openTEPES

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

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Introduction

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version 4.18.1

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Open Generation, Storage, and Transmission Operation 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 and in the list of energy models published under open source licenses.

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) Update 2023-2030 in September 2024.

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

openTEPES: summary presentation (English), présentation (French), and installation guide

downloads 136k

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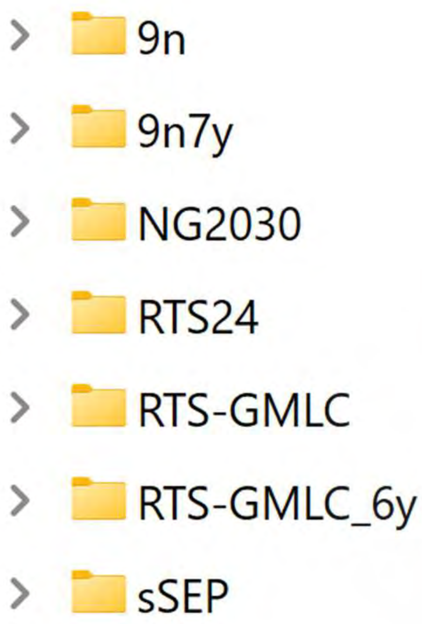
openTEPES-tutorial

https://github.com/IIT-EnergySystemModels/openTEPES-tutorial

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)

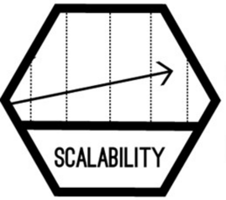
Case studies provided



- 9 nodes, single year
- 9 nodes, 7 years, 13 representative weeks
- Nigeria 2030
- Reliability Test System, 24 nodes
- Reliability Test System Grid Modernization Lab Consortium (GMLC), 73 nodes, single-year
- Reliability Test System Grid Modernization Lab Consortium (GMLC), 73 nodes, 6 years, 13 representative weeks
- Small Mainland Spanish System, with a hydro basin

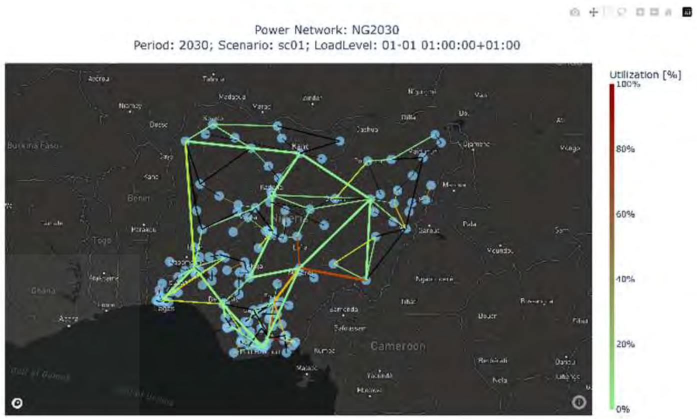
Robust and scalable optimization model

Simplicity



- Simplicity and transparency
- Code written to be read by humans (easy to understand)
- Scalability: from small- to large-scale cases
- Careful implementation and orientation to computational efficiency
  - Numerical stability. Scaling variables and constraints around 1
  - Tight and compact formulation of some constraints
- Highly detailed model documentation
- Developed in Python/Pyomo
- Installable as a Python library
- Input data and output results in text format (csv)

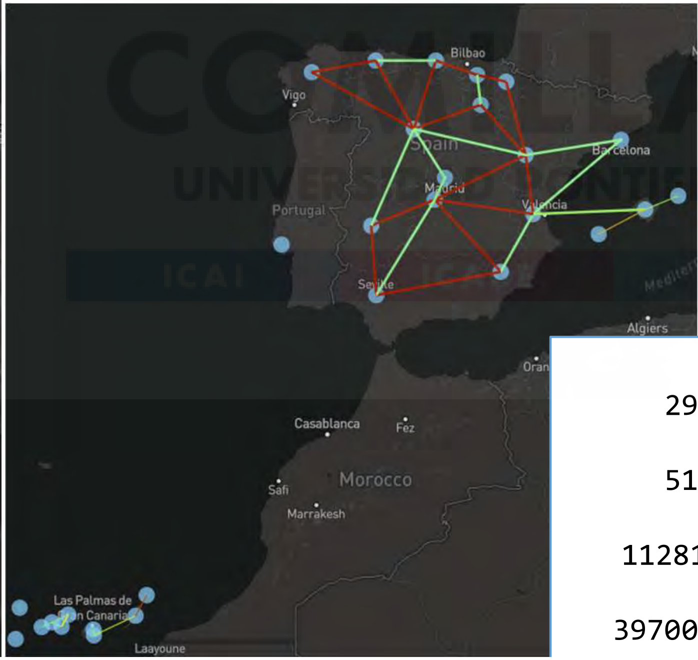
Variety of case studies
High temporal and spatial resolution



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 Mainland Spain 2023,2025,2030,2040,2050
11281454 rows, 11676523 columns and 39548590 nonzeros
Case Europe TF2030
39700167 rows, 34702184 columns and 123300396 nonzeros

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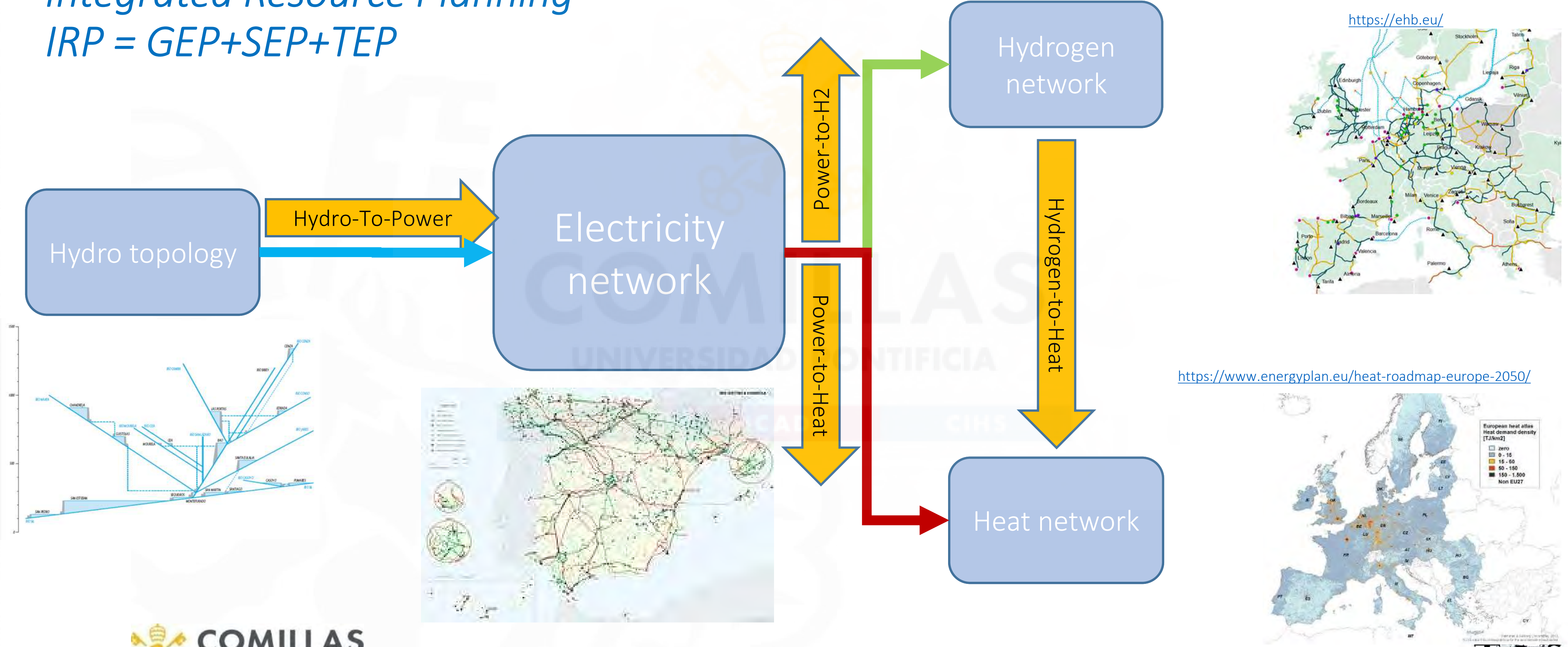
Modeling

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

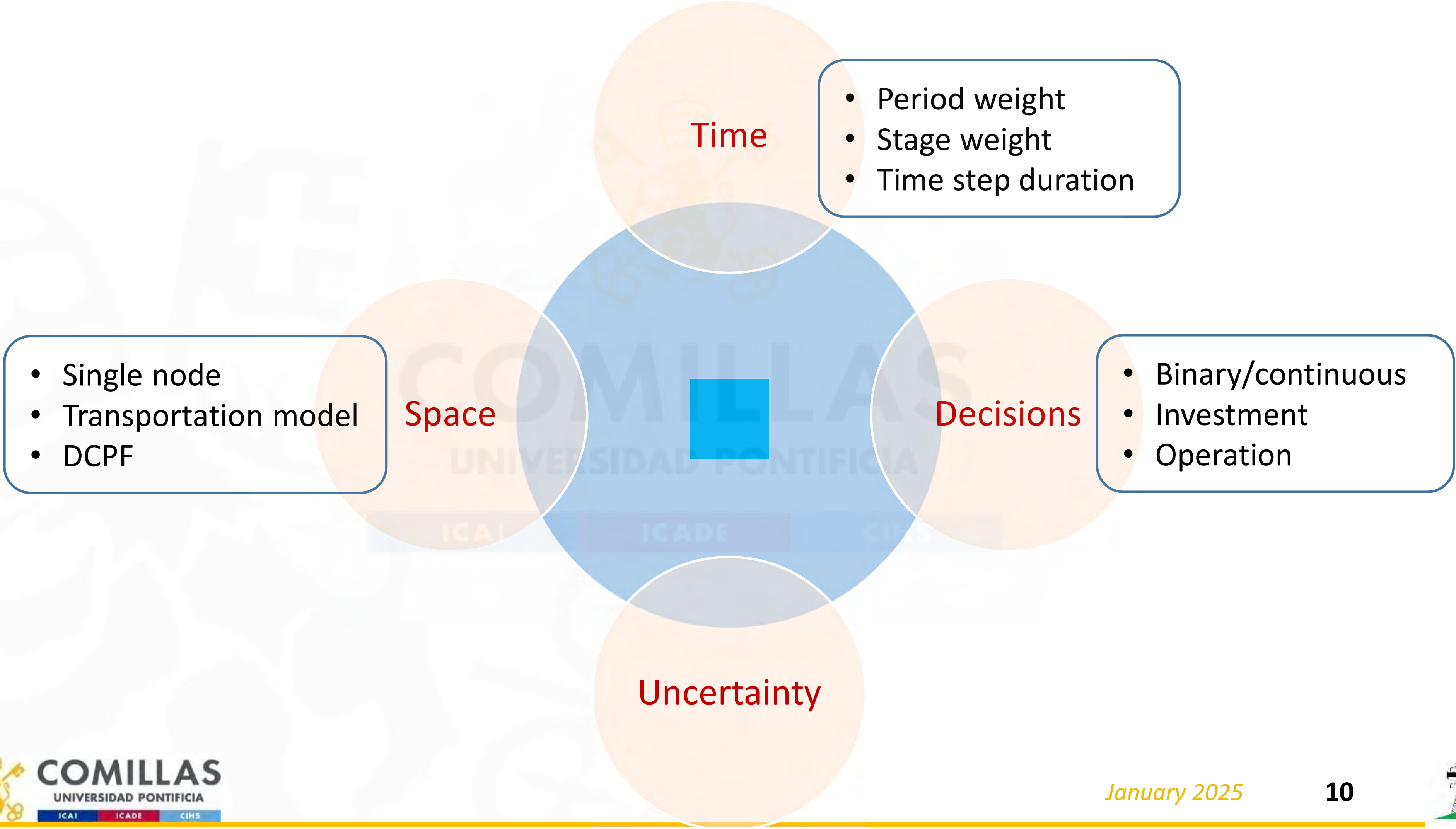
Integrated Resource Planning
IRP = GEP+SEP+TEP



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

- Determines the optimal 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.

