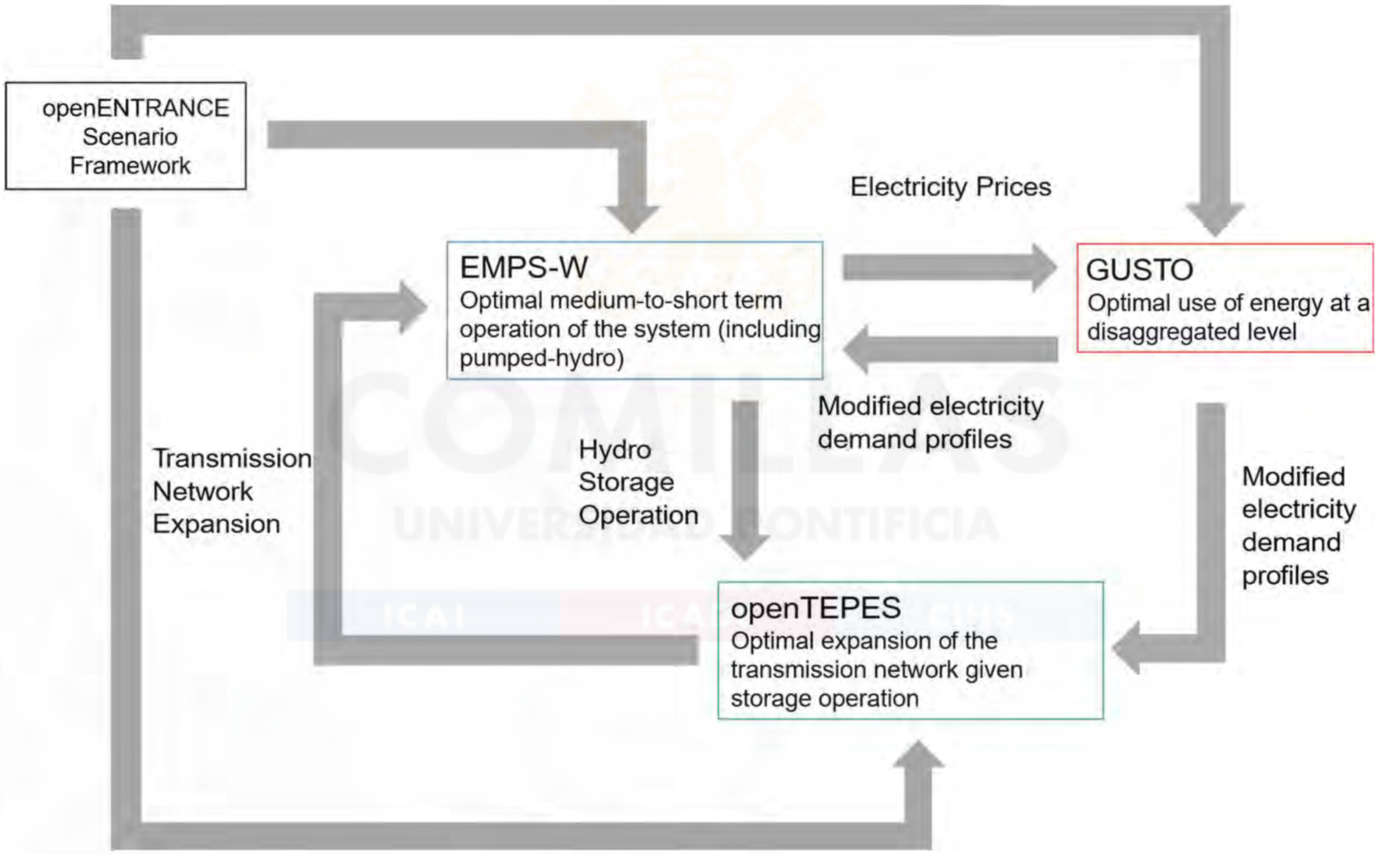
- Analysis of the impact on the system operation, the transmission network development, the level of use of the several flexibility sources, and wholesale electricity prices of local energy communities (LECs)
- Assessing to what extent the flexibility provided by LECs is a substitute for that to be provided by centralized storage (batteries, pumped hydro) and the grid
- The introduction of LECs is only considered within the Spanish and the Norwegian systems, which are represented with a higher level of detail (several areas per country and more detailed modeling of storage management)
- The rest of the European system is only represented at an aggregate level (single node per country and more simplified management of storage)
- Only the development of the transmission grid is affected by an increase in the penetration of LECs
- TechnoFriendly Scenario considered: high environmental awareness, bottom-up societal revolution, and top-down technology revolution
- Static planning: 1 year (2030 horizon) with hourly resolution

