MITEI-IAP24

Computational modeling for clean, reliable, and affordable electricity

Massachusetts Institute of Technology (MIT)

Impact of renewable energy sources in short-term generation planning

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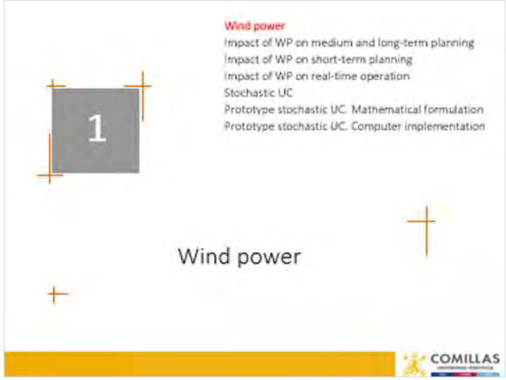

Wind power
Impact of WP on medium and long-term planning
Impact of WP on short-term planning
Impact of WP on real-time operation
Stochastic UC
Prototype stochastic UC. Mathematical formulation
Prototype stochastic UC. Computer implementation

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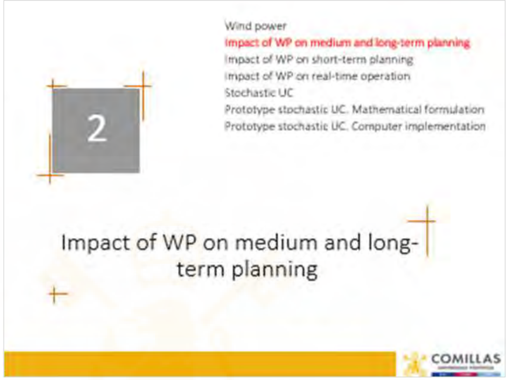

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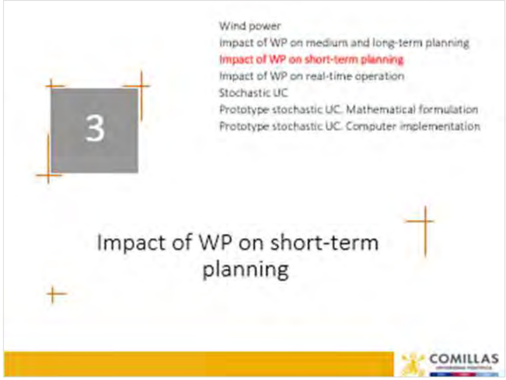
Impact of WP on medium and long-term planning



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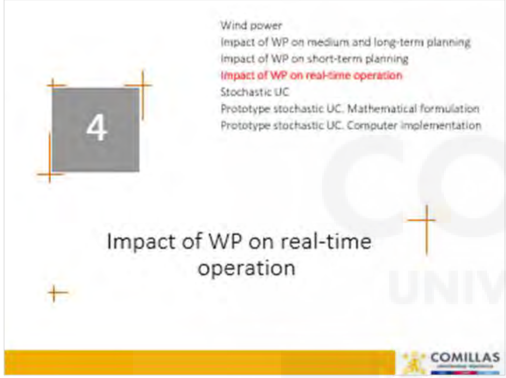

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Impact of WP on real-time operation

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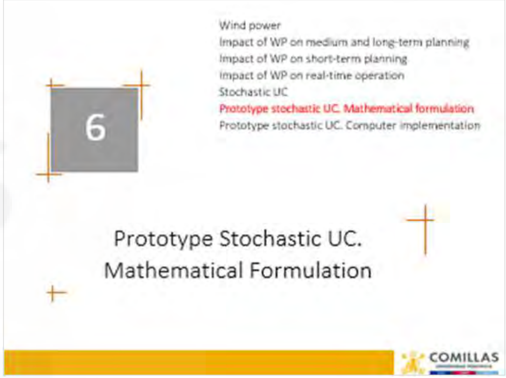
Stochastic Unit Commitment



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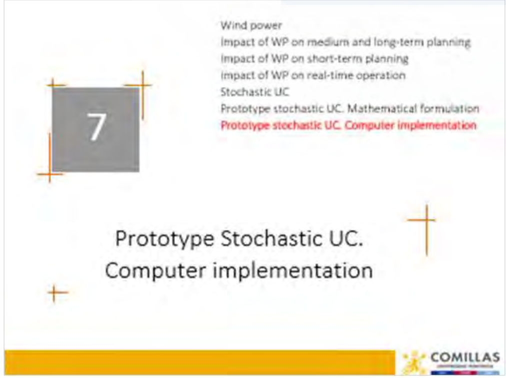
Prototype Stochastic UC. Mathematical Formulation



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Prototype Stochastic UC. Computer implementation

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Wind power

Uncertain resources/demands

- Renewable Energy Sources (RES)
  - Wind Power (WP)
  - Solar Photovoltaic
  - Small Hydro. Run of the river
  - Solar Thermal. Concentrated Solar Power (CSP)
  - Biomass
  - Solid Waste
- Cogeneration or Combined Heat and Power (CHP)