Main modeling trade-offs



Modeling overview

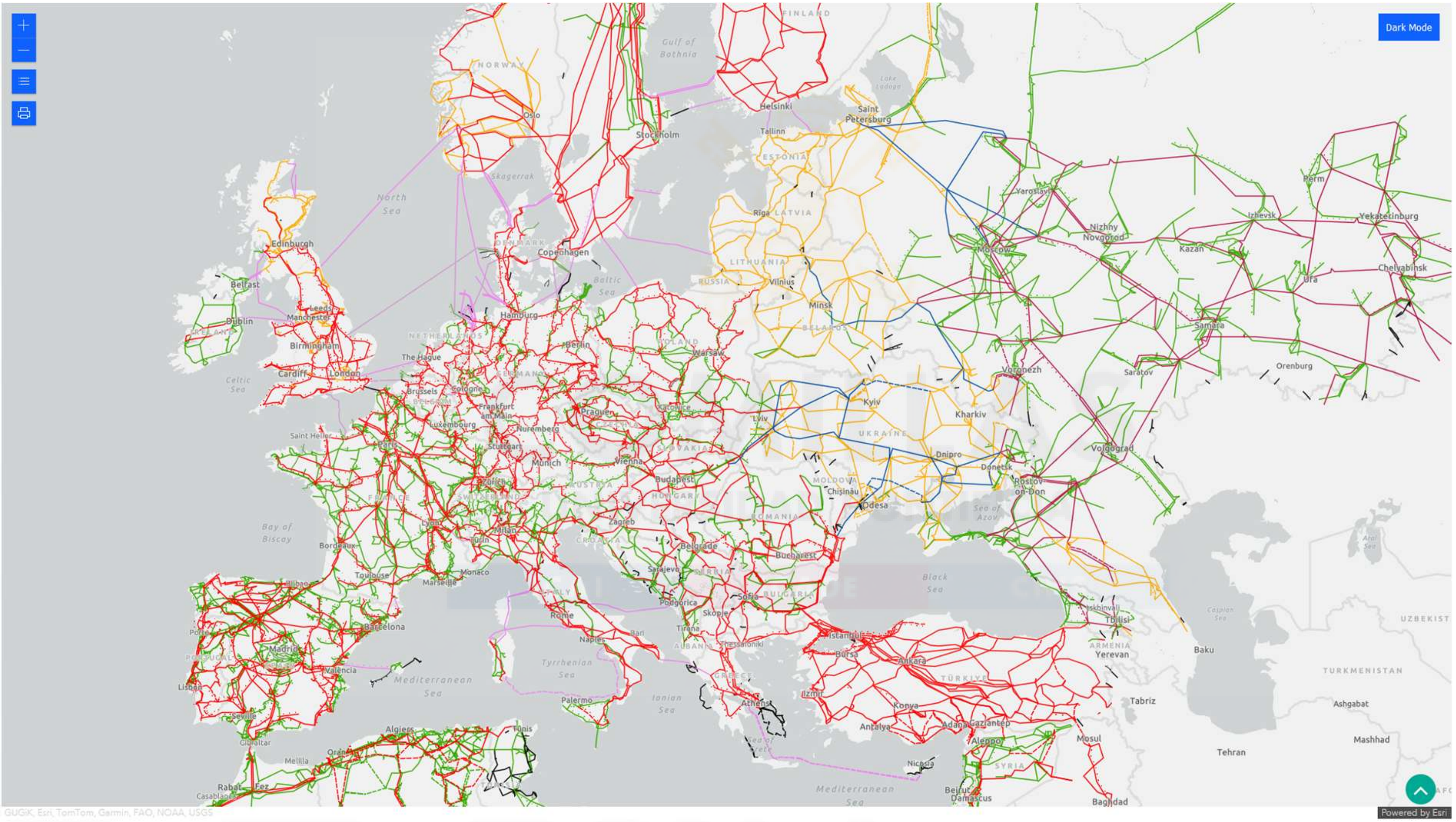
- Bottom-up paradigm
- Medium- and long-term analysis
- Time domain
  - Multiyear (dynamic, perfect foresight) scope with 8736 hours/year or representative stages
    - Period (e.g., year), scenario (e.g., climate year), load level (e.g., hour), stage (e.g., representative days/weeks)
  - Flexible duration of the time step (e.g., bi-hour, 3-hour, 4-hour time step)
- It uses mixed-integer linear programming (solvers GUROBI, CPLEX, HiGHS, GAMS, GLPK, or CBC)

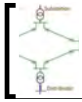
Source: EPRI

Time resolution

- Period/year
  - Period weight allows replication of a year (weight 5 for the year 2030 represents years 2030 up to 2034)
- Stage
  - Optimization problem formulated consecutively for each stage
  - No constraint connection between two consecutive stages (ramps, up/down time ignored)
  - Used for creating representative days/weeks; e.g., case 9n7y uses one week per year for seven years.
  - Stage weight allows the replication of each stage (weight 4 of stage/week 1 represents the first moon month)

Geographical representation





Node

Electrical node

Zone

NUTS2, NUTS3

Area

Country

Region

CSW, CSE, CCS

Modeling options

Generation & Storage 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
- Considering up/down ramp constraints
- Considering minimum up/down time constraints

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

Item	Description	
IndBinGenInvest	Binary generation expansion decisions	{0 continuous, 1 binary, 2 ignore investments}
IndBinGenRetirement	Binary generation retirement decisions	{0 continuous, 1 binary, 2 ignore retirements}
IndBinRsrInvest	Binary reservoir expansion decisions (only used for reservoirs modeled with water units)	{0 continuous, 1 binary, 2 ignore investments}
IndBinNetInvest	Binary electricity network expansion decisions	{0 continuous, 1 binary, 2 ignore investments}
IndBinNetH2Invest	Binary hydrogen network expansion decisions	{0 continuous, 1 binary, 2 ignore investments}
IndBinNetHeatInvest	Binary heat network expansion decisions	{0 continuous, 1 binary, 2 ignore investments}
IndBinGenOperat	Binary generation operation decisions	{0 continuous, 1 binary}
IndBinGenRamps	Considering or not the up/down ramp constraints	{0 no ramps, 1 ramp constraints}
IndBinGenMinTime	Considering or not the min up/down time constraints	{0 no min time constraints, 1 min time constraints}
IndBinSingleNode	Single node case study	{0 network, 1 single node}
IndBinLineCommit	Binary transmission switching decisions	{0 continuous, 1 binary}
IndBinNetLosses	Network losses	{0 lossless, 1 ohmic losses}

Dealing with uncertainty

- Several stochastic parameters that can affect the optimal expansion decisions are considered
- The operation scenarios are associated with:
  - Natural hydro inflows/outflows
  - Max/min generation/consumption of generating units
  - Max/min energy per generating unit
  - Max/min storage per generating unit
  - Fuel/emission cost
  - Electricity demand
  - Up/down operating reserves
  - Inertia requirements

Policy and resource constraints

- Minimum electricity 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]

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 (interruptibility)

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

F. Labora et al. "*An efficient model for Nuclear Power Plant constraints to flexible operation*" working paper

Variable renewable energy (VRE)

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

Hydro and energy storage subsystems

- Operation scheduling of medium- and short-term storage (i.e., pumped-hydro storage, batteries).
- Hydro, open- and closed-loop pumped-hydro storage (PHS), PHS treated individually, and system battery storage, demand side management (DSM), and solar thermal
- EV (V1G, V2G)
- ESS energy inventory [GWh] [hm^3]
- Energy outflows to represent H2 production or km for EV
- 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]

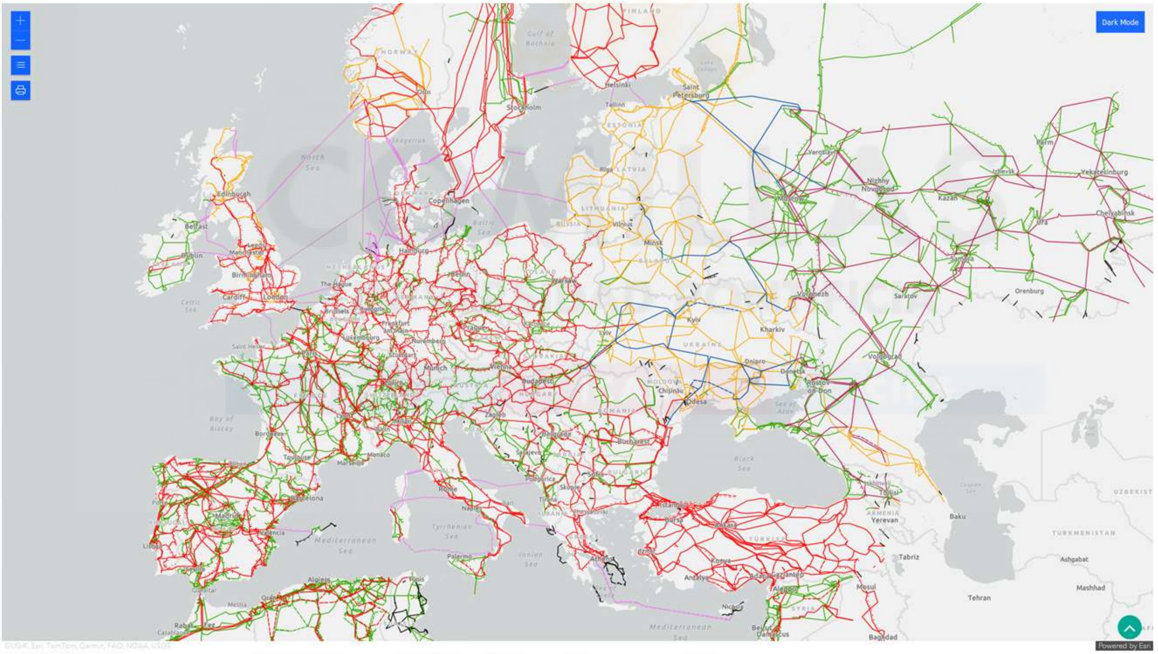
Hydro cascade basins

Topological representation of basins (cascaded reservoirs and volume magnitudes)

Source: Iberdrola

Network flow modeling

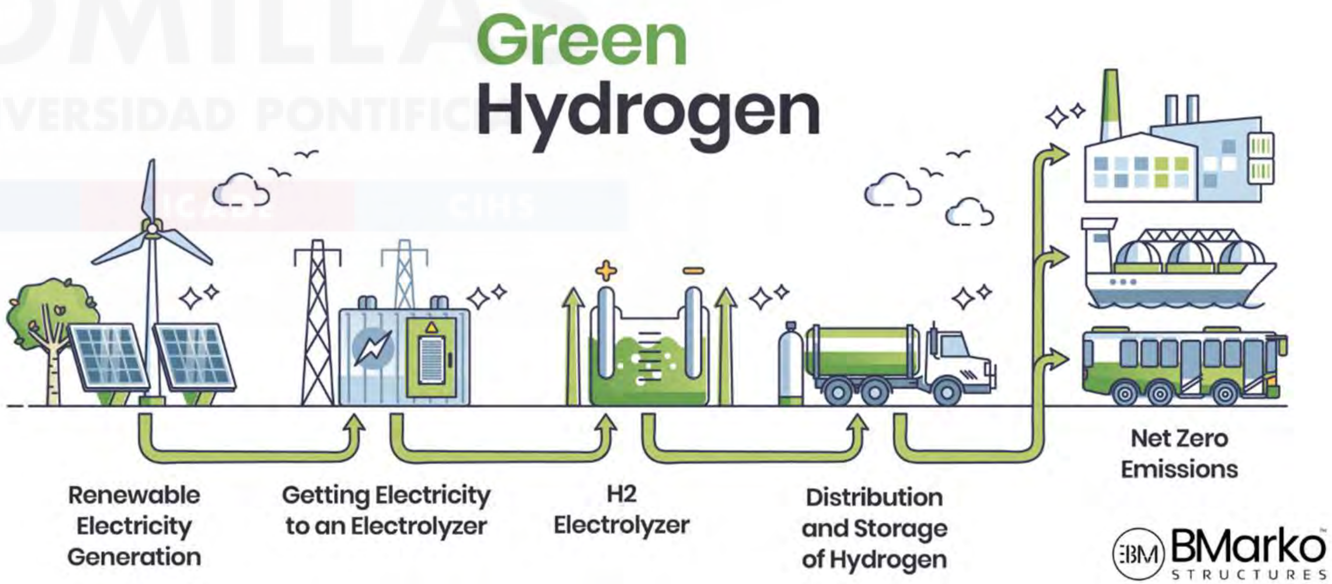
- DC power flow (DCPF) with/without ohmic losses
- Network-constrained unit commitment (NCUC)