Europe TF2030



Workflow


Bi-directional soft-linking

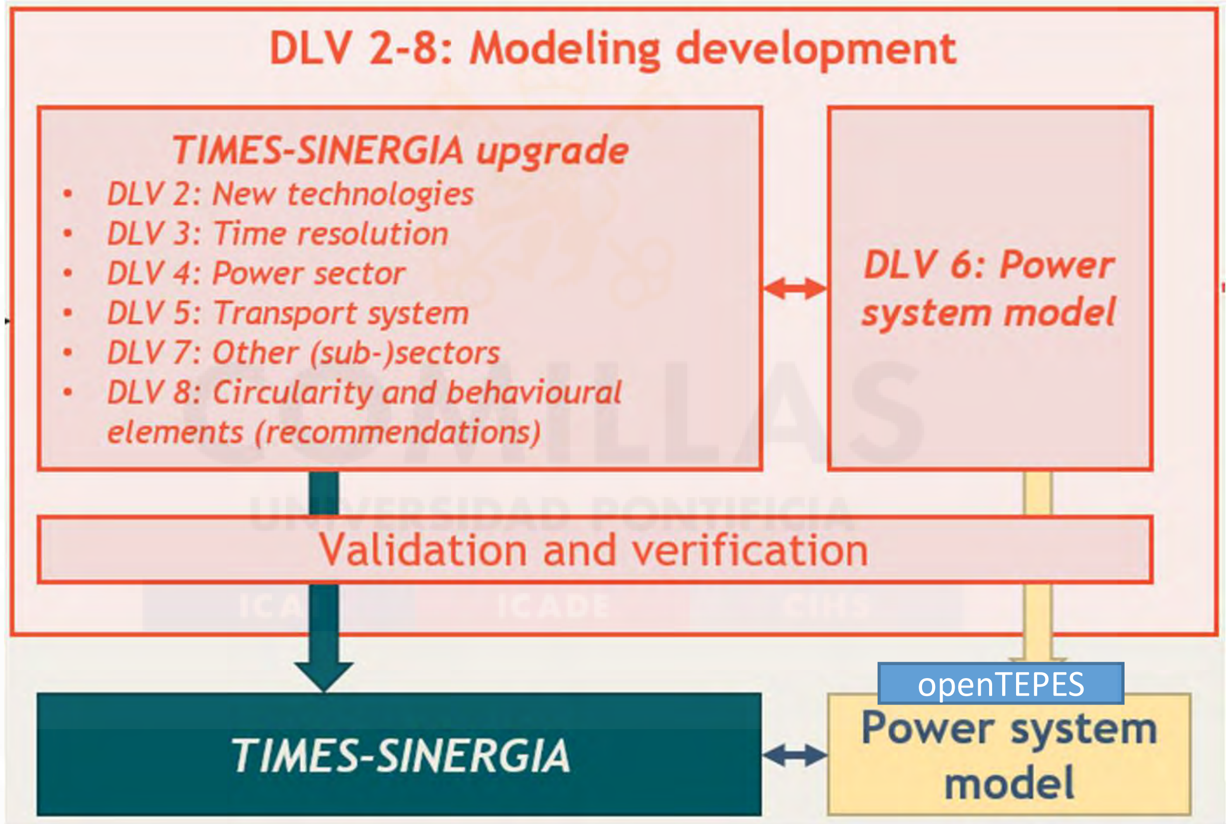

openENTRANCE Scenario Framework
Electricity Prices
EMPS-W
Optimal medium-to-short term operation of the system (including pumped-hydro)
GUSTO
Optimal use of energy at a disaggregated level
Modified electricity demand profiles
Transmission Network Expansion
Hydro Storage Operation
Modified electricity demand profiles
openTEPES
Optimal expansion of the transmission network given storage operation

Connection of an ESM with a power-sector model

- Improving energy system modelling tools and capacity, developed for the European Commission. October 2020 - June 2022. S. Lumbreras, A. Ramos, P. Linares, D. Santos, M. Pérez-Bravo, A.F. Rodríguez Matas, J.C. Romero
  - It aims to improve 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 including transmission constraints, with openTEPES.

Workflow


Unidirectional soft-linking


DLV 2-8: Modeling development
TIMES-SINERGIA upgrade
• DLV 2: New technologies
• DLV 3: Time resolution
• DLV 4: Power sector
• DLV 5: Transport system
• DLV 7: Other (sub-)sectors
• DLV 8: Circularity and behavioural elements (recommendations)
DLV 6: Power system model
Validation and verification
TIMES-SINERGIA
openTEPES
Power system model

Scope of the analysis

- Development of additional features of energy system model TIMES-SINERGIA to improve the Spanish energy system
- Top-down connection with power sector model openTEPES
- Both models are the core for the update of the Spain NECP

DIAMOND – Connection of an IAM model with a power sector model

- Delivering the next generation of open Integrated Assessment MOdels for Net-zero, sustainable Development (DIAMOND), developed for the European Union. October 2022 - August 2025. S. Lumbreras, L. Olmos, A. Ramos
  - It will update, upgrade, and fully open six IAMs that are emblematic in scientific and policy processes, improving their sectoral and technological detail, spatiotemporal resolution, and geographic granularity. It will further enhance modeling capacity to assess the feasibility and desirability of Paris-compliant mitigation pathways, their interplay with adaptation, circular economy, and other SDGs, their distributional and equity effects, and their resilience to extremes, as well as robust risk management and investment strategies.

Scope of the analysis

- Interoperable interface of the openTEPES model will be developed for GCAM-Europe, OMNIA, and OPEN-PROM, allowing assessment the network needs in IAM scenarios and identifying no-regret investments common among scenarios toward constituting the basic architecture of a European expansion plan

ECEMF - On the tradeoff between hydrogen and electricity for heat production

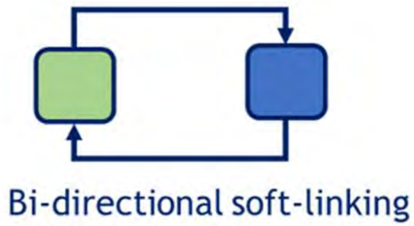
- European Climate and Energy Modelling Forum (ECEMF), developed for the European Union. May 2021 - December 2024. S. Lumbreras, A. Ramos, L. Olmos, C. Mateo, D. Santos Oliveira
  - It aims to provide the knowledge to inform the development of future energy and climate policies at national and European 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 program of events and novel IT-based communications channel will enable researchers to identify and co-develop the most pressing policy-relevant research questions with various stakeholders to meet ambitious European energy and climate policy goals, particularly the European Green Deal and the transformation to a climate-neutral society.