and as other uncertain demands

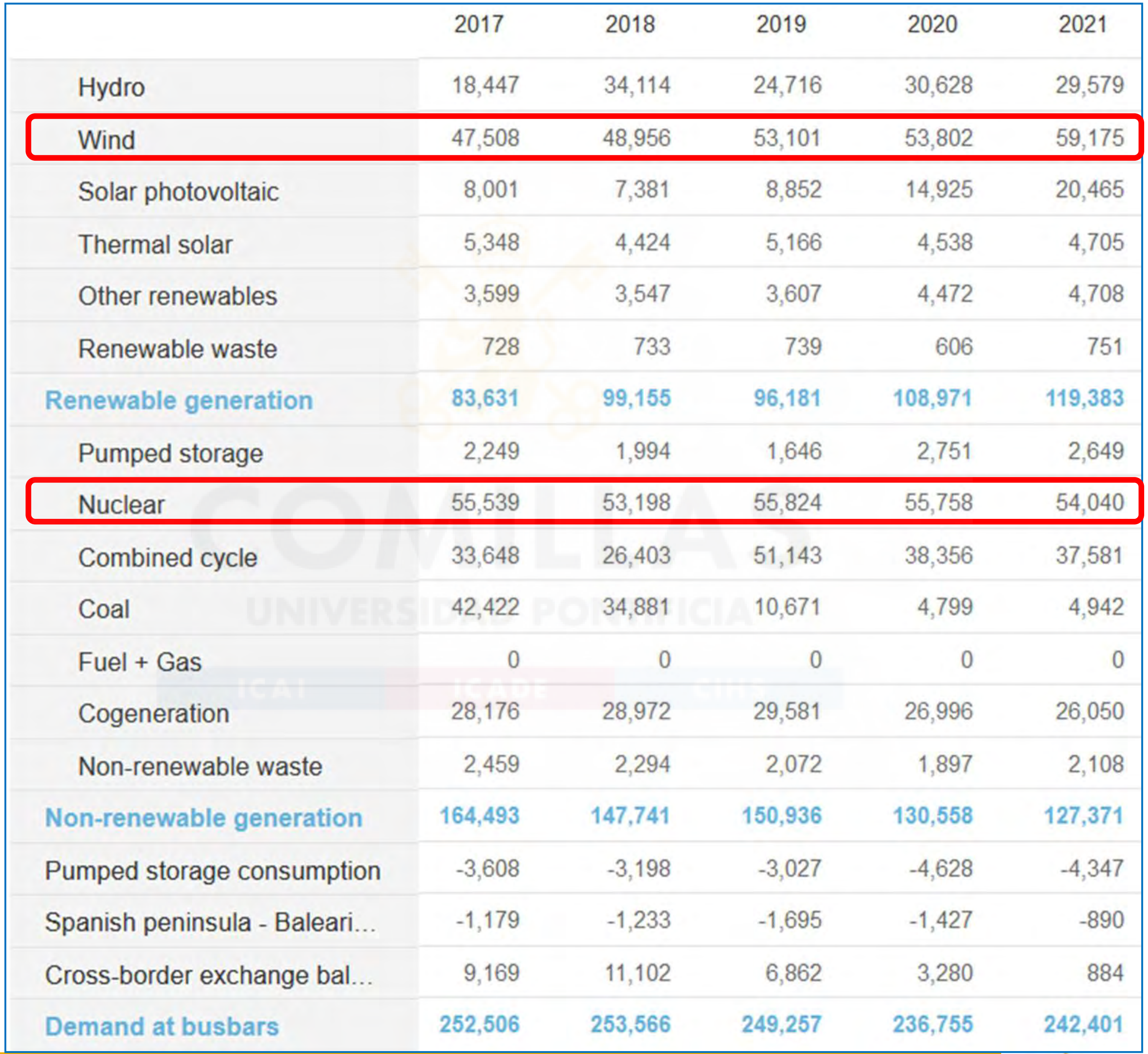
- Demand Response (DR)
- Electric Vehicle (EV)

Lessons Learned Along Europe's Road to Renewables

- Ch. Roselund and J. Bernhardt Lessons Learned Along Europe's Road to Renewables IEEE Spectrum May 2015 http://spectrum.ieee.org/energy/renewables/lessons-learned-along-europes-road-to-renewables
  - Denmark, Portugal, and Spain have all made a rapid transition away from fossil fuels for electricity, but each in a different way
    - In 2013, the highest share of wind power in **one hour** was on 1 December 2013 between 4-5 h was 135.8 %. The highest share of wind power in **one day** was on Saturday, 21 December, with 102 % of the electricity consumption. In **December 2013**, wind power in Denmark, for the first time, reached a level corresponding to more than half of the electricity consumption (54.8 %). On the contrary, the share of wind was only 69.1 % on 28 October 2013 when the hurricane hit Denmark.
    - 39.1 % of Denmark's electricity consumption was covered by wind generation in 2014

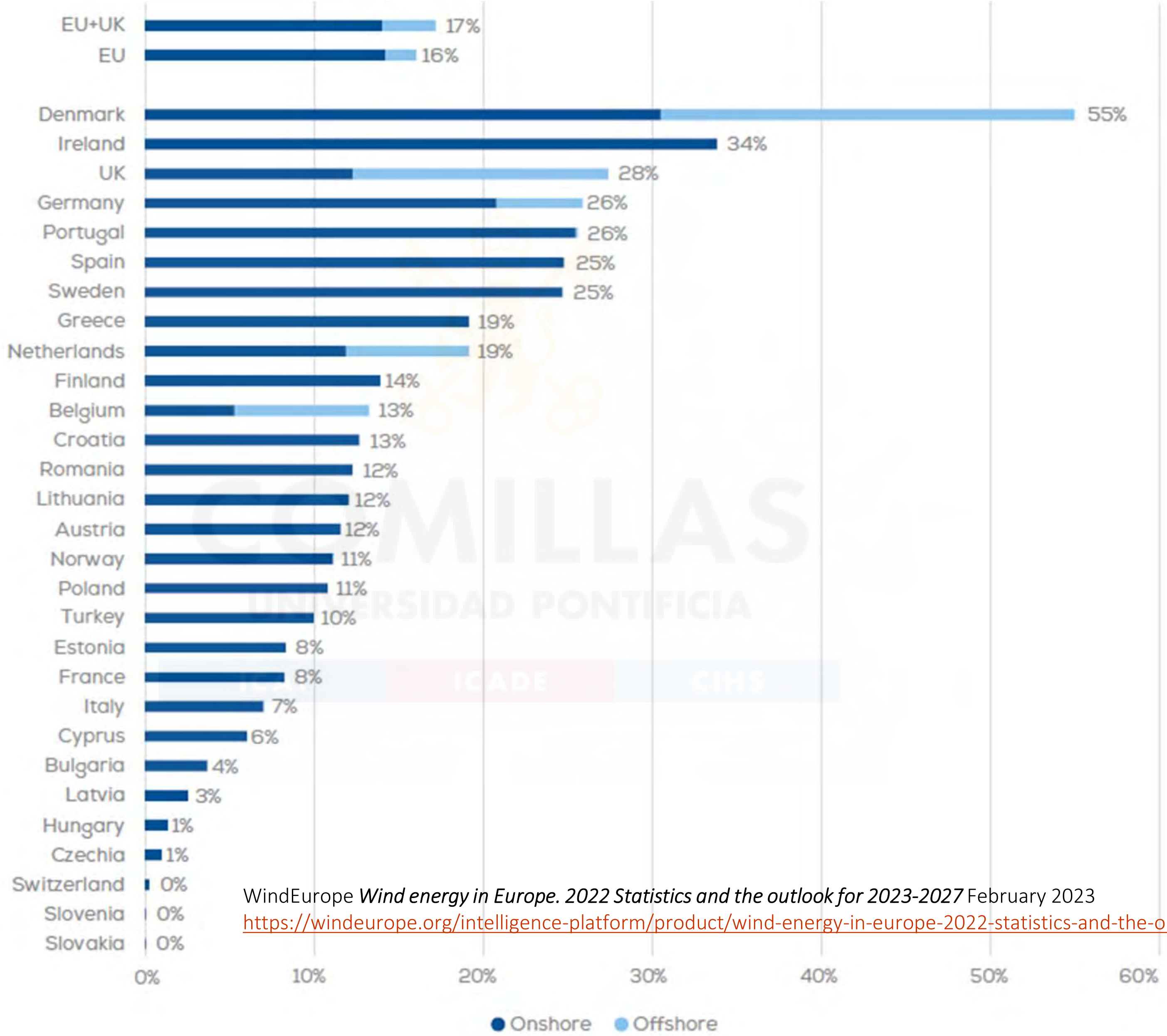
- Why have these three countries succeeded in integrating renewable generation?