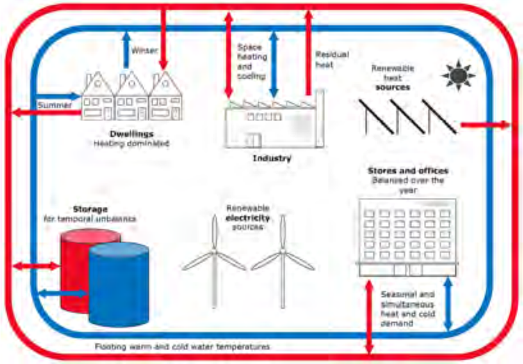
Hydrogen energy carrier

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

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



Heat energy carrier



- Heat demand
- Minimum heat adequacy reserve margin [p.u.]
- 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)
- Heat network

Electric, hydro, hydrogen, and heat systems input data

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

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Navigation

Electric System Input Data

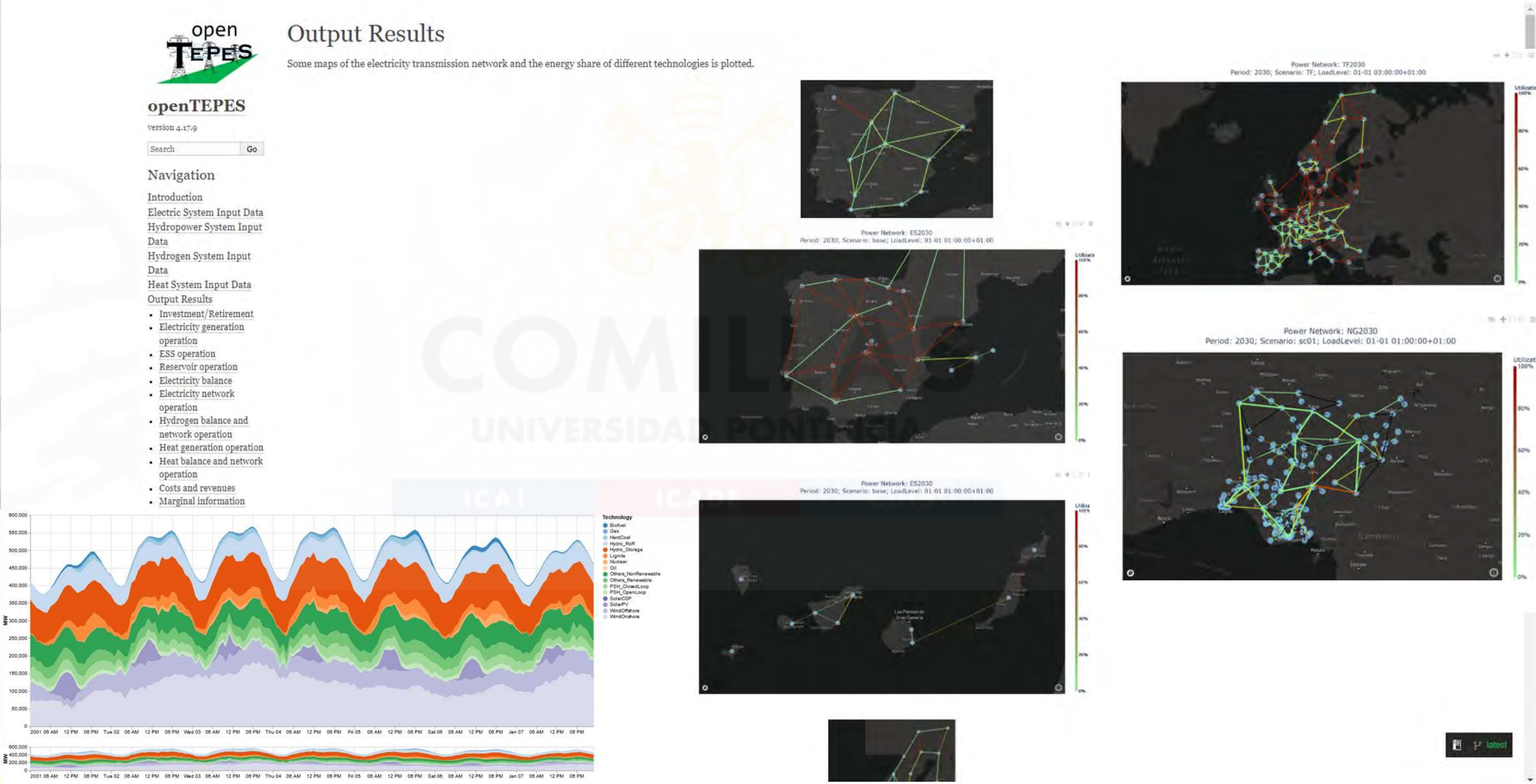
All the input files must be located in a folder with the name of the case study.

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
CC	Capacity Credit
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power. Cogeneration (produces electricity and heat simultaneously)
DC	Direct Current
DCPF	DC Optimal Power Flow
DR	Demand Response
DSM	Demand-Side Management (e.g., load shifting)
DSR	Demand-Side Response (e.g., interruptibility)
EB	Electric Boiler
EHU	Electrical Heating Unit (Power to Heat: consumes electricity to produce heat, e.g., heat pump, electric boiler)
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
FHU	Fuel Heating Unit (Fuel to Heat: consumes any fuel other than hydrogen to produce heat, e.g., biomass/natural gas/oil boiler)
GEP	Generation Expansion Planning
mFRR	Manual Frequency Restoration Reserve
H_2	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
IRP	Integrated Resource Planning
NTC	Net Transfer Capacity
OCGT	Open Cycle Gas Turbine
PHS	Pumped-Hydro Storage
PNS	Power Not Served

Output results

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



Output results

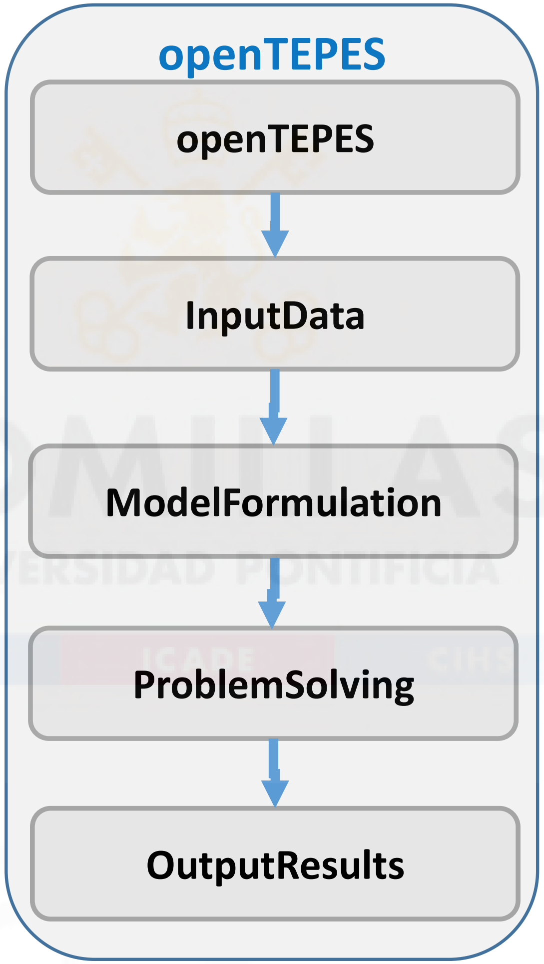
- Investment: (generation, storage, hydro reservoirs, electric lines, hydrogen pipelines, and heat pipes) investment decisions
- Operation: unit commitment, startup, and shutdown of non-renewable units, unit output and aggregation by technologies (thermal, storage hydro, pumped-hydro storage, RES), RES 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 [1] : Locational Short-Run Marginal Costs (LSRMC), stored energy value, water volume value, reserve margin, emission cap, minimum RES, operating reserve
- 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

1 *Computing the marginal information (dual variables) involves solveing first with binary variables, fixing them, and rerunning it again.*

3

Case Studies

openTEPES module structure



Many and varied 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)

- 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

- Linkage with energy system models (integrated assessment models IAM) 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

D.S. Oliveira, S. Lumbreras, E.F. Alvarez, A. Ramos, L. Olmos *Model-based energy planning: a methodology to choose and combine models to support policy decisions*. International Journal of Electrical Power and Energy Systems, 159, August 2024, 110048 10.1016/j.ijepes.2024.110048.

Studies conducted. Storage analysis (ii)

- Cost-benefit analysis (CBA) of candidate pumped-hydro storage units
  - Economic and operational 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 (2-4 h of storage), pumped-hydro storage units (8-60 h of storage), and solar thermal (6-9 h of storage)
- Penetration of EV and type of charge
  - Impact of the EV in the system operation and the charge type (V1G, V2G)
- Impact of local energy communities (LEC) on transmission investments and storage (BESS and H2) 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

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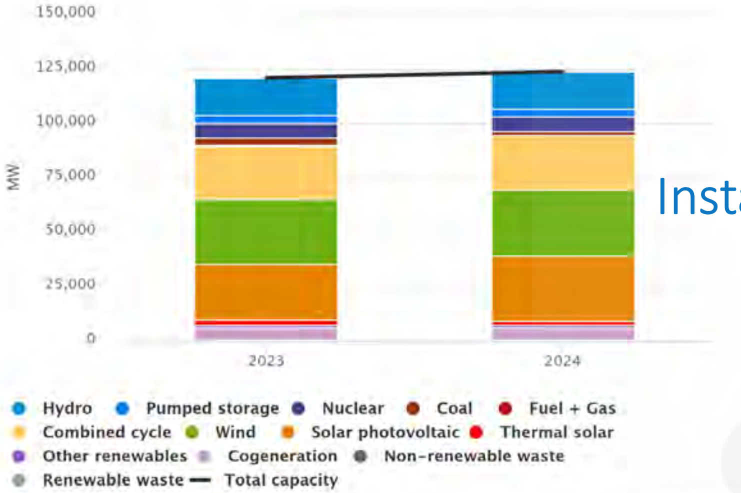
Studies conducted. Security of supply (iii)

- 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?

3.1

Mainland Spain 2030

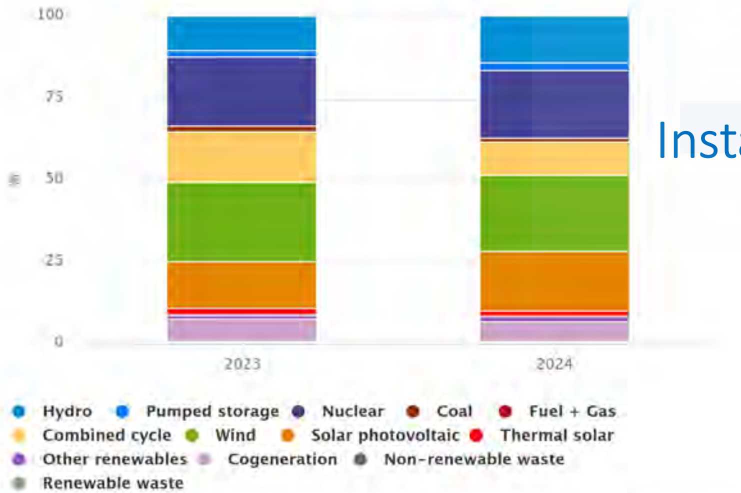
Mainland Spain 2024



Installed capacity [MW]

Energy [GWh]

	2023	2024
Hydro	25,337	31,298
Pumped storage	5,205	4,995
Nuclear	54,276	46,828
Coal	3,808	2,491
Fuel + Gas	0	0
Combined cycle	39,283	22,828
Wind	61,341	52,638
Solar photovoltaic	36,748	40,566
Thermal solar	4,696	4,010
Other renewables	3,586	3,252
Cogeneration	17,291	14,376
Non-renewable waste	1,185	1,049
Renewable waste	707	565
Total generation	**253,463**	**224,896**



Installed capacity [%]

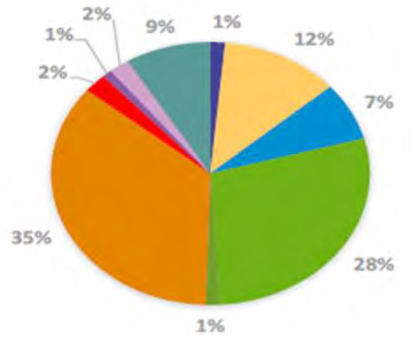
Energy [%]