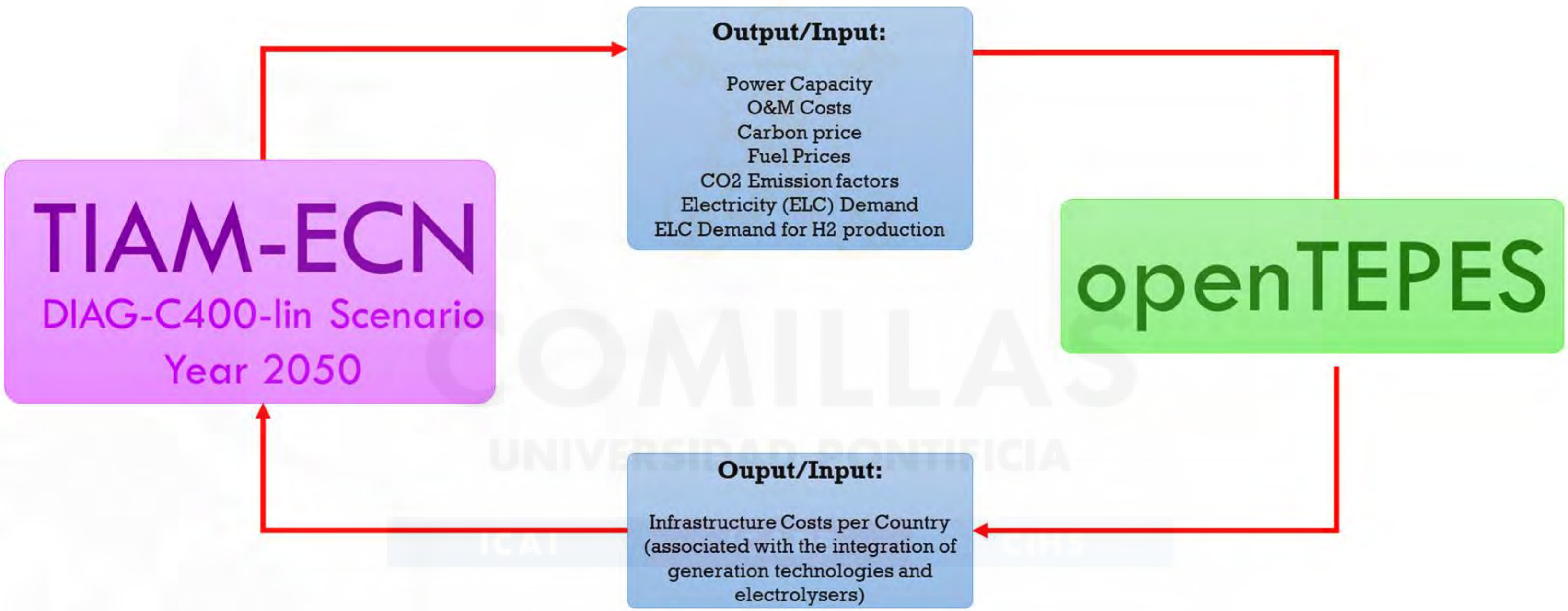
EUROPEAN CLIMATE + ENERGY MODELLING FORUM

Scope of the analysis

- Research question: What is the tradeoff between hydrogen and electricity for heat production?
- Scenario: DIAG-C400-lin, Target Year = 2050
- Target technologies (deployment and use to be optimized):
  - Hydrogen production (electrolyzers)
  - RES generation for heat
  - Transmission network
- Use of TYNDP 2022 Distributed Energy 2050 for data disaggregation