Wind power became the main source of electricity generation in Spain in 2021



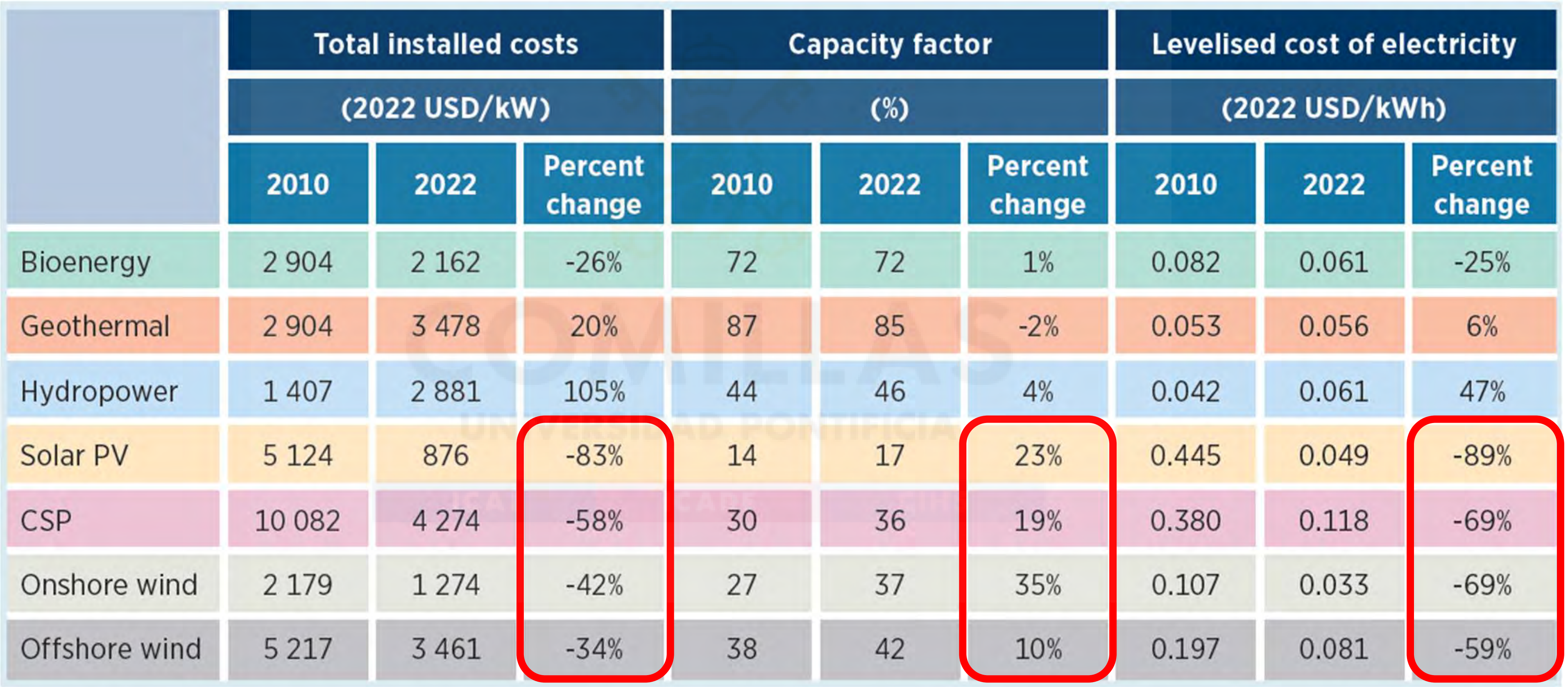
	2017	2018	2019	2020	2021
Hydro	18,447	34,114	24,716	30,628	29,579
Wind	47,508	48,956	53,101	53,802	59,175
Solar photovoltaic	8,001	7,381	8,852	14,925	20,465
Thermal solar	5,348	4,424	5,166	4,538	4,705
Other renewables	3,599	3,547	3,607	4,472	4,708
Renewable waste	728	733	739	606	751
Renewable generation	**83,631**	**99,155**	**96,181**	**108,971**	**119,383**
Pumped storage	2,249	1,994	1,646	2,751	2,649
Nuclear	55,539	53,198	55,824	55,758	54,040
Combined cycle	33,648	26,403	51,143	38,356	37,581
Coal	42,422	34,881	10,671	4,799	4,942
Fuel + Gas	0	0	0	0	0
Cogeneration	28,176	28,972	29,581	26,996	26,050
Non-renewable waste	2,459	2,294	2,072	1,897	2,108
Non-renewable generation	**164,493**	**147,741**	**150,936**	**130,558**	**127,371**
Pumped storage consumption	-3,608	-3,198	-3,027	-4,628	-4,347
Spanish peninsula - Baleari...	-1,179	-1,233	-1,695	-1,427	-890
Cross-border exchange bal...	9,169	11,102	6,862	3,280	884
Demand at busbars	**252,506**	**253,566**	**249,257**	**236,755**	**242,401**

Percentage of the average annual electricity demand covered by wind



WindEurope *Wind energy in Europe. 2022 Statistics and the outlook for 2023-2027* February 2023
https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2022-statistics-and-the-outlook-for-2023-2027/