	2023	2024
Hydro	10.0	13.9
Pumped storage	2.1	2.2
Nuclear	21.4	20.8
Coal	1.5	1.1
Fuel + Gas	0.0	0.0
Combined cycle	15.5	10.2
Wind	24.2	23.4
Solar photovoltaic	14.5	18.0
Thermal solar	1.9	1.8
Other renewables	1.4	1.4
Cogeneration	6.8	6.4
Non-renewable waste	0.5	0.5
Renewable waste	0.3	0.3
Total generation	**100.0**	**100.0**

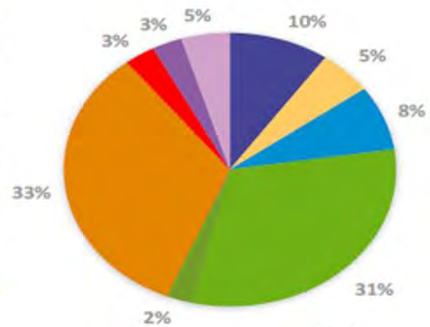
Mainland Spain 2030
National Energy and Climate Plan (NECP)

- Installed capacity: 203 GW
- Only three nuclear units remain at the end of 2030 (3.1 GW), no coal units, existing CCGT (24.5 GW)
- Significant investments in solar PV (42.3 GW) and onshore wind (26.8 GW)
- Existing storage hydro and pumped-storage hydro (20.4 GW)
- Additional pumped-storage hydro (2.5 GW)
- Additional batteries (2.5 GW)

	MW	%
Nuclear	3041	1%
Carbón	0	0%
Ciclos	24499	12%
Hidráulica (sin bombeo)	14562	7%
Eólica terrestre	57737	28%
Eólica offshore	2800	1%
Solar FV	72130	35%
Termosolar	4804	2%
Resto RES	1964	1%
Cogeneración y otros	4205	2%
Almacenamiento	17612	9%
Total sistema	**203353**	**100%**
Electrolizadores	**11980**	



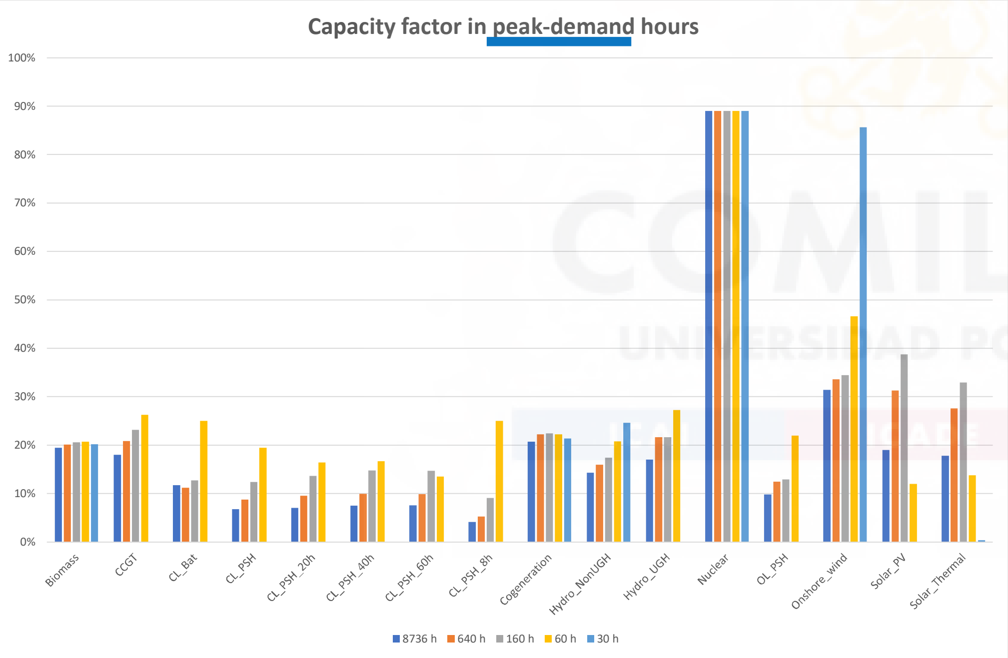
	GWh	%	Horas utilización
Nuclear	36881	10%	7224
Carbón	0	0%	0
Ciclos	19750	5%	806
Hidráulica (sin bombeo)	28932	8%	1987
Eólica terrestre	117450	31%	2034
Eólica offshore	9695	3%	3463
Solar FV	125377	33%	1738
Termosolar	11426	3%	2378
Resto RES	10993	3%	5597
Cogeneración y otros	17859	5%	4247
Generación [1]	**378362**	**100%**	

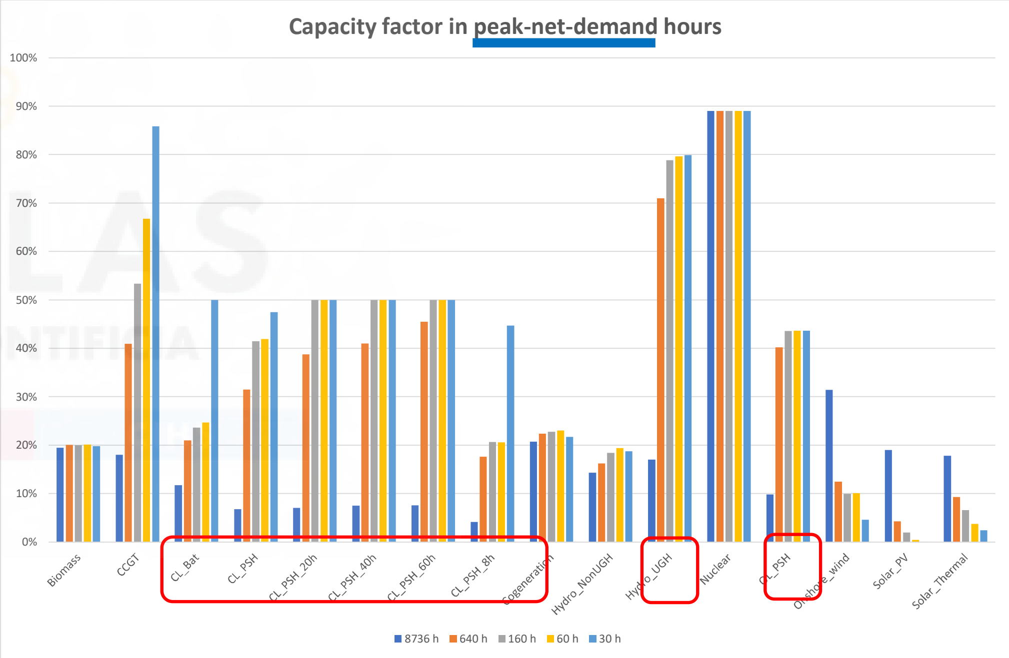


Firmness/Electric Load-Carrying Capability (ELCC) Equivalent Firm Capacity (EFC)

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

Pumped-storage hydro contributes more at critical hours than



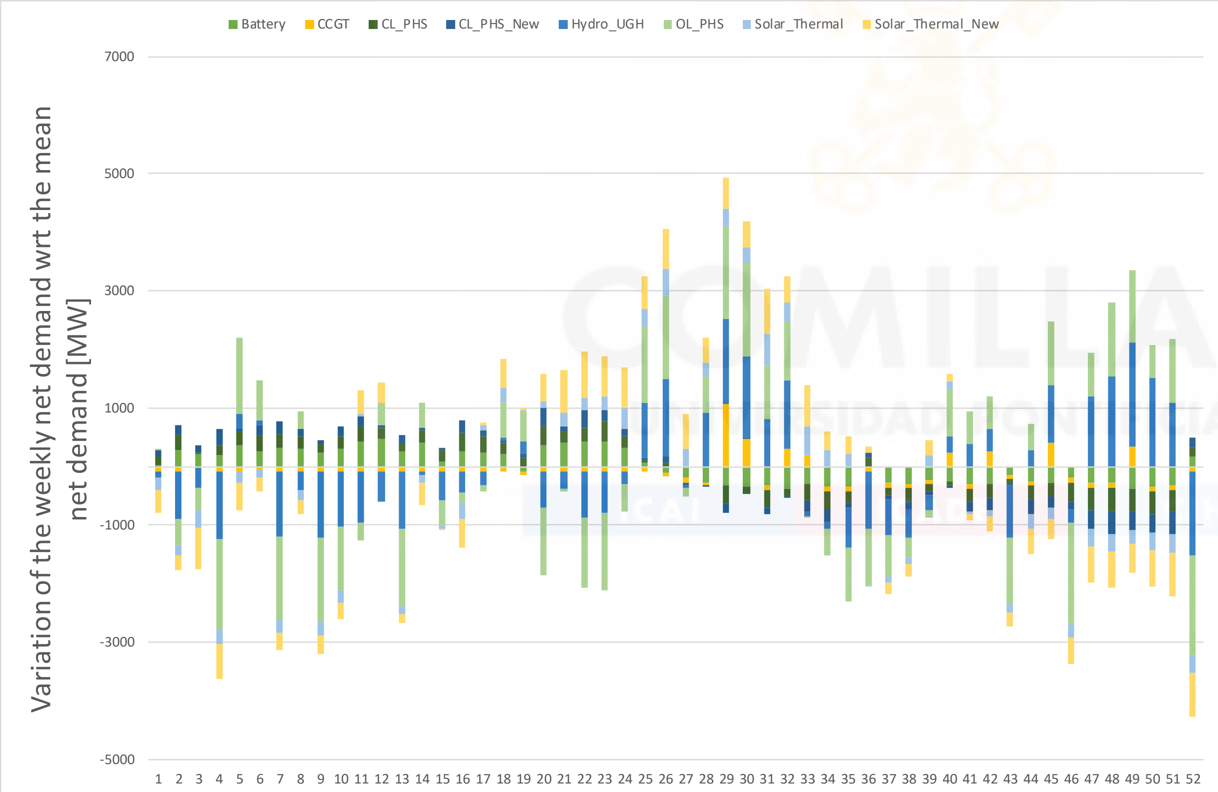


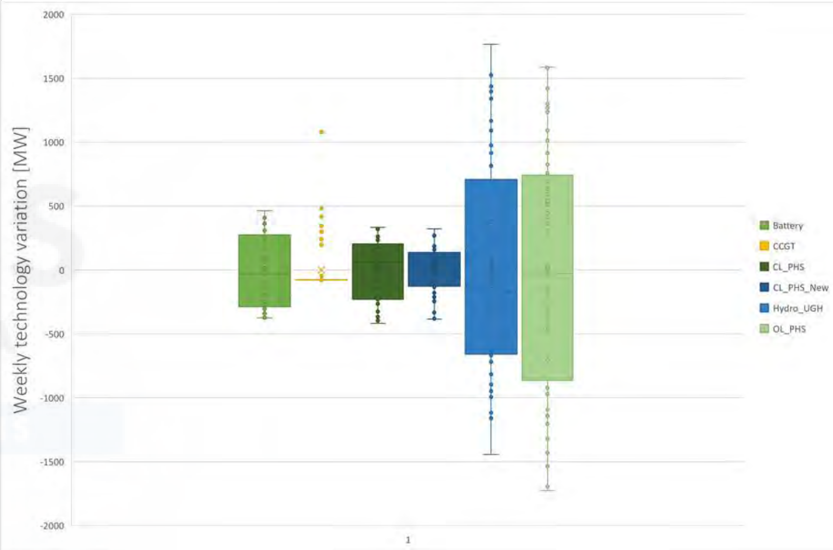
S. Huclin, J.P. Chaves, A. Ramos, M. Rivier, T. Freire-Barceló, F. Martín-Martínez, T. Gómez San Román, Á. Sánchez Miralles *Exploring the roles of storage technologies in the Spanish electric system with high share of renewable energy* Energy Reports 8:4041-4057, November 2022. 10.1016/j.egyr.2022.03.032

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

National Energy and Climate Plan (NECP) Flexibility

Contribution of each flexible technology to the variation of the weekly net demand with respect to the mean net demand