Workflow

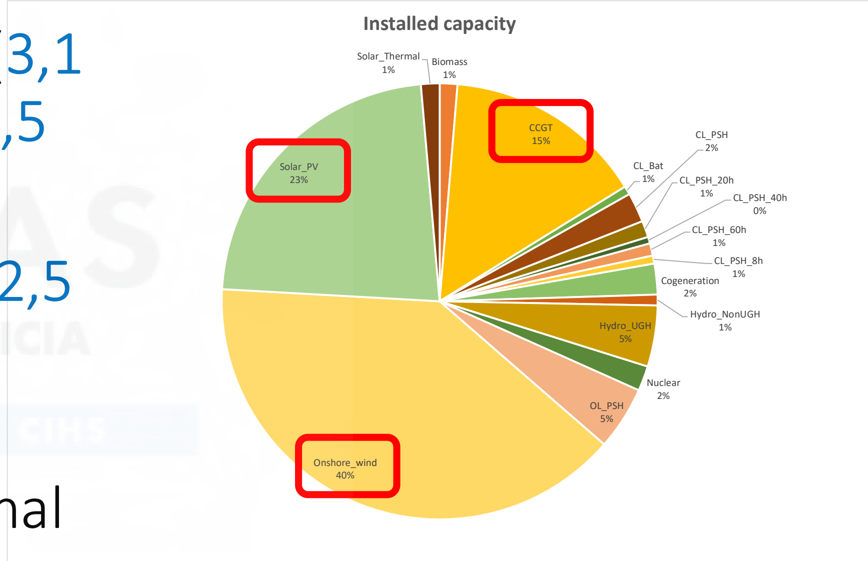




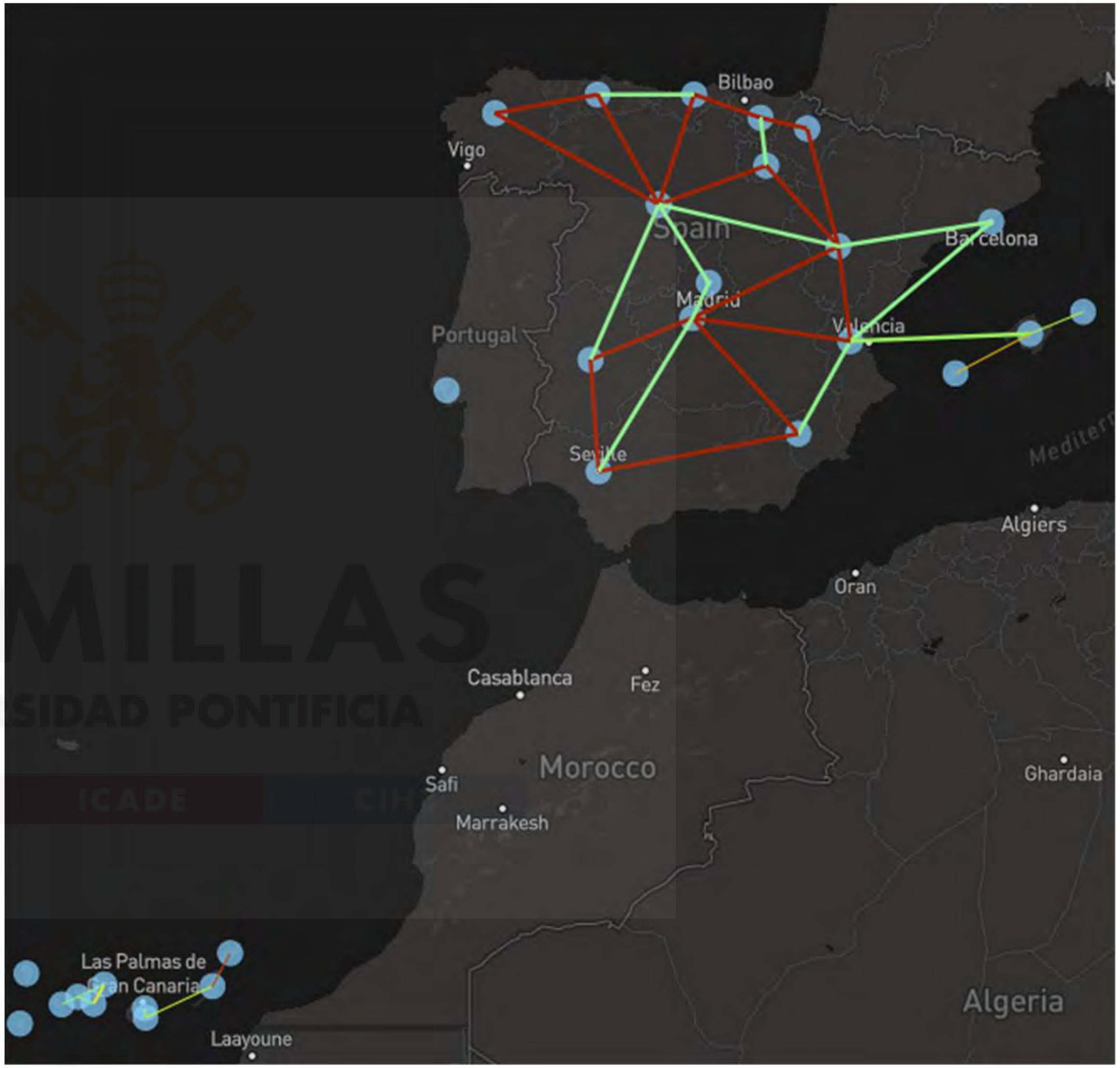
Convergence Criterion: Expansion results in two consecutive iterations

Mainland Spain SEP2030

- 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 in 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)

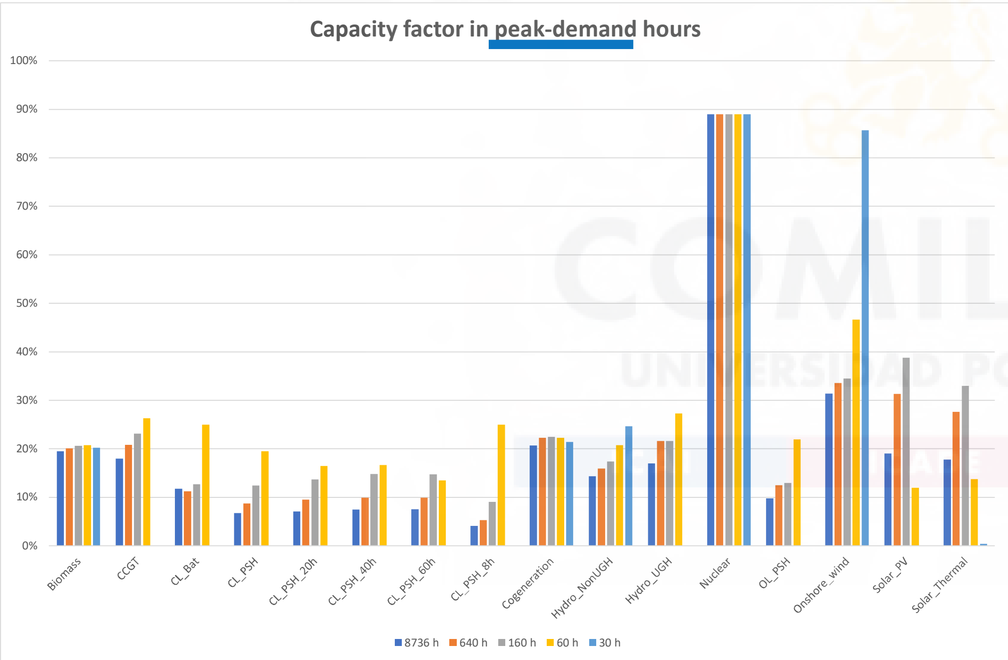


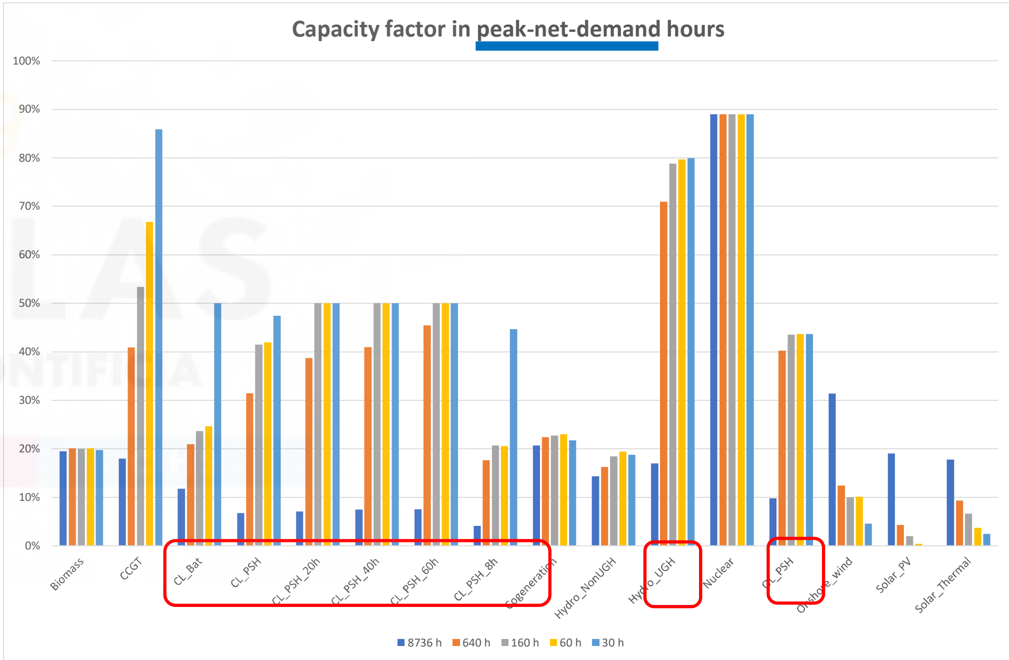
Spain ES2030



Firmness/Electric Load-Carrying Capability (ELCC) Equivalent Firm Capacity (EFC)