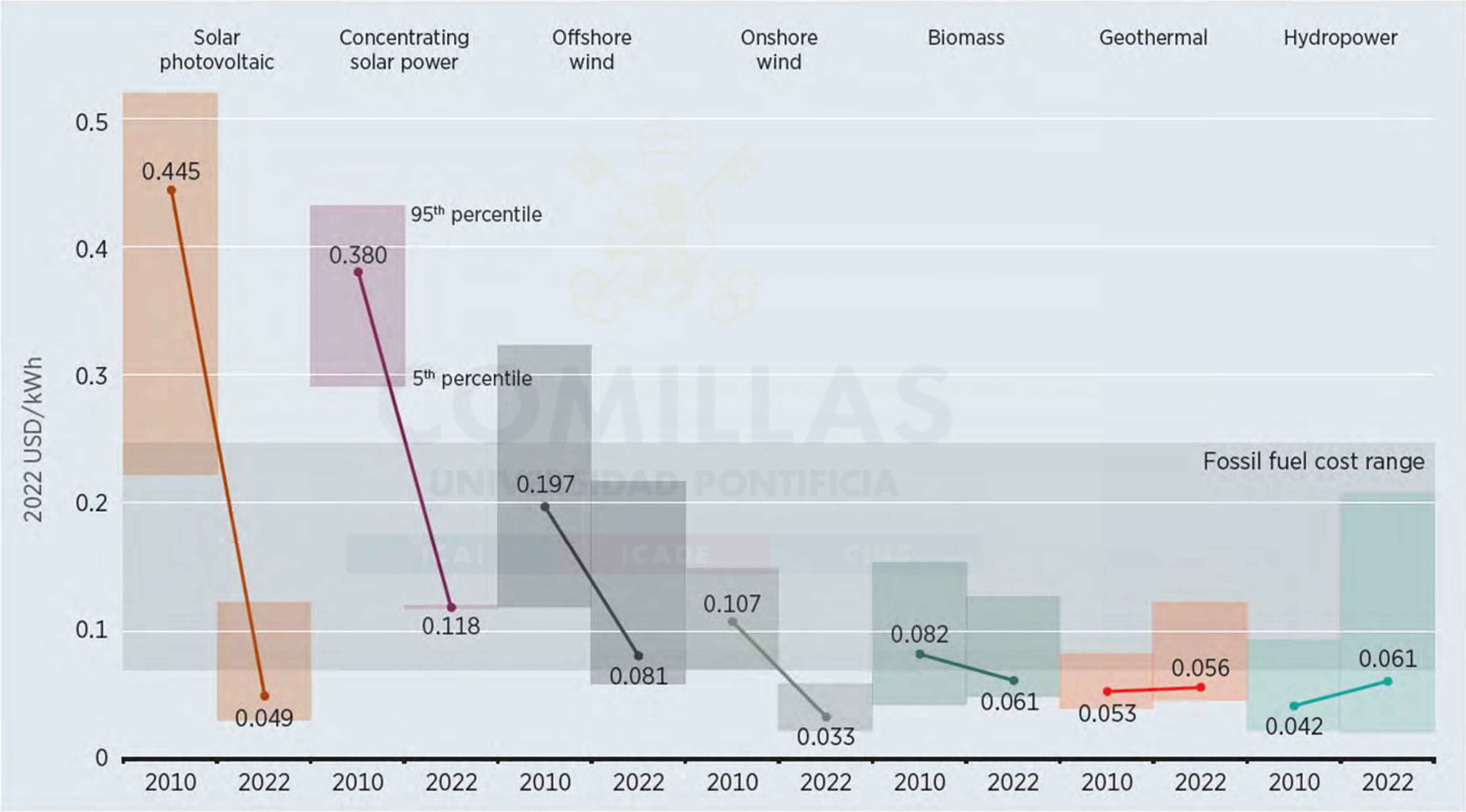
Total installed cost, capacity factor and levelized cost of electricity (LCOE) trends by technology, 2010 and 2022



	Total installed costs (2022 USD/kW)			Capacity factor (%)			Levelised cost of electricity (2022 USD/kWh)		
	2010	2022	Percent change	2010	2022	Percent change	2010	2022	Percent change
Bioenergy	2 904	2 162	-26%	72	72	1%	0.082	0.061	-25%
Geothermal	2 904	3 478	20%	87	85	-2%	0.053	0.056	6%
Hydropower	1 407	2 881	105%	44	46	4%	0.042	0.061	47%
Solar PV	5 124	876	-83%	14	17	23%	0.445	0.049	-89%
CSP	10 082	4 274	-58%	30	36	19%	0.380	0.118	-69%
Onshore wind	2 179	1 274	-42%	27	37	35%	0.107	0.033	-69%
Offshore wind	5 217	3 461	-34%	38	42	10%	0.197	0.081	-59%

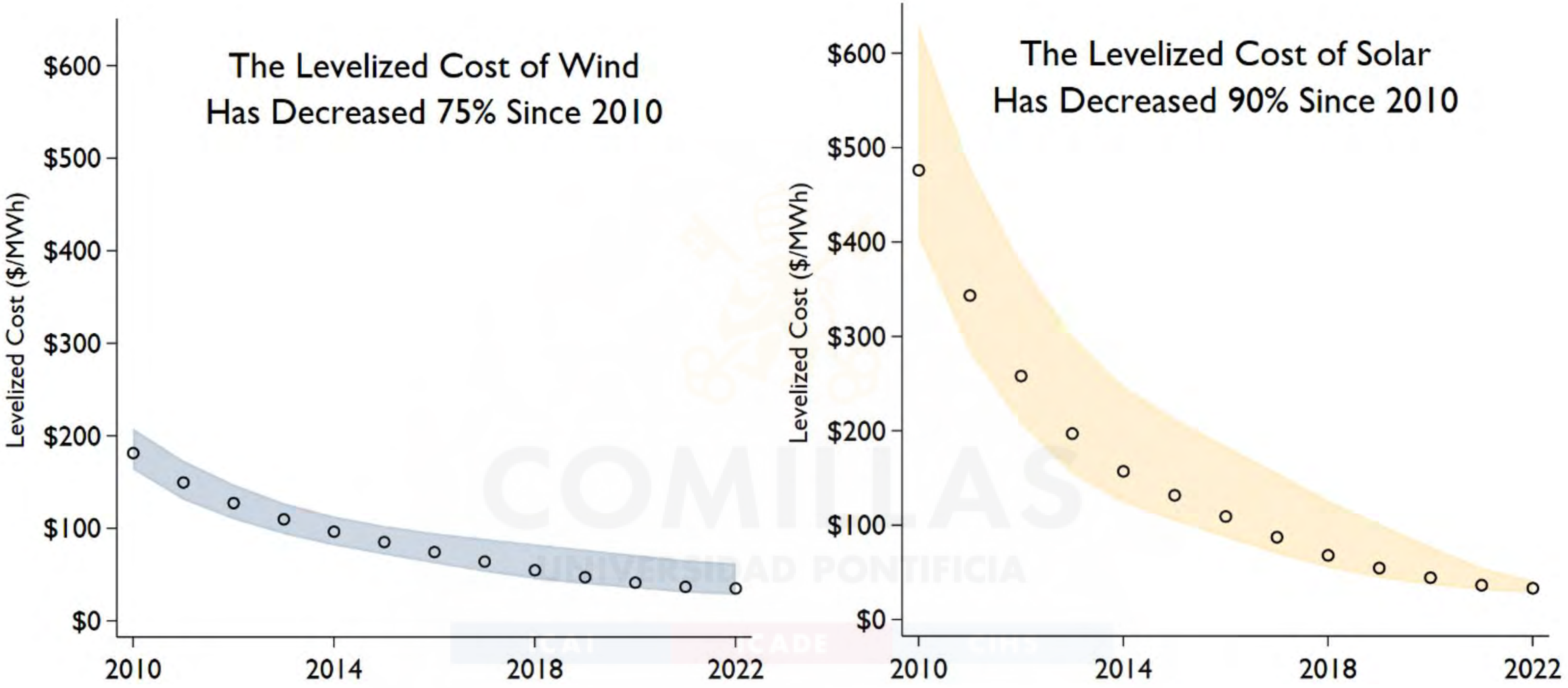
IRENA (2022) *Renewable Power Generation Costs in 2022*
https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022

Global LCOEs from newly commissioned, utility-scale renewable power generation technologies, 2010-2022



IRENA (2022) *Renewable Power Generation Costs in 2022*
https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022