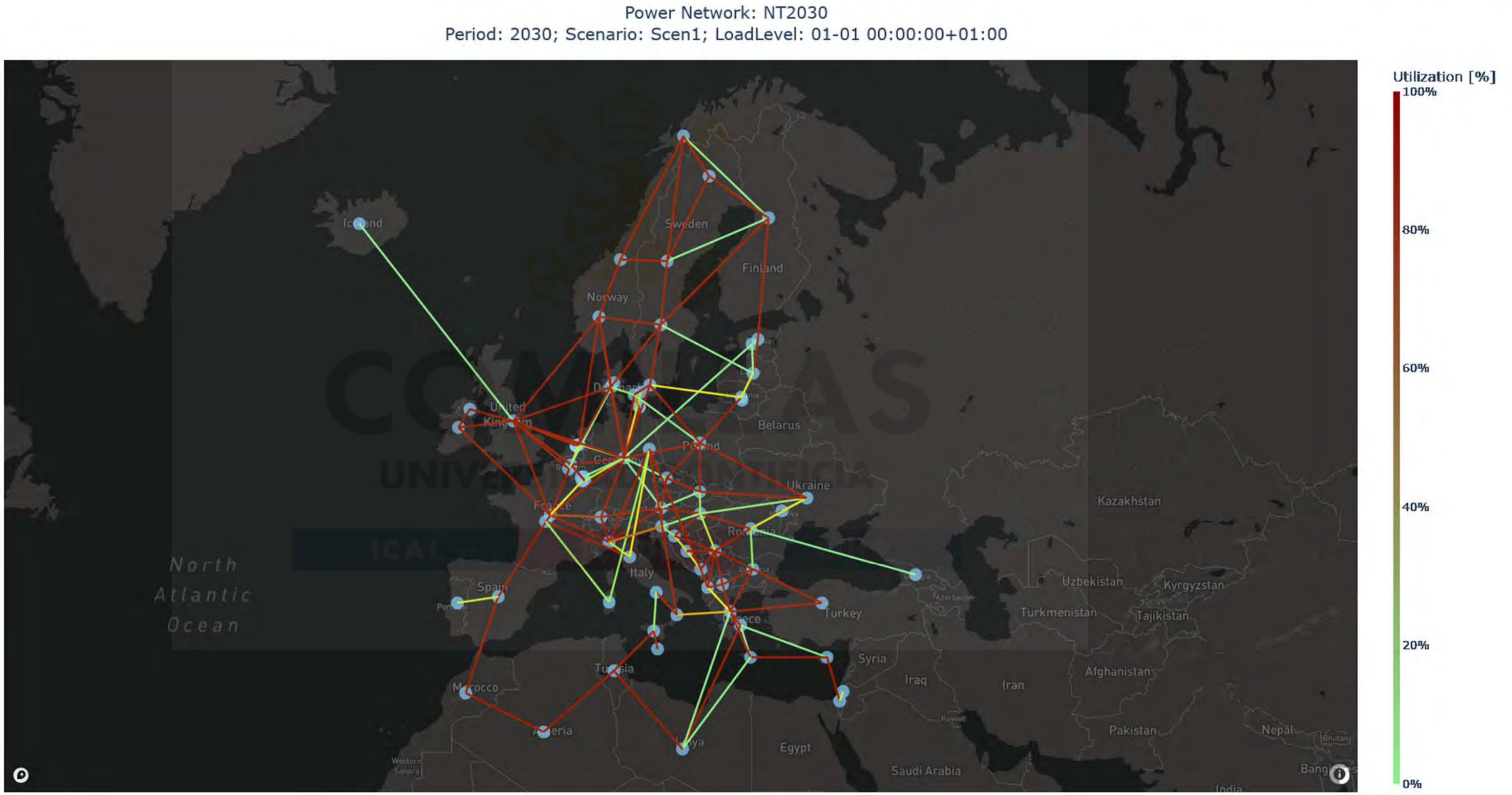
A. Ramos, S. Huclin, J.P. Chaves *Analysis of different flexible technologies in the Spain NECP for 2030*. Frontiers in Built Environment 9, October 2023 [10.3389/fbuil.2023.1065998](https://doi.org/10.3389/fbuil.2023.1065998)

3.2

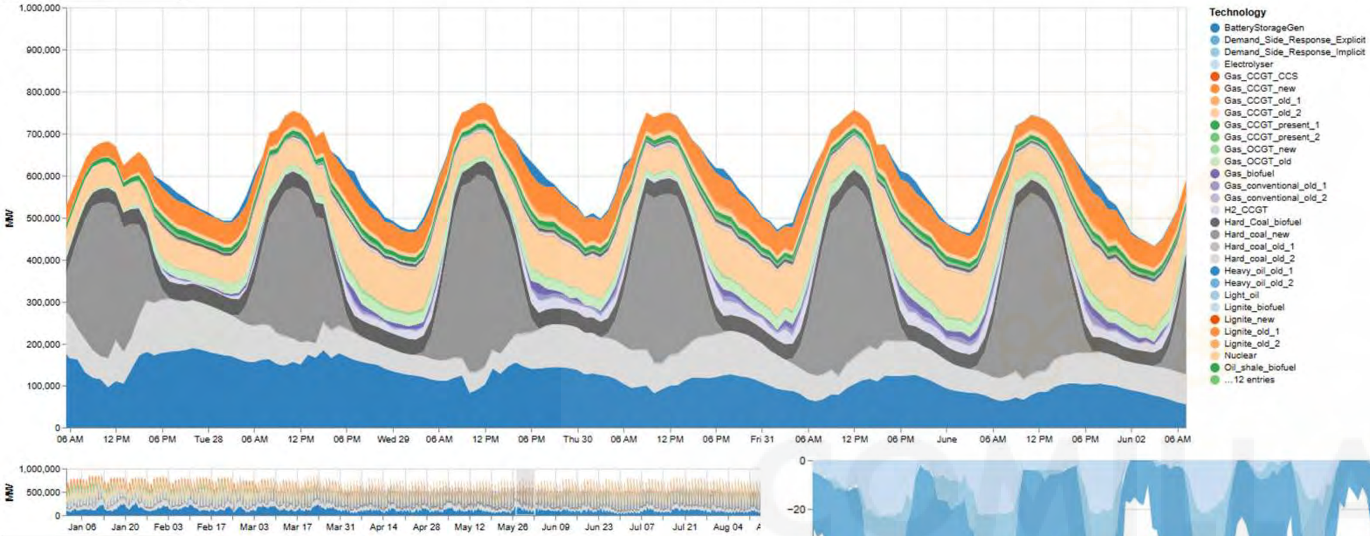
Europe. National Trends 2030

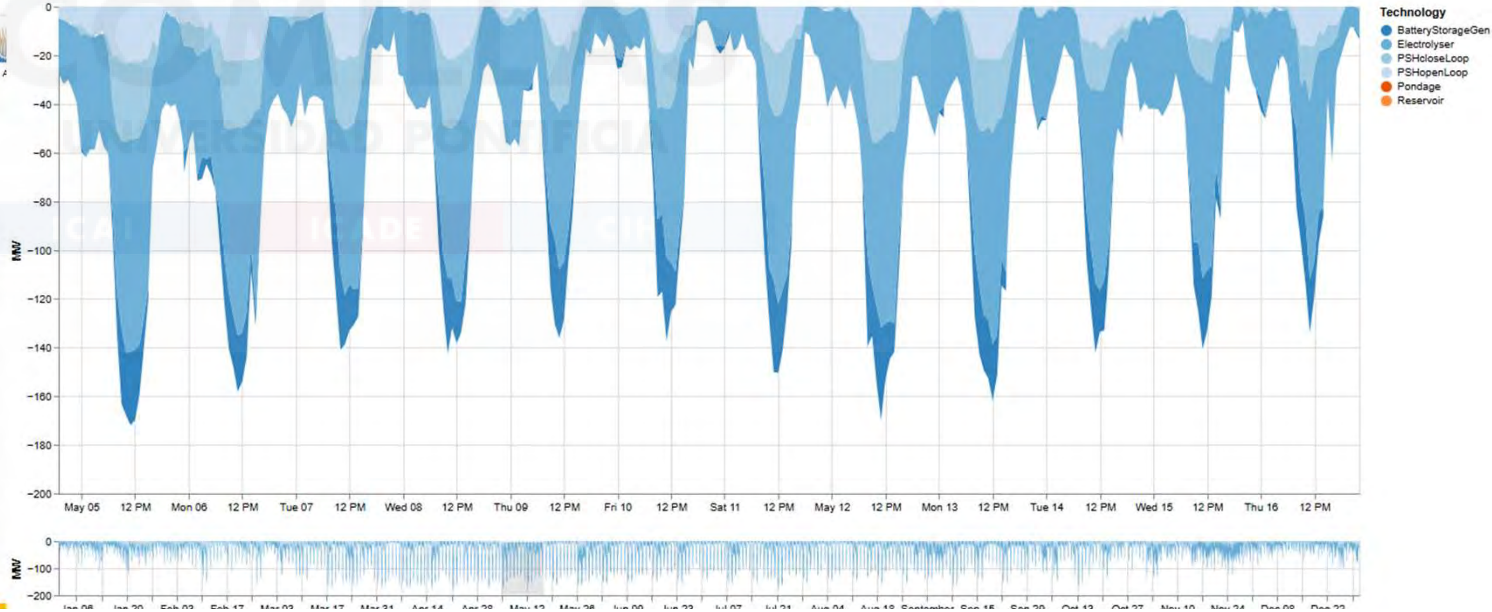
TYNDP 2024. National Trends 2030

(https://tyndp.entsoe.eu/)