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



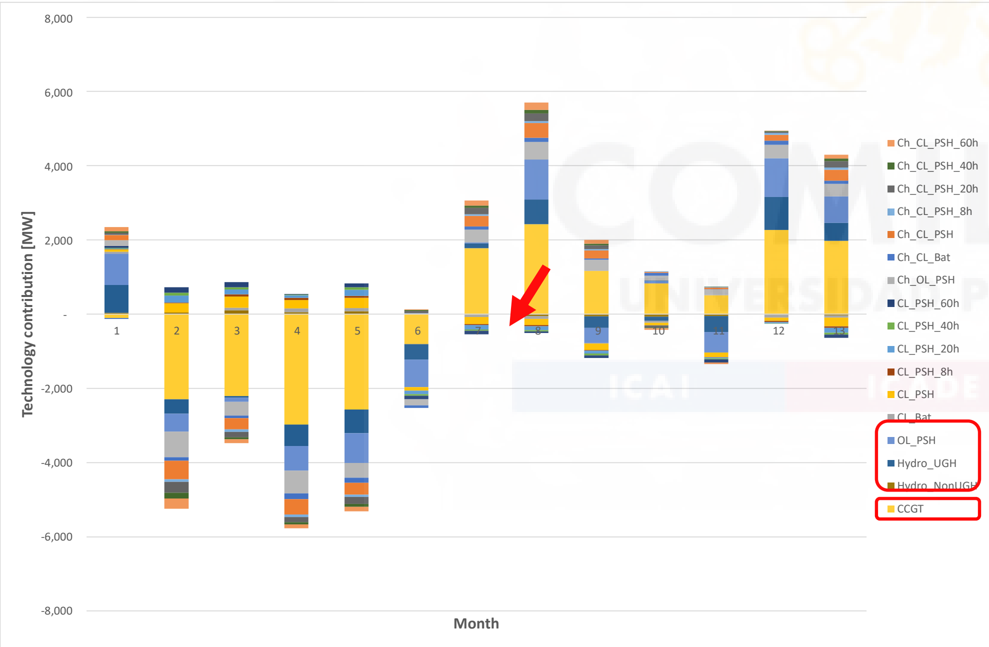


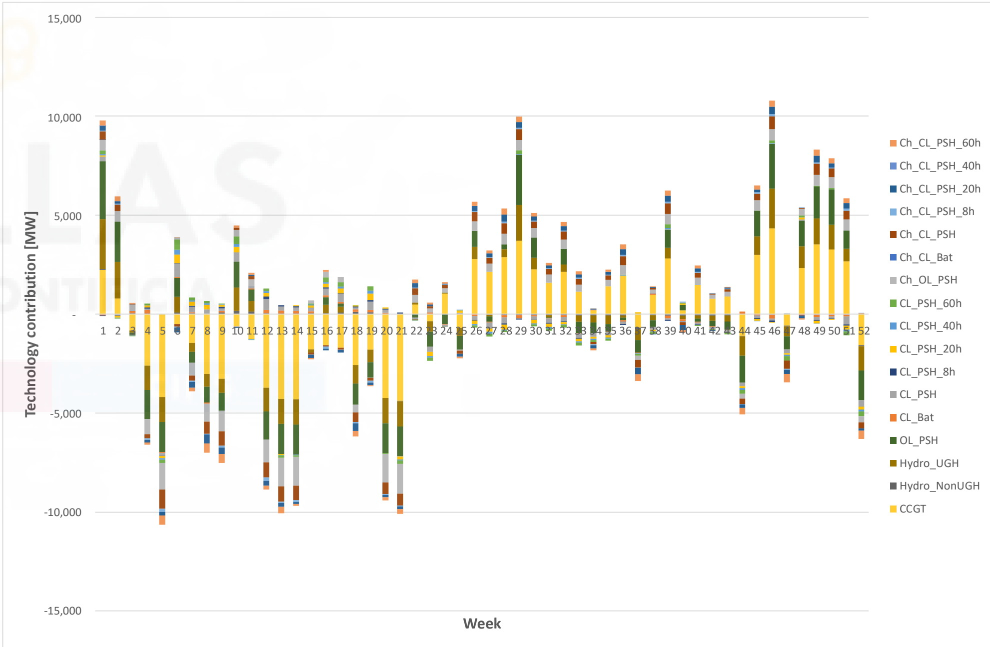
S. Huclin, J.P. Chaves, A. Ramos, M. Rivier, T. Freire-Barceló, F. Martín-Martínez, T. Gómez San Román, Á. Sánchez Miralles *Exploring the roles of storage technologies in the Spanish electric system with high share of renewable energy* Energy Reports 8:4041-4057, November 2022. 10.1016/j.egyr.2022.03.032

A. Ramos, S. Huclin, J.P. Chaves *Analysis of different flexible technologies in the Spain NECP for 2030*. Frontiers in Built Environment 9, October 2023 10.3389/fbuil.2023.1065998