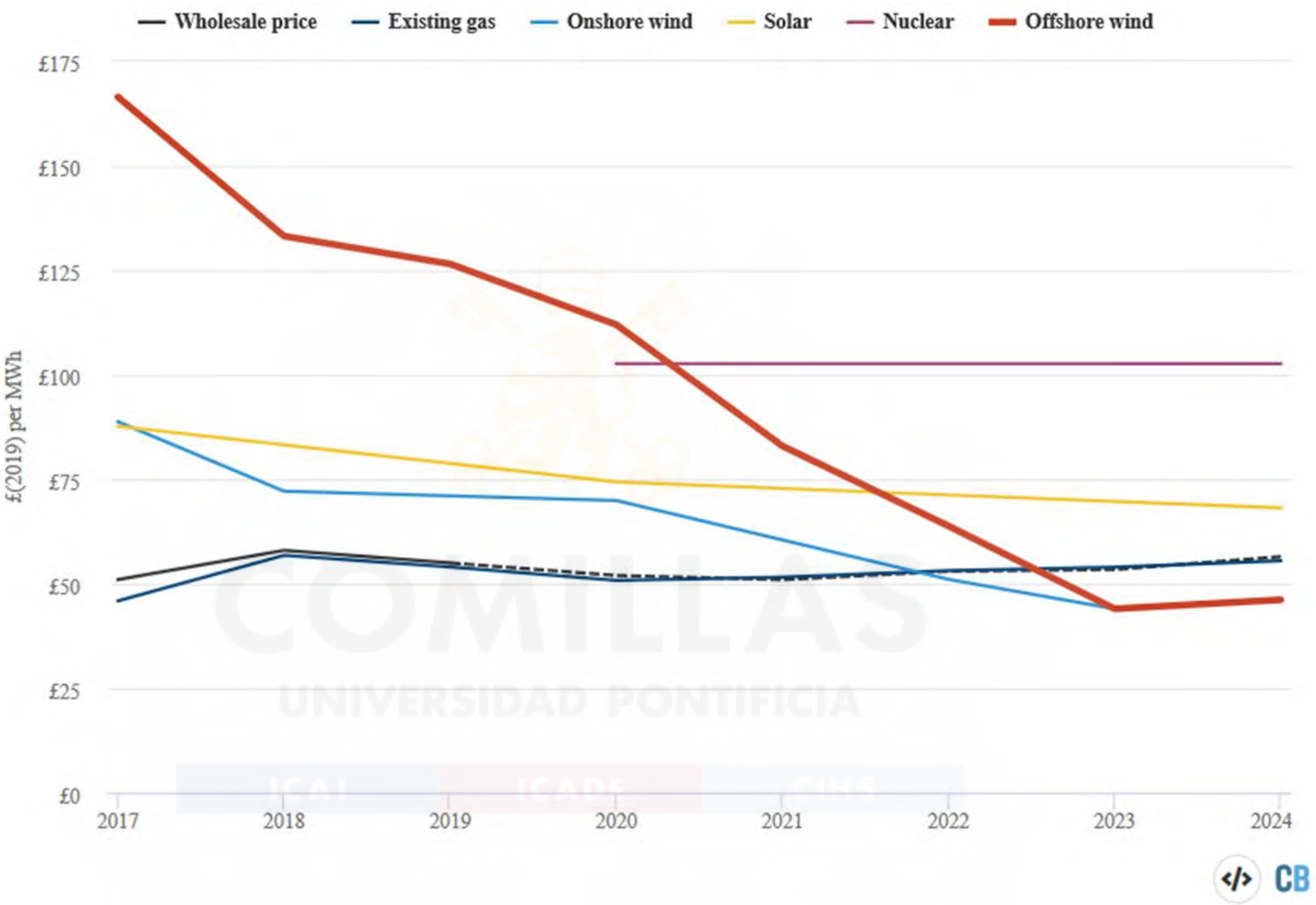
Decreasing Cost of Grid-Scale Renewables in the USA



Note: This figure was created by the authors using levelized costs calculations from the US Department of Energy (2010-2022), and reflects lifetime project costs including construction, financing, and operations. The circles indicate the US average levelized cost in each year without tax credits for onshore wind and solar photovoltaics. The range indicates regional variation. A small amount of smoothing has been applied to emphasize the overall pattern rather than idiosyncratic year-to-year fluctuations. All values in the paper have been deflated to reflect year 2022 dollars.

L. Davis, C. Hausman, and N. Rose "Transmission Impossible? Prospects for Decarbonizing the US Grid"
Energy Institute at HAAS WP 338. June 2023

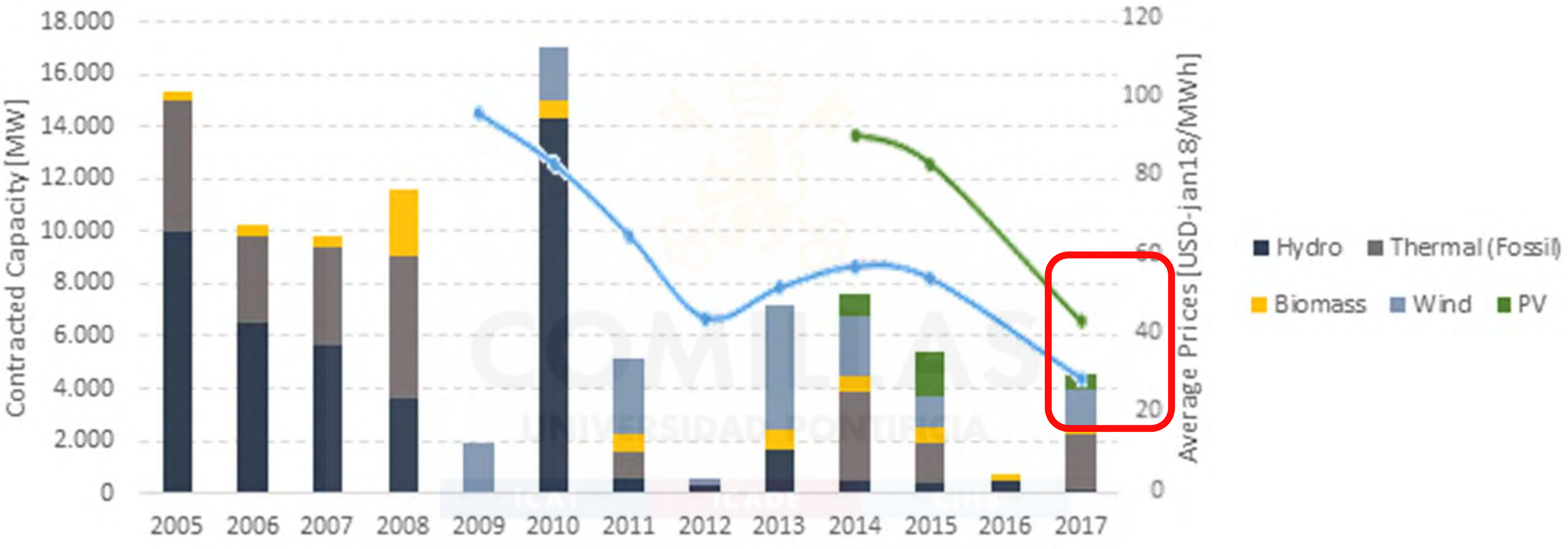
UK Offshore Wind Strike Prices for 2023 auctioned in 2019