TYNDP 2024
Generation and consumption





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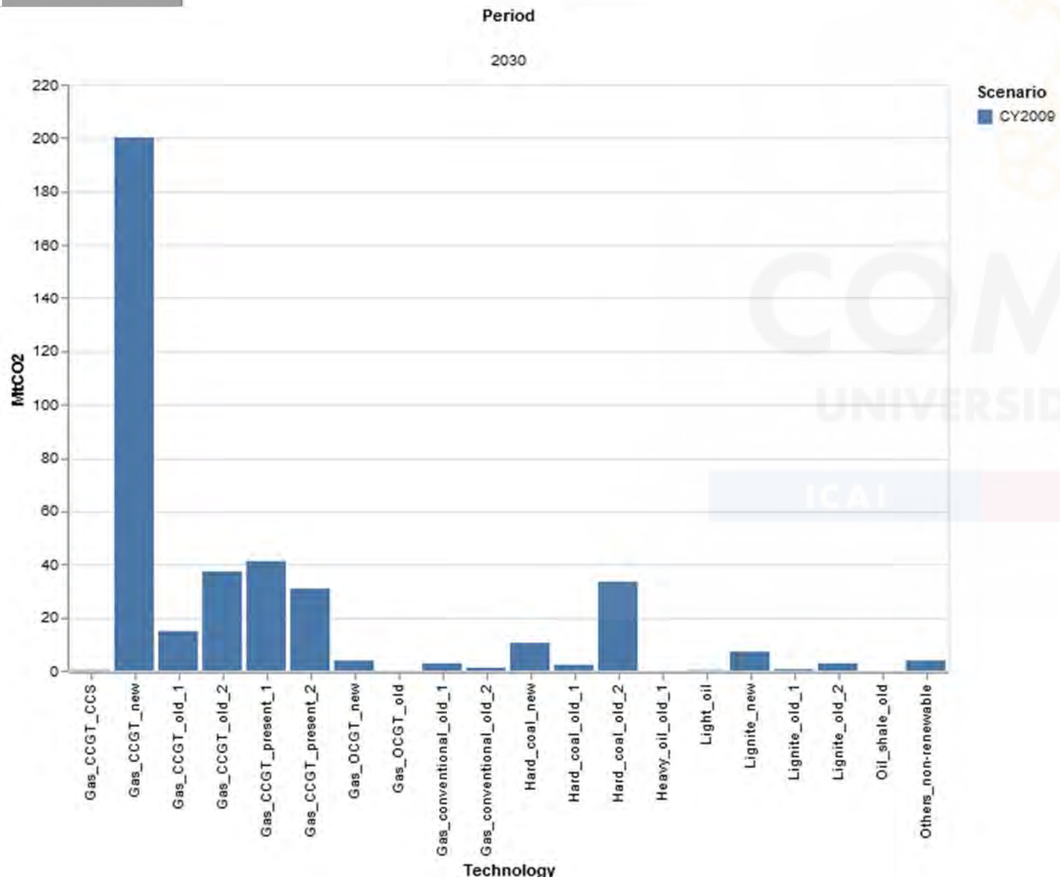
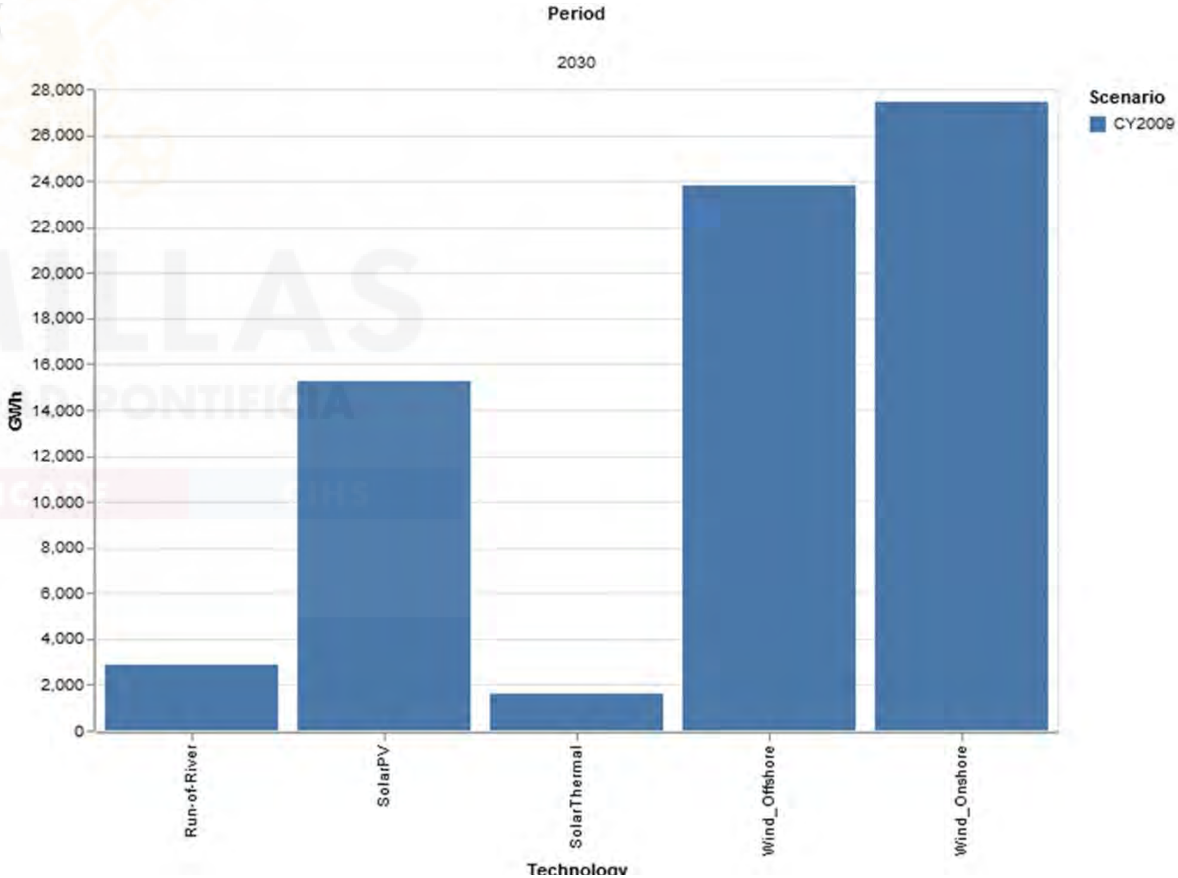
TYNDP 2024
Emissions and RES curtailment

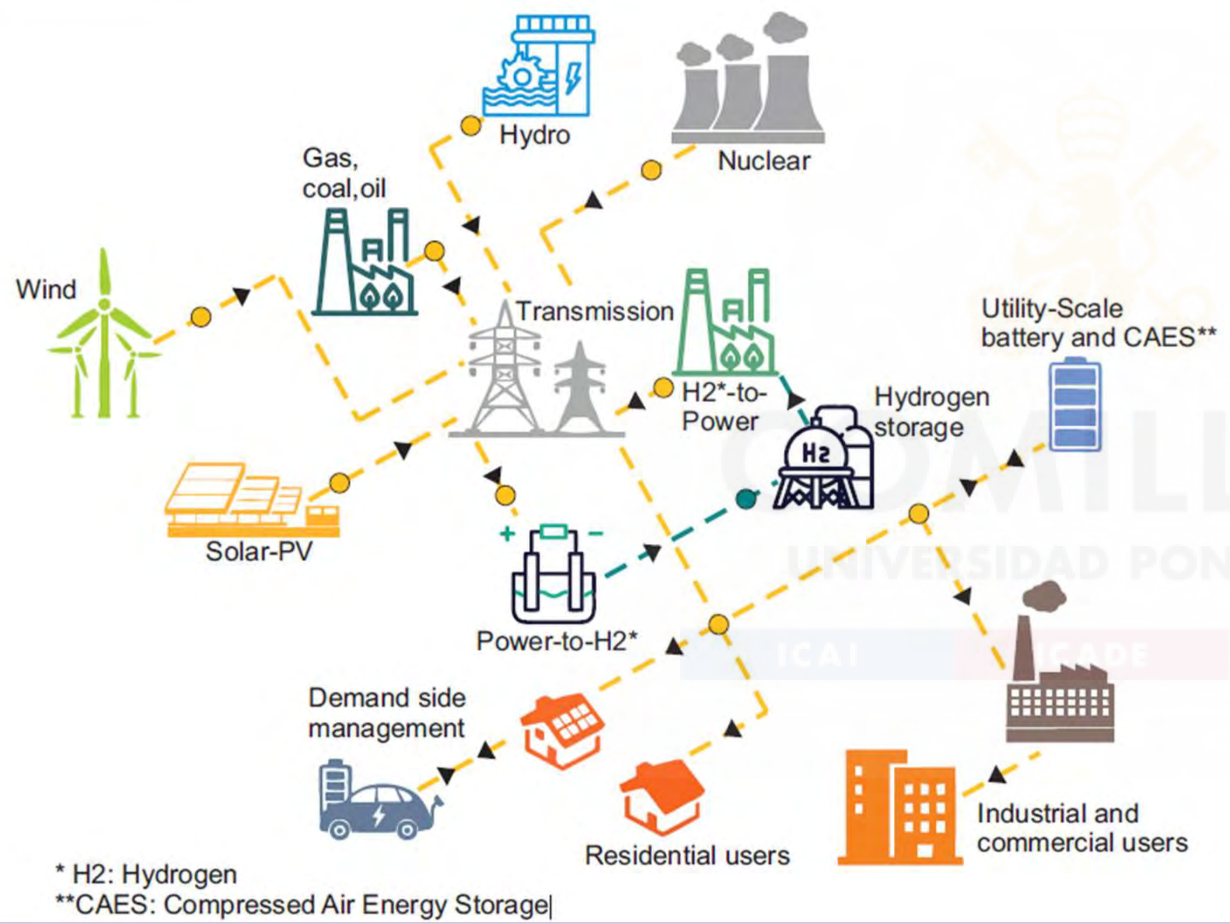




3.3

Europe. TYNDP 2024. National Trends 2040

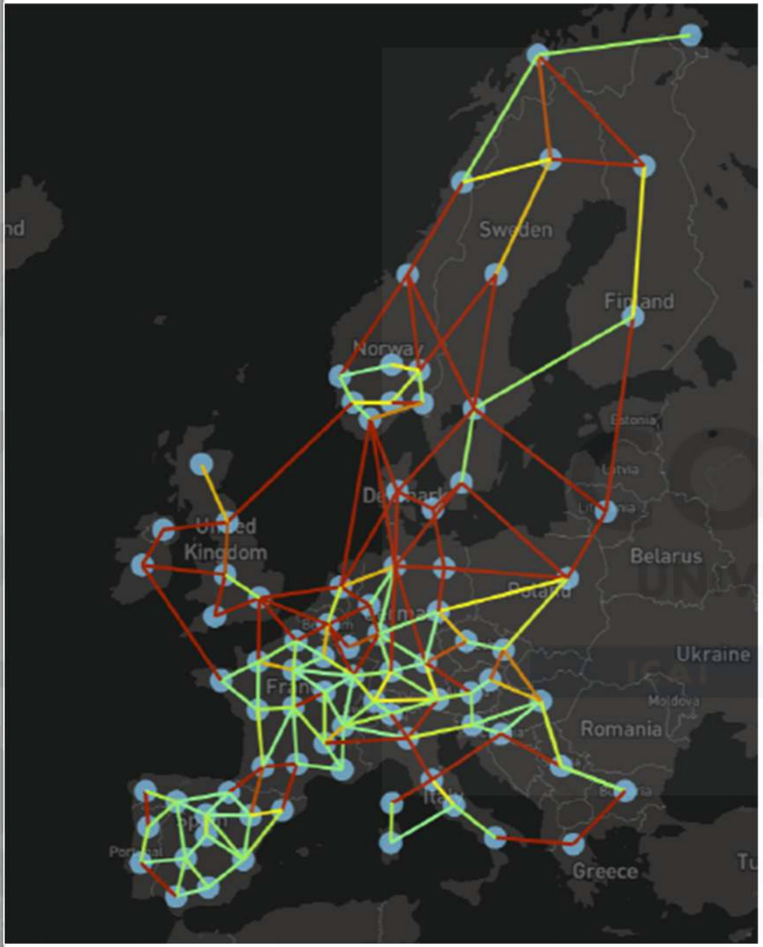
Role of Utility-Scale Storage and Grid for Europe



- Demand-side management
  - Load shifting
  - Max shift capacity: #% of hourly profile
  - Number of shifting hours: 4
  - Total daily electricity demand is fixed
- Hydrogen subsystems:
  - Production by using electrolyzers
  - Storage in H2 tanks
  - Consumption by thermal power plants
  - Pipelines

E. Alvarez “*Improving Modelling for Optimal Expansion Planning of Power Transmission Systems*”
PhD Thesis. Comillas Pontifical University. January 2025

European system



- Case study
  - European-scale electric system (84 buses)
    - Representative week for each season (summer, winter, etc.)
  - Predefined candidates: utility-scale storage
  - Algorithm to define transmission lines candidates
    - AC and DC
- Execution performance
  - Problem size
    - 3853859 rows and 2669399 columns
  - Computation time approx.: 30 min

Assessment of different case studies

Scenario	Scenario denominations	
	Demand Increase [%]	DSM Participation [%]
1	0	0
2	0	10
3	0	20
4	2.5	0
5	2.5	10
6	2.5	20
7	5	0
...	...	...
12	7.5	20

Input Data

X

Pathway	Investment type			
	National Line	International Line	BESS	H2 subsystem
1	✓	-	-	-
2	-	✓	-	-
3	✓	✓	-	-
4	-	-	✓	-
5	-	-	-	✓
6	-	-	✓	✓
7	✓	-	-	✓
8	-	✓	-	✓
9	✓	✓	-	✓
10	✓	-	✓	-
11	-	✓	✓	-
12	✓	✓	✓	-
13	✓	-	✓	✓
14	-	✓	✓	✓
15	✓	✓	✓	✓