Flexibility

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





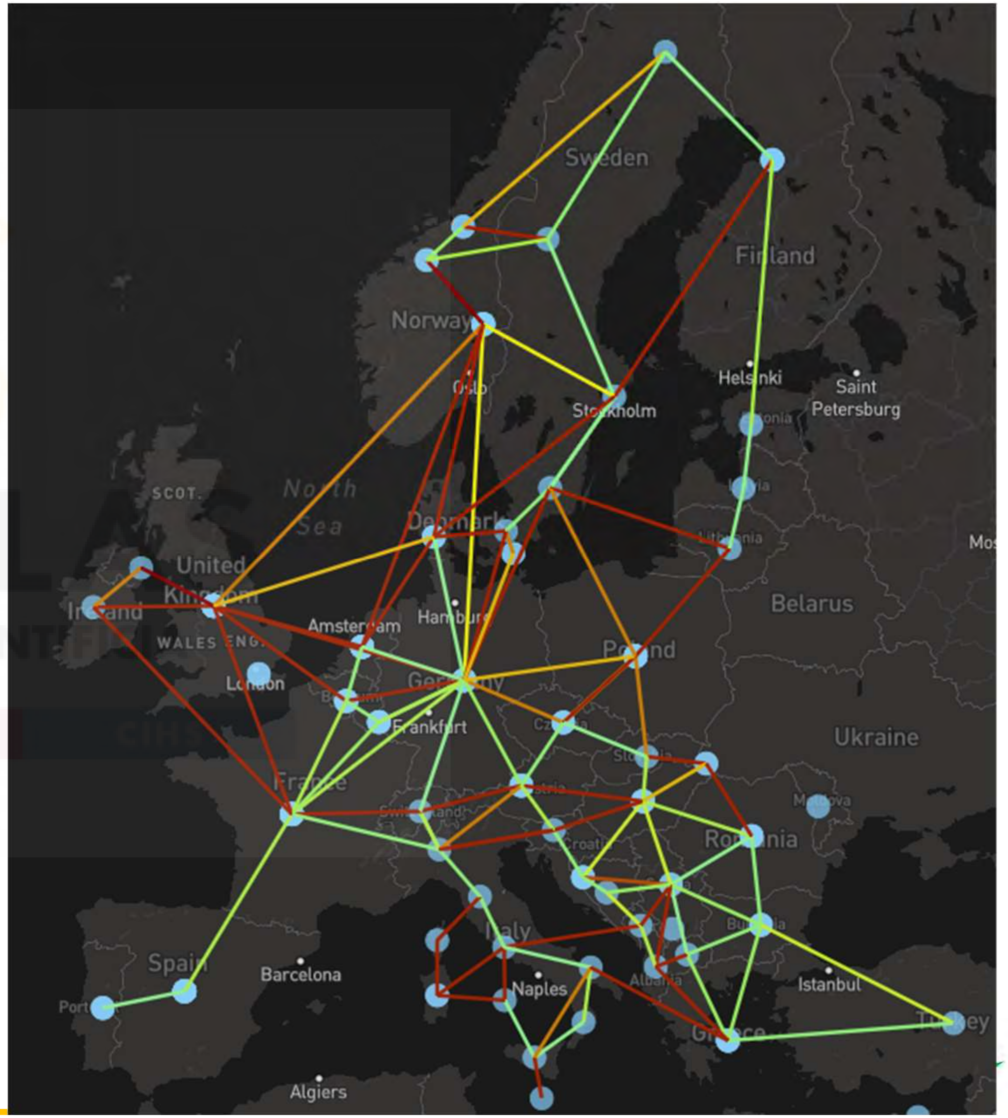
A. Ramos "*Assessing the operational flexibility provided by energy storage systems. The Spanish system in 2030*" IEA Wind Task 25 Spring 2021 meeting. April 2021

Mid-Term Adequacy Forecast MAF2030

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

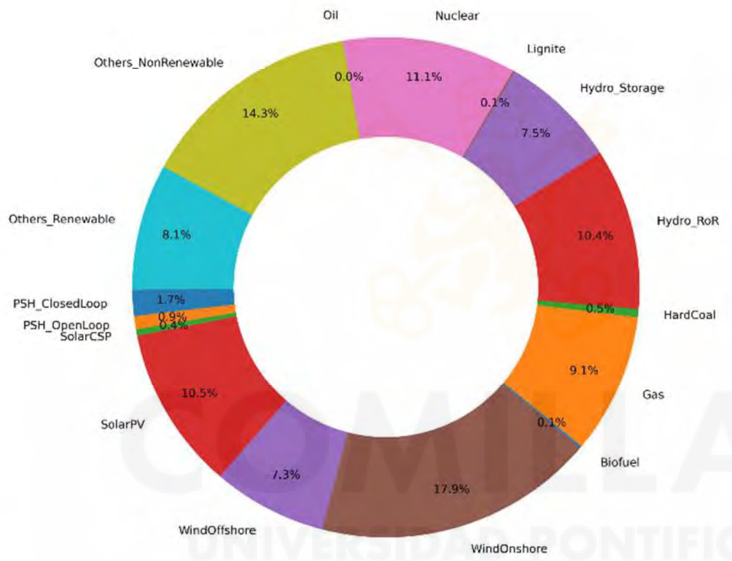
- How will the European system be in 2025 and 2030 from an adequacy point of view?