Cost of UK electricity generation in £/MWh (current prices) for various technologies. Wholesale prices are actual (solid black line) and projected (dashed line), using the BEIS intermittent reference price for 2023 and 2024 from today's auction. Costs for existing gas generation based on Carbon Brief analysis, using wholesale gas and CO2 price projections from BEIS, with estimates of operational and maintenance costs from Cornwall Energy. Renewable costs reflect contracts awarded in £2012, adjusted for inflation to today's prices. Solar prices in the 2020s based on 2016 BEIS projections, which are likely a significant overestimate. Sources: BEIS projections, CfD auction results and Cornwall Energy. Chart by Carbon Brief using Highcharts.

https://www.carbonbrief.org/analysis-record-low-uk-offshore-wind-cheaper-than-existing-gas-plants-by-2023

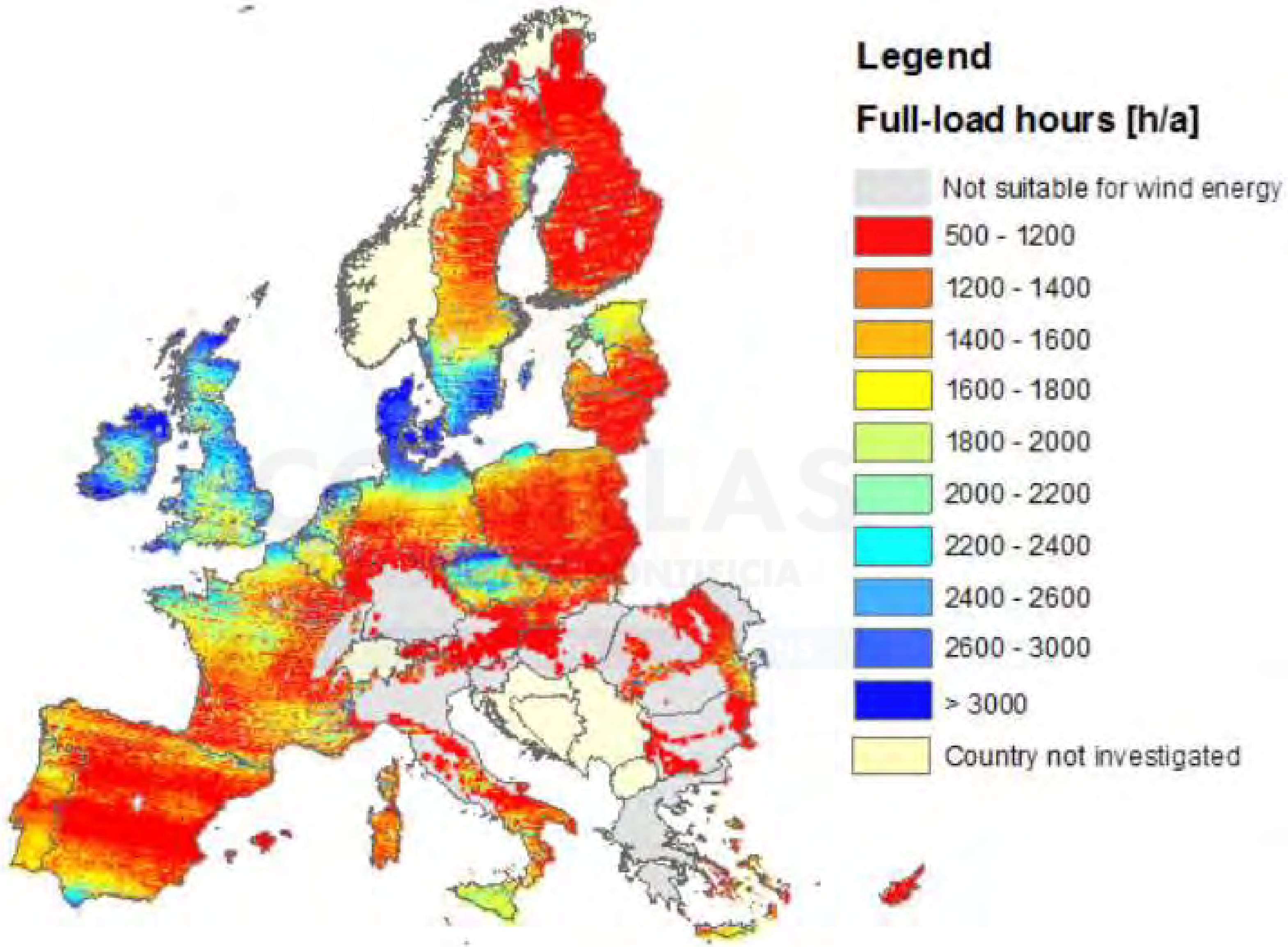
Brazil: wind & solar auction results



Data: CCEE, IPEA (2018)