Only transmission lines

Focus on storage

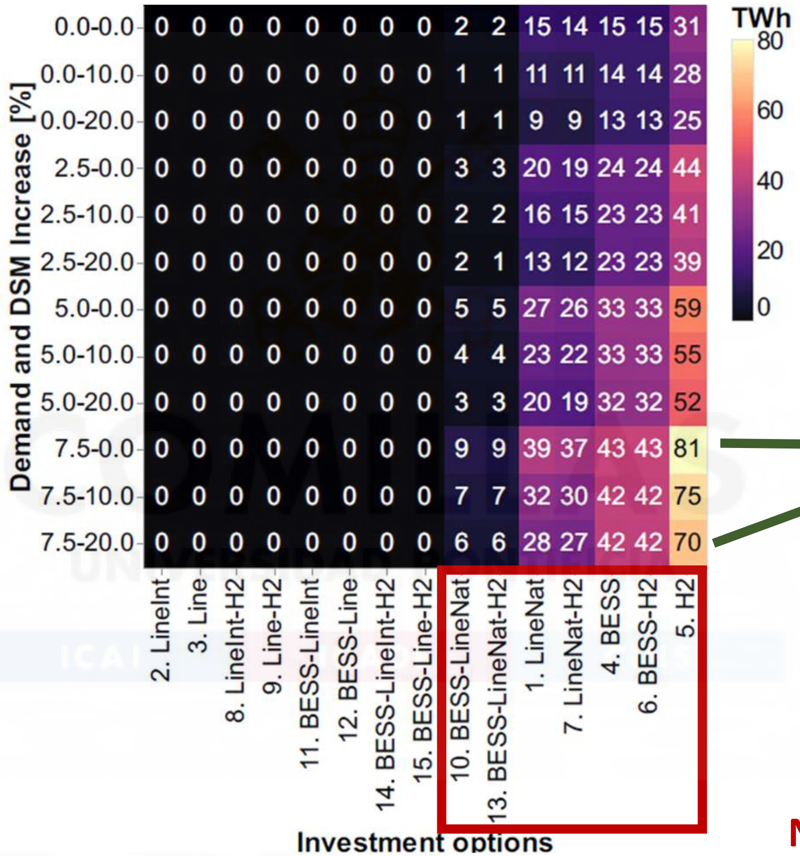
Everything, except international lines

Formulation

= **180 runs** ≈ 90 h of simulation

Results. Feasibility

Energy not served



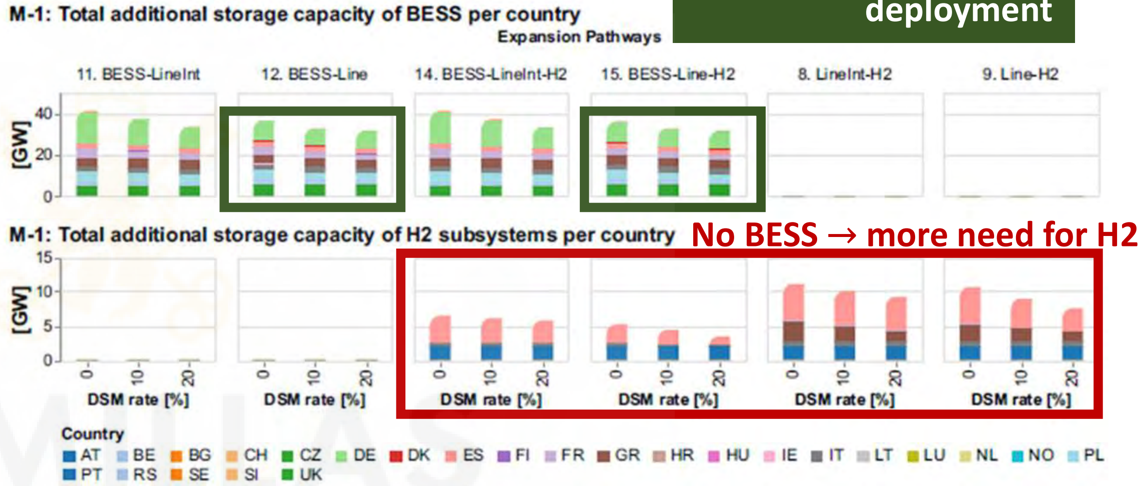
DSM (at 20%) impact: 14% of reduction in the ENS

No international lines: 84 executions

Results. Capacity deployed

New storage

H2 doesn't affect BESS deployment



No BESS → more need for H2

New transmission

BESS impact

Role of Utility-Scale Storage. Conclusions

- Utility-scale BESS and H2 subsystems provide flexibility for grid operation, especially in high-RES scenarios.
- Reduced RES curtailment and improved management through joint operational coordination.
- The strategic deployment of BESS increases the flexibility and resiliency of the grid and enables operators to meet rising demand with minimal infrastructure investments.

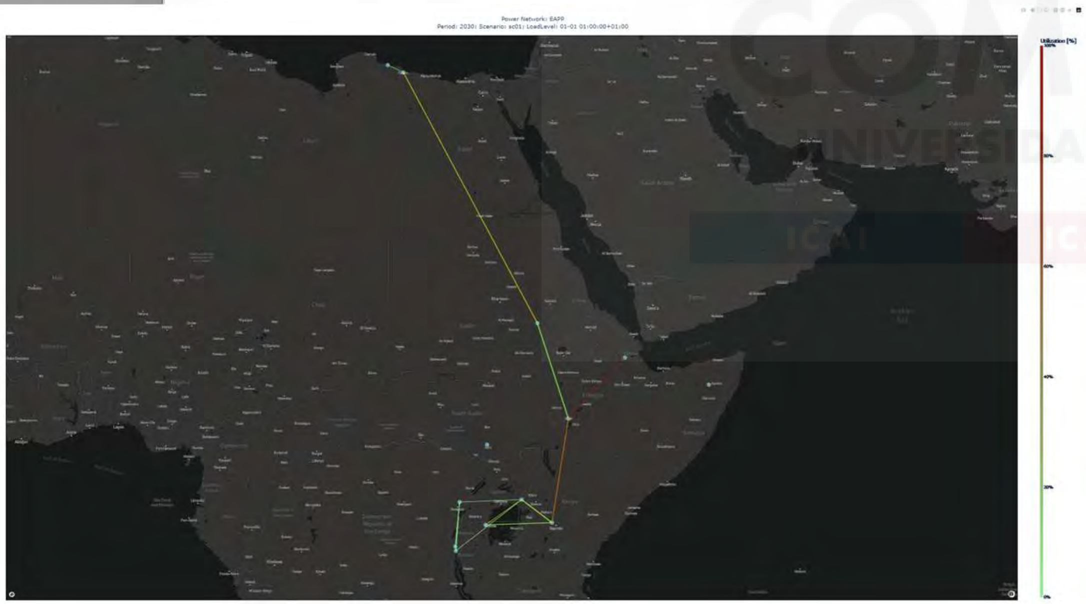
3.4

Africa. East African Power Pool (EAPP) 2030

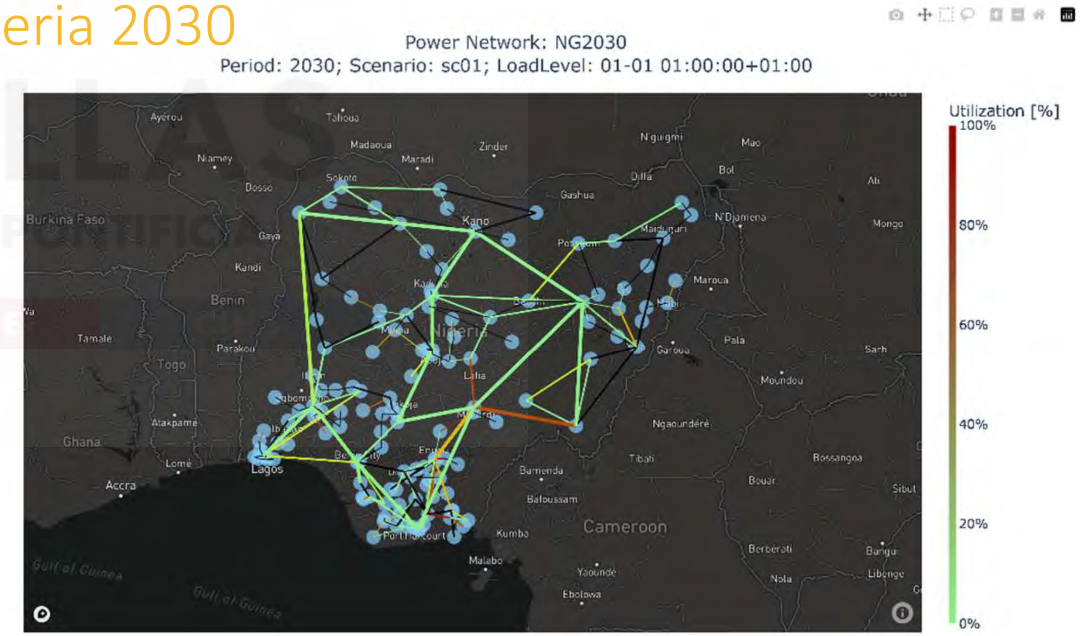
OpenMod4Africa Project
Case studies for East and West African Power Pools

- Generation and/or transmission expansion planning
- Operational analyses of flexibility technologies

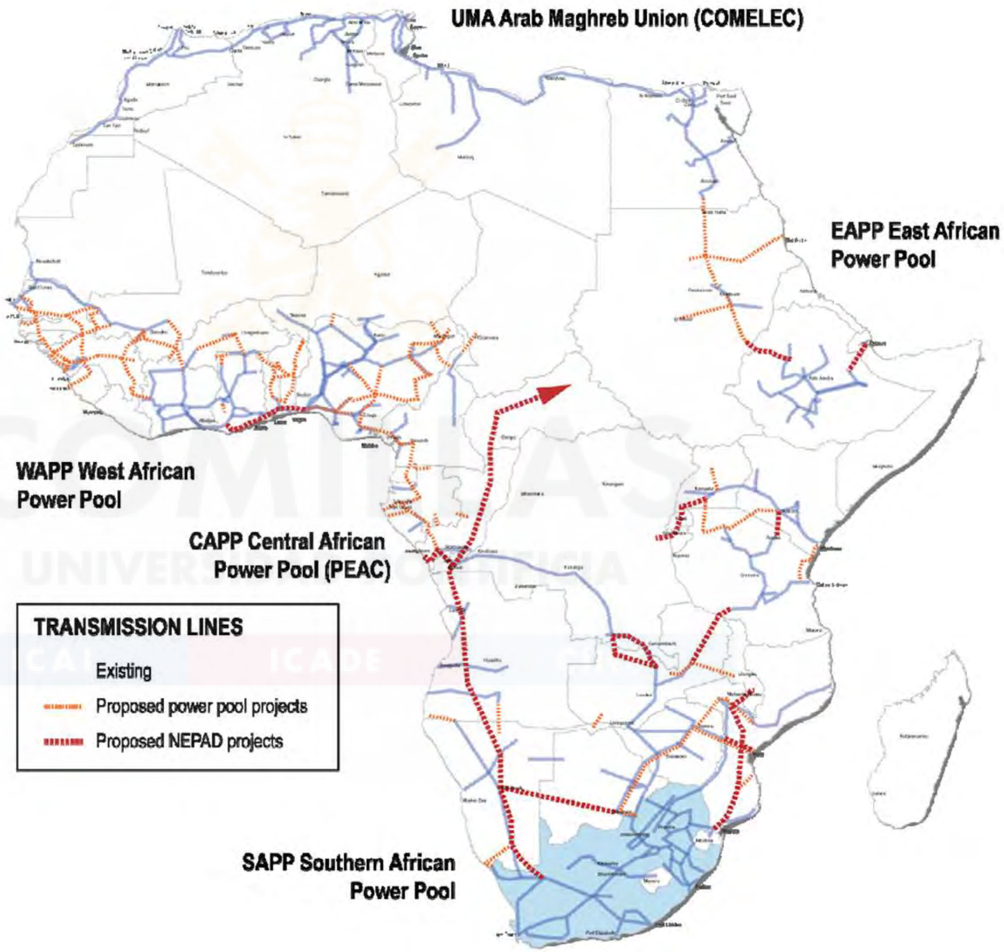
EAPP 2030



Nigeria 2030



Africa Transmission Network



https://www.geni.org/globalenergy/library/national_energy_grid/africa/africanelectricitygrid.shtml