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

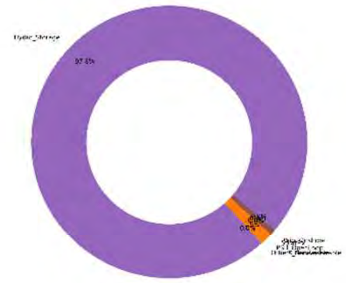


Energy generation mix

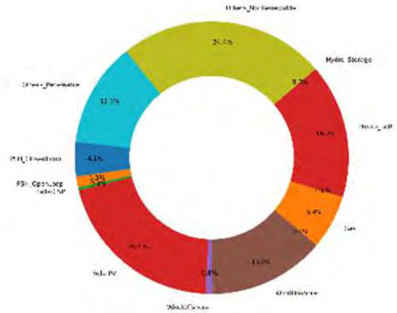
Europe



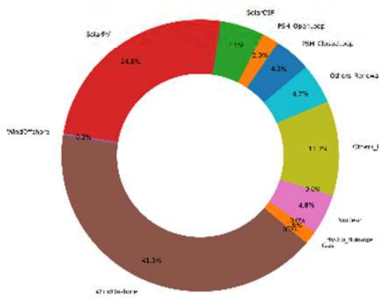
Norway



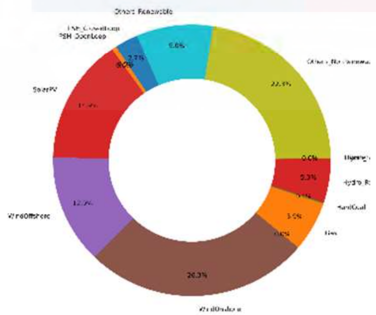
Italy



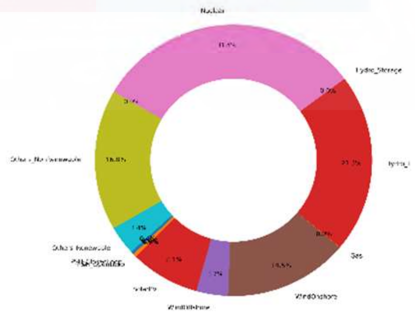
Spain



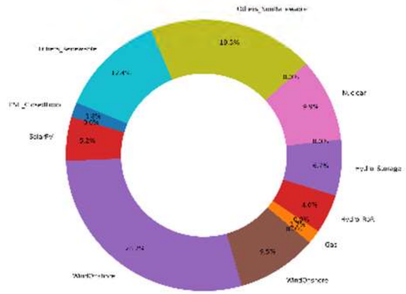
Germany



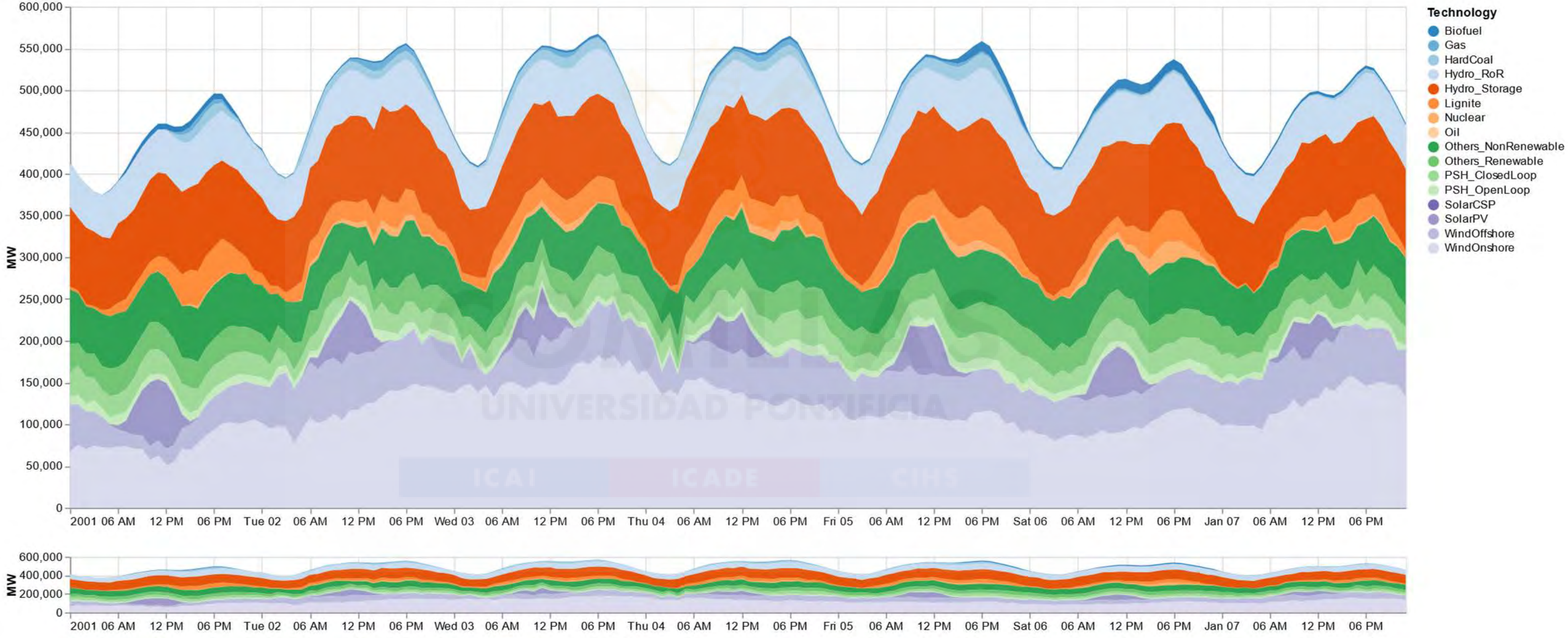
France



UK

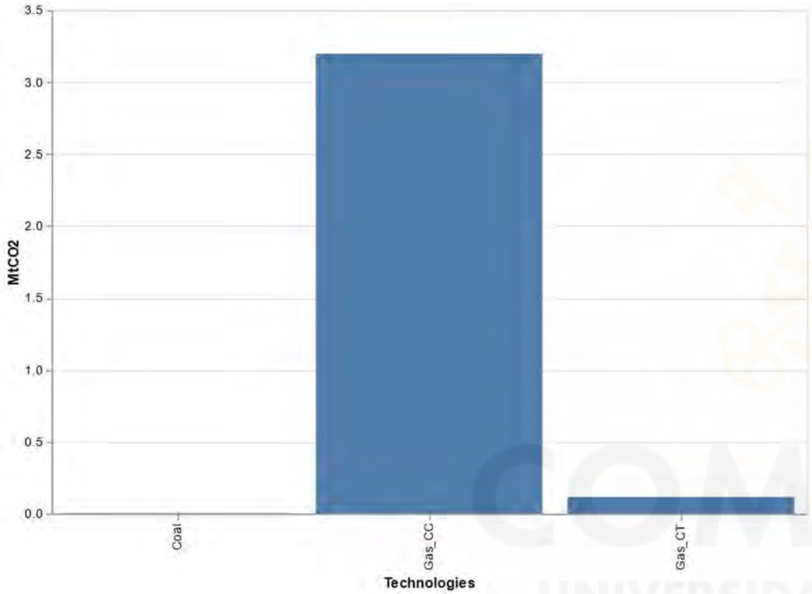