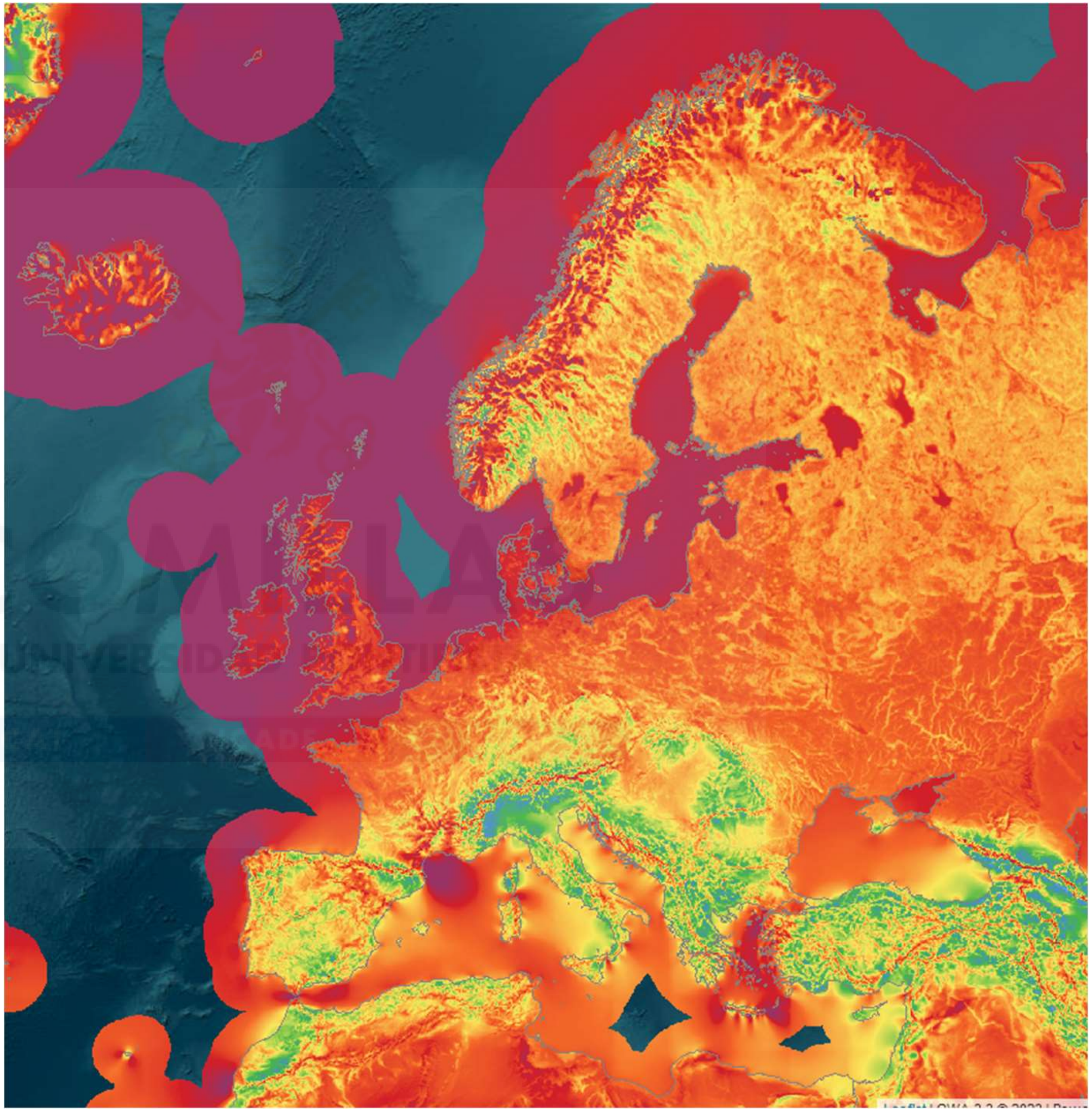
Source: L. Barroso. PSR

Annual full-load hours for onshore wind energy



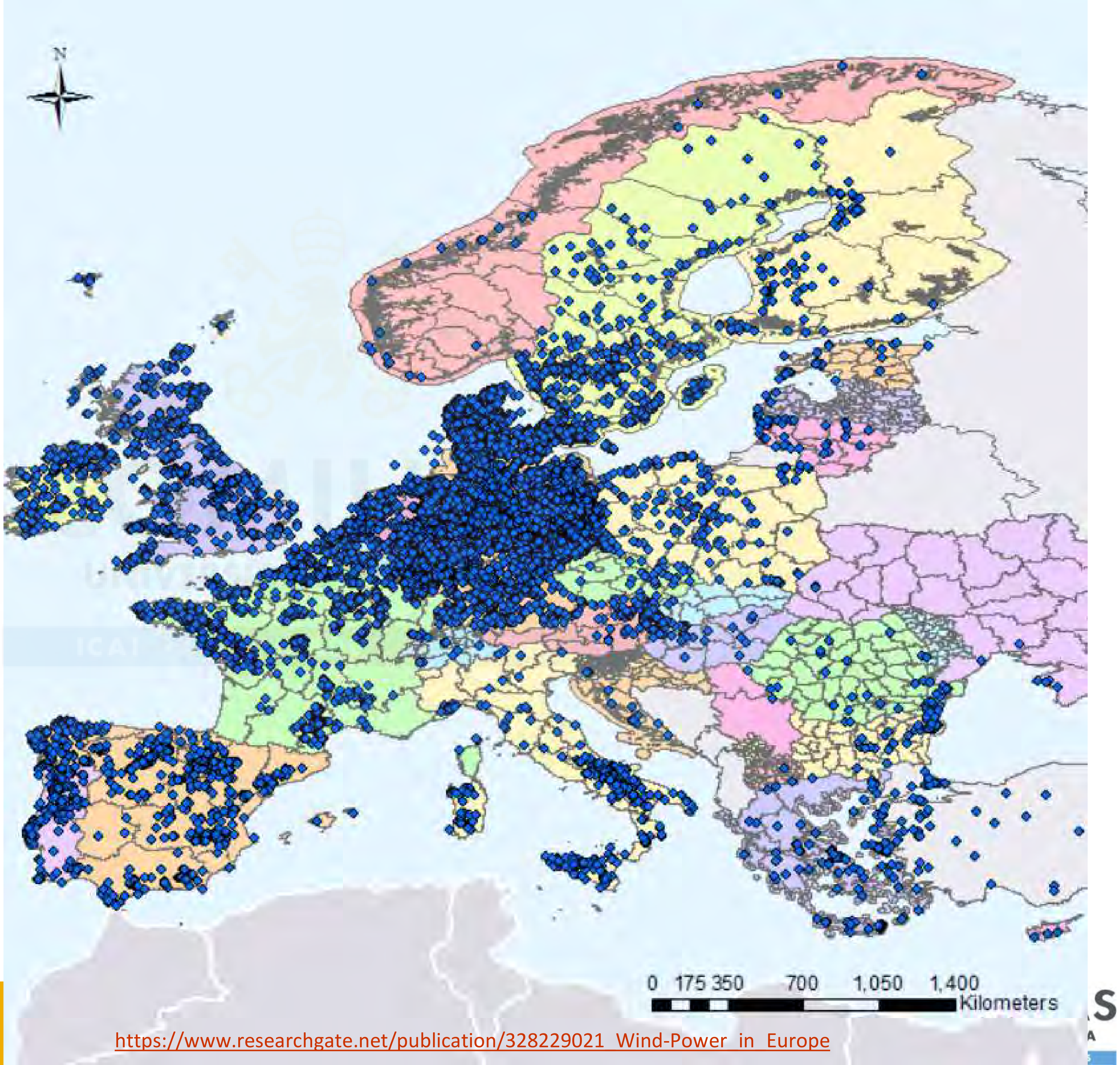
https://green-x.at/RS-potdb/potdb-long_term_potentials.php