3.5

Linking IAM models with openTEPES

openENTRANCE Project

Impact of LECs on the power system functioning

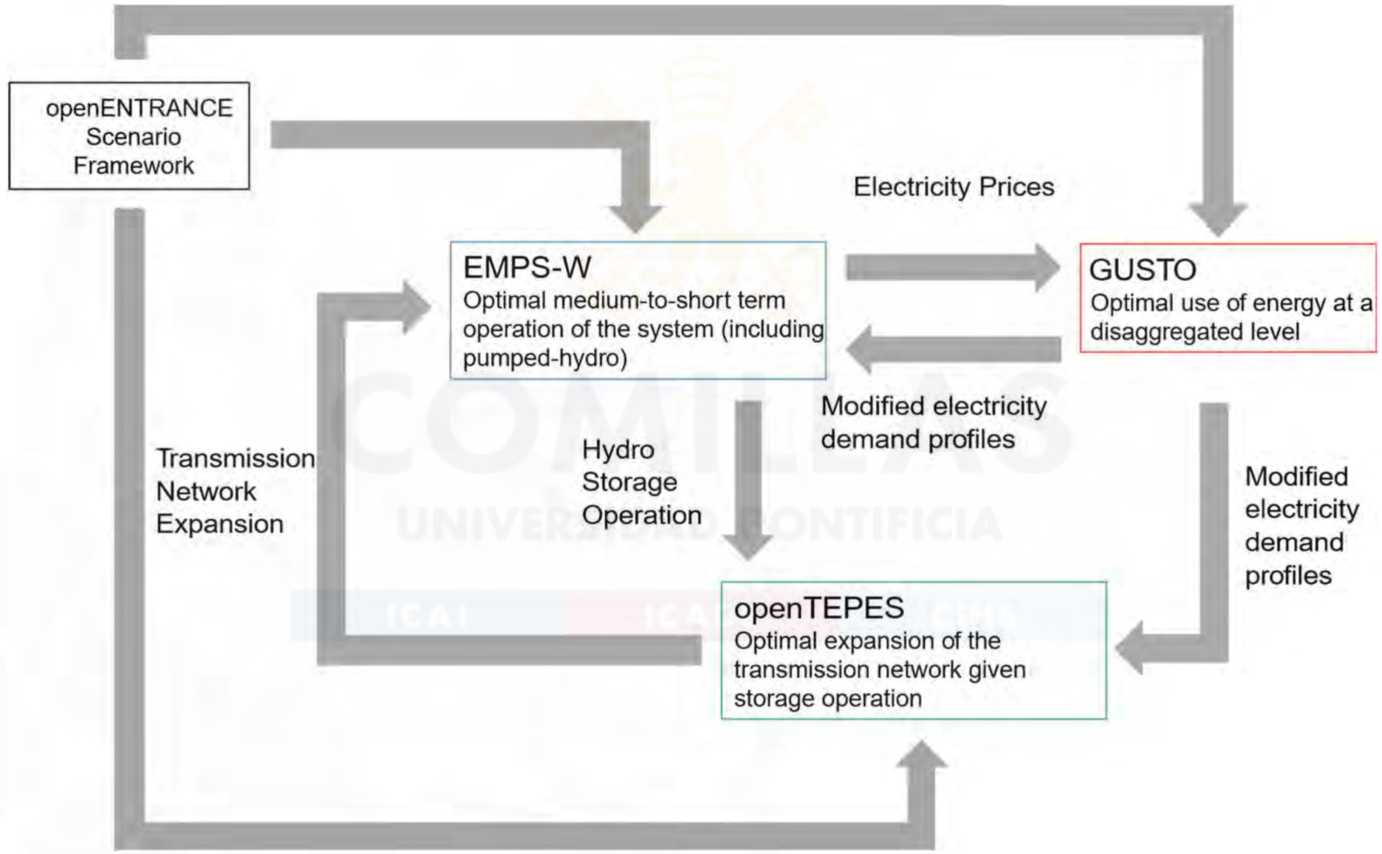
open ENTRANCE

- [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.

openENTRANCE Project
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
- LECs are 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

openENTRANCE Project Workflow

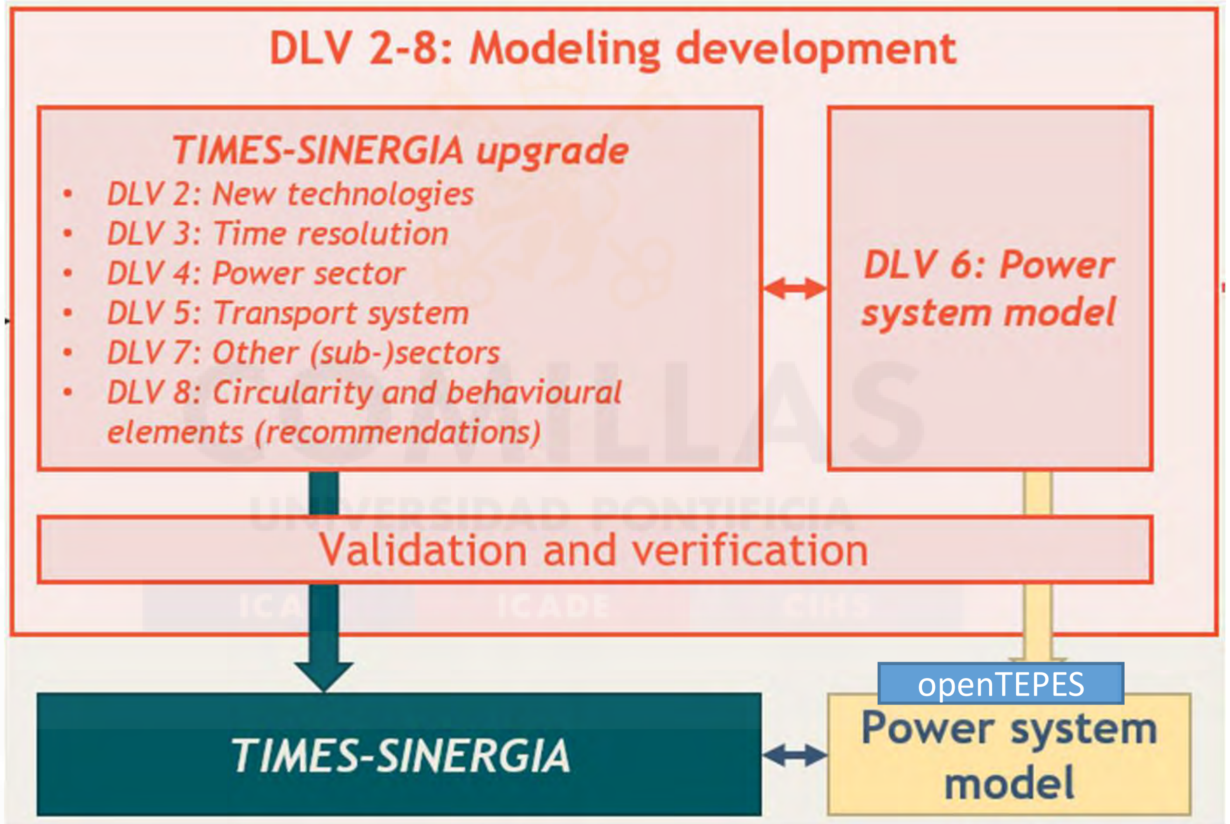


TIMES-SINERGIA → openTEPES

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.

TIMES-SINERGIA → openTEPES Workflow



TIMES-SINERGIA → openTEPES
Scope of the analysis

- Development of additional features of the 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

ECEMF Project

On the tradeoff between hydrogen and electricity for heat production

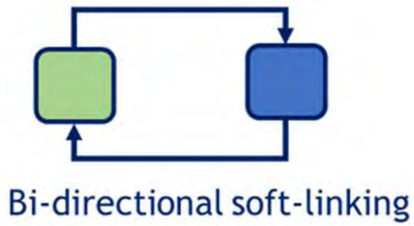
- European Climate and Energy Modelling Forum (ECEMF), developed for the European Union. May 2021 - December 2024. S. Lumbreras, A. Ramos, L. Olmos, C. Mateo, D. Santos Oliveira
  - It aims to provide the knowledge to inform the development of future energy and climate policies at national and European 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.

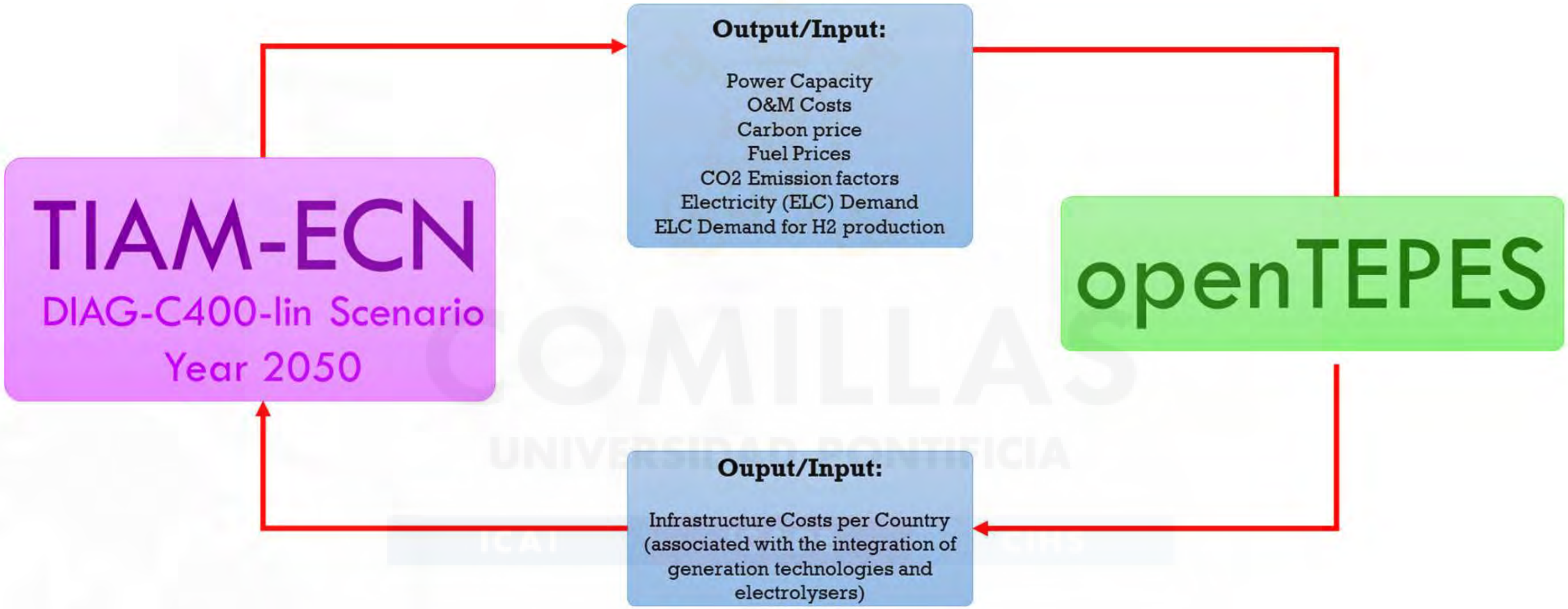
EUROPEAN CLIMATE + ENERGY MODELLING FORUM

ECEMF Project
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

ECEMF Project Workflow





Convergence Criterion: Expansion results in two consecutive iterations

DIAMOND Project

Connection of IAM models 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.

DIAMOND Project
Scope of the analysis

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

4

Modeling details

Generation. Special attributes

- StorageType: based on storage capacity
  - Daily *storage type* means the ESS inventory is assessed every time step. For the daily storage type, it is evaluated at the end of every hour; for the weekly storage type, it is evaluated at the end of every day; for the monthly storage type, it is evaluated at the end of every week; and yearly storage type is assessed at the end of every month.
- OutflowsType: based on the electricity demand extracted from the storage
  - Represents when the energy extracted from the storage must be satisfied (for daily outflows type at the end of every day, i.e., the energy consumed must equal the sum of outflows daily).
- EnergyType: based on the max/min energy to be produced by the unit
  - Represents when the minimum or maximum energy to be produced by a unit must be satisfied (for daily energy type at the end of every day, i.e., the sum of the energy generated by the unit must be lower/greater than the sum of max/min energy for every day)

Hydro and Energy Storage Systems (ESS)

	Hourly profile					
Energy Storage System (modeled in **energy units**)	Generation Discharge [MW]	Consumption Charge [MW]	Max/min Storage [GWh]	Inflows [MWh/h]	Outflows [MWh/h]	Max/min Ramps [MW/h]
Conventional storage hydro	✓		✓	✓		✓
Open-loop Pumped-hydro Storage	✓	✓	✓	✓		✓
Closed-loop Pumped-hydro Storage	✓	✓	✓			✓
Battery	✓	✓	✓			✓
Solar thermal	✓		✓	✓		✓
Demand Side Management	✓	✓	✓			✓
Electrolyzer		✓	✓		✓	✓
Electric Vehicle (V1G)		✓	✓		✓	✓
Electric Vehicle (V2G)	✓	✓	✓		✓	✓

	Hourly profile					
Hydro basins (modeled in **water units**)	Turbine [MW]	Pump [MW]	Max/min Storage [hm^3]	Inflows [m^3/s]	Outflows [m^3/s]	Max/min Ramps [MW/h]
Hydropower plant	✓	✓				✓
Hydro reservoir			✓	✓		

Thank you for your attention

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