Hourly technology output

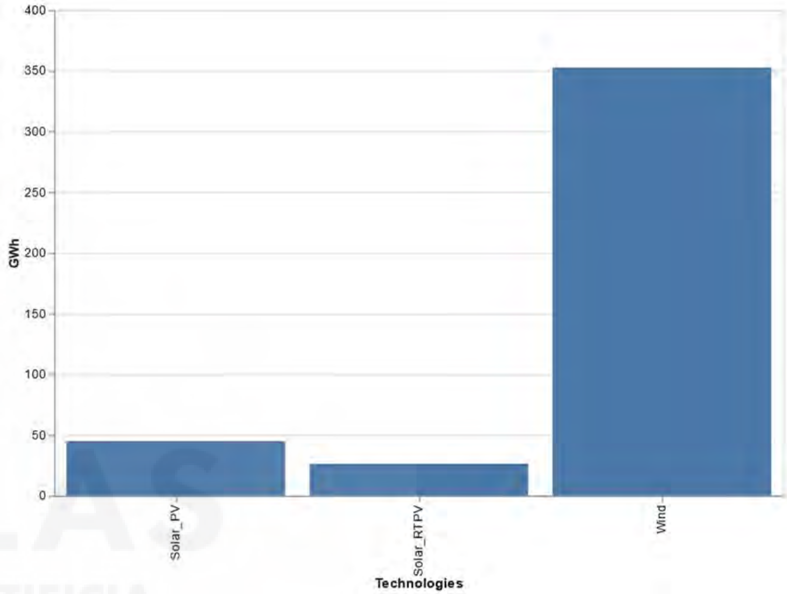


Other output results

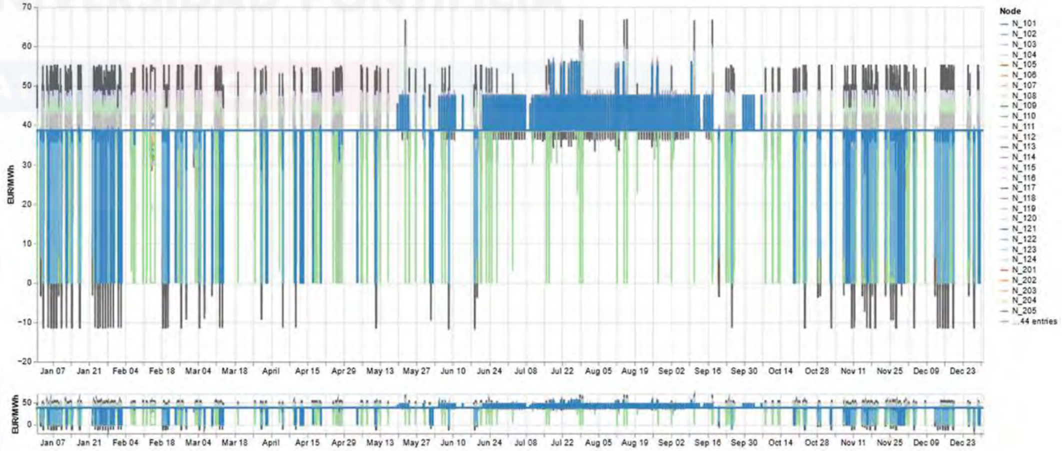
Emissions



Curtailment



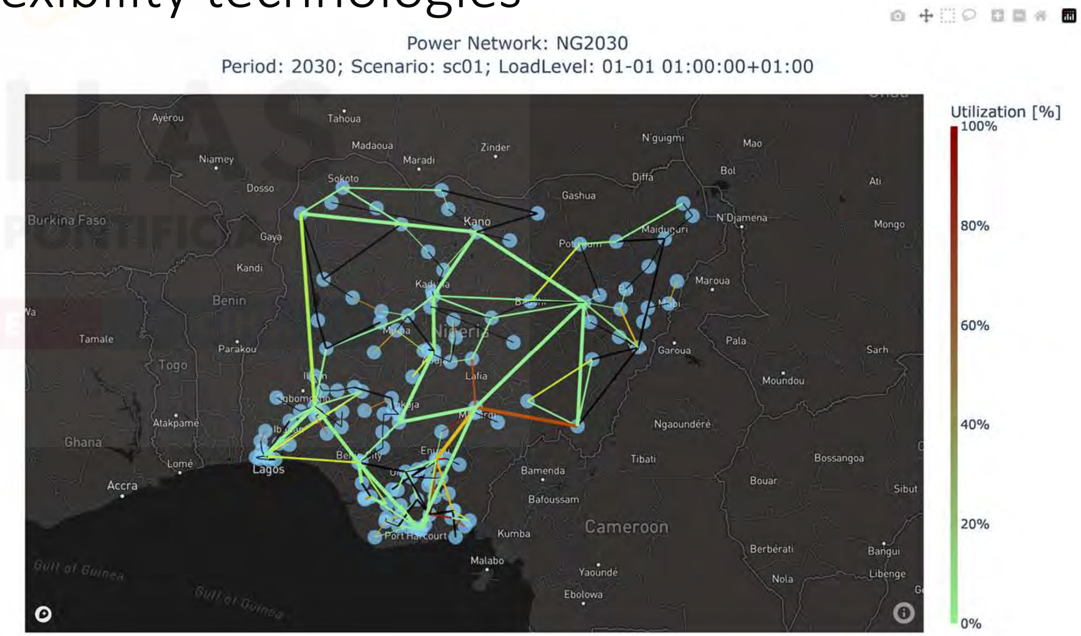
LSRMC



Possible studies in OpenMod4Africa

- Similar studies conducted previously applied to any of the regional power pools
  - Generation and/or transmission expansion
  - Operational analyses of flexibility technologies

Nigeria 2030



Thank you for your attention

Andres.Ramos@comillas.edu