Global Wind Atlas at 100 m



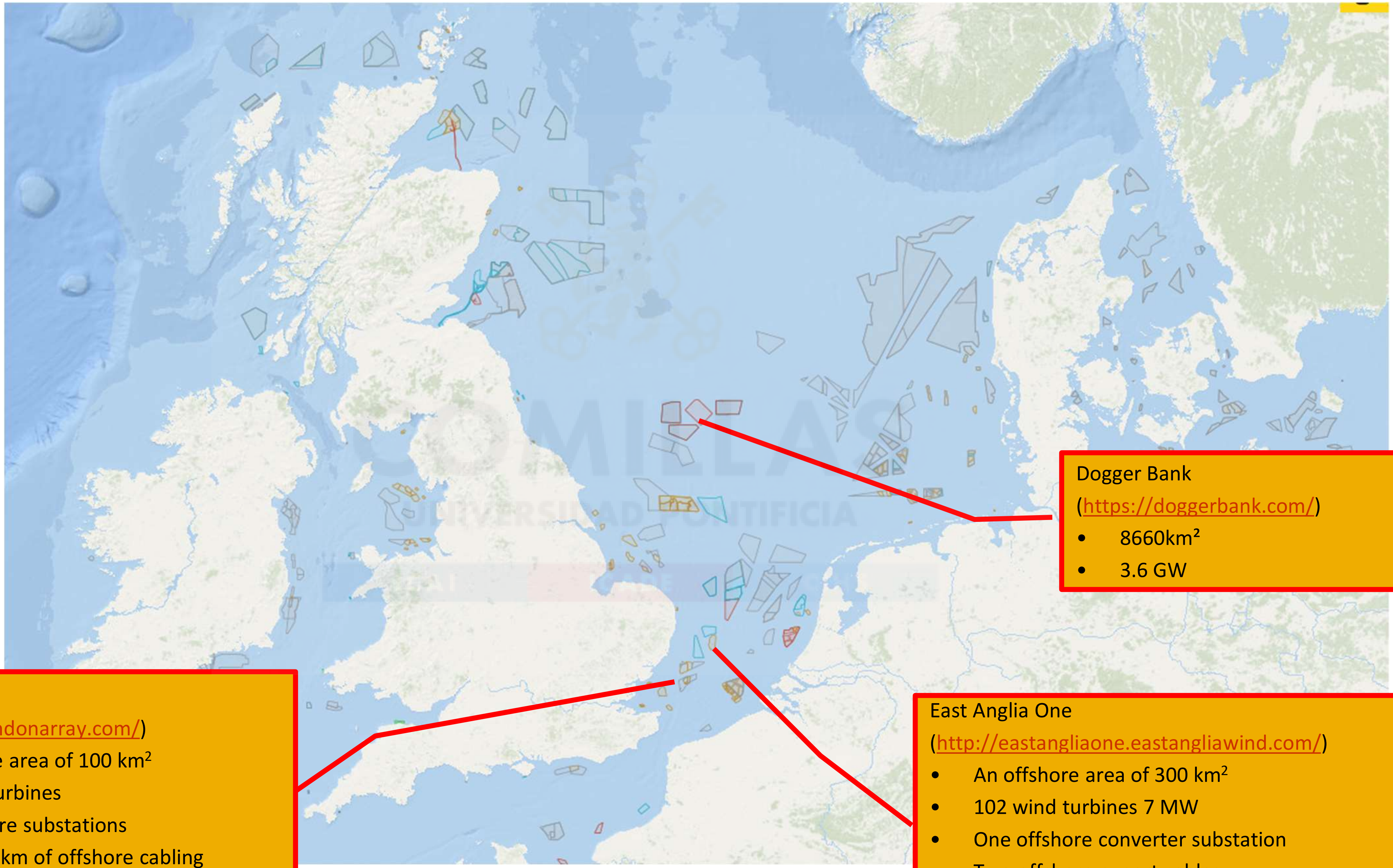
https://globalwindatlas.info/en

Map of European wind farms



https://www.researchgate.net/publication/328229021_Wind-Power_in_Europe

Off-shore wind farms in the North Sea and Baltic Sea



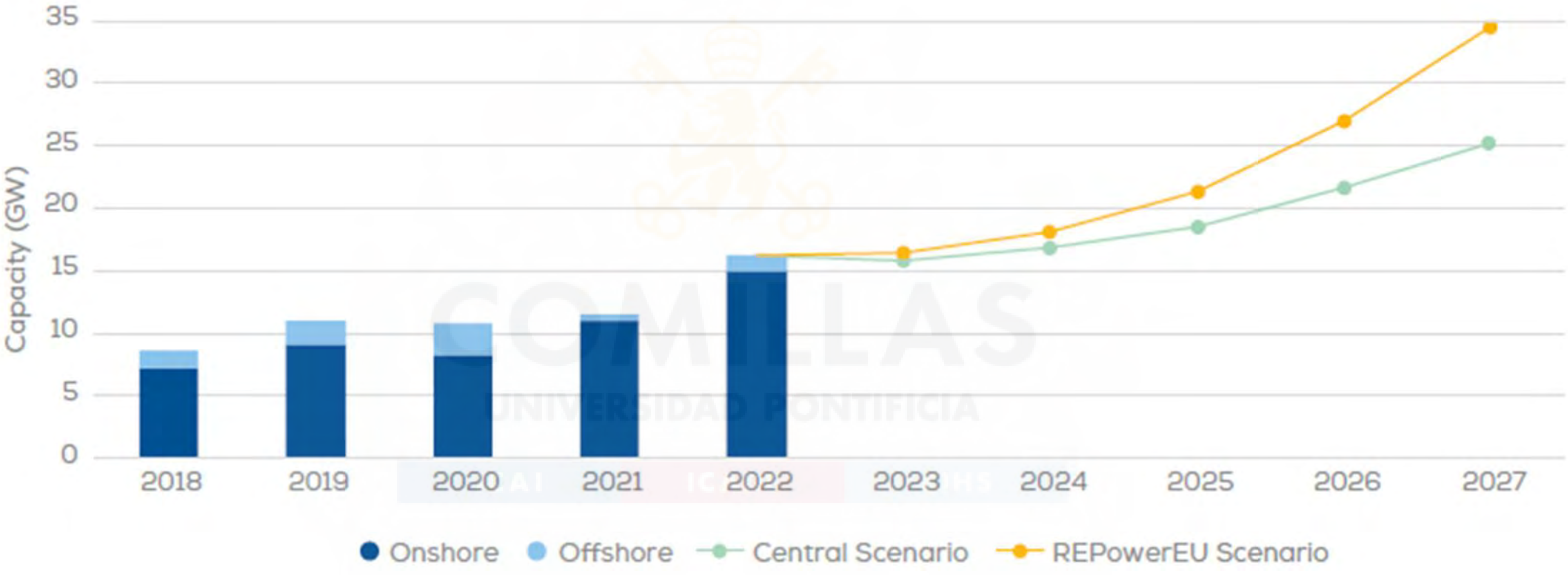
Dogger Bank
(https://doggerbank.com/)
- 8660km²
- 3.6 GW

London Array
(http://www.londonarray.com/)
- An offshore area of 100 km²
- 175 wind turbines
- Two offshore substations
- Nearly 450 km of offshore cabling
- One onshore substation
- 630 MW of capacity

East Anglia One
(http://eastangliaone.eastangliawind.com/)
- An offshore area of 300 km²
- 102 wind turbines 7 MW
- One offshore converter substation
- Two offshore export cables
- 714 MW of capacity

https://www.4coffshore.com/offshorewind/

2023-2027 new onshore and offshore wind installations in Europe – WindEurope's scenarios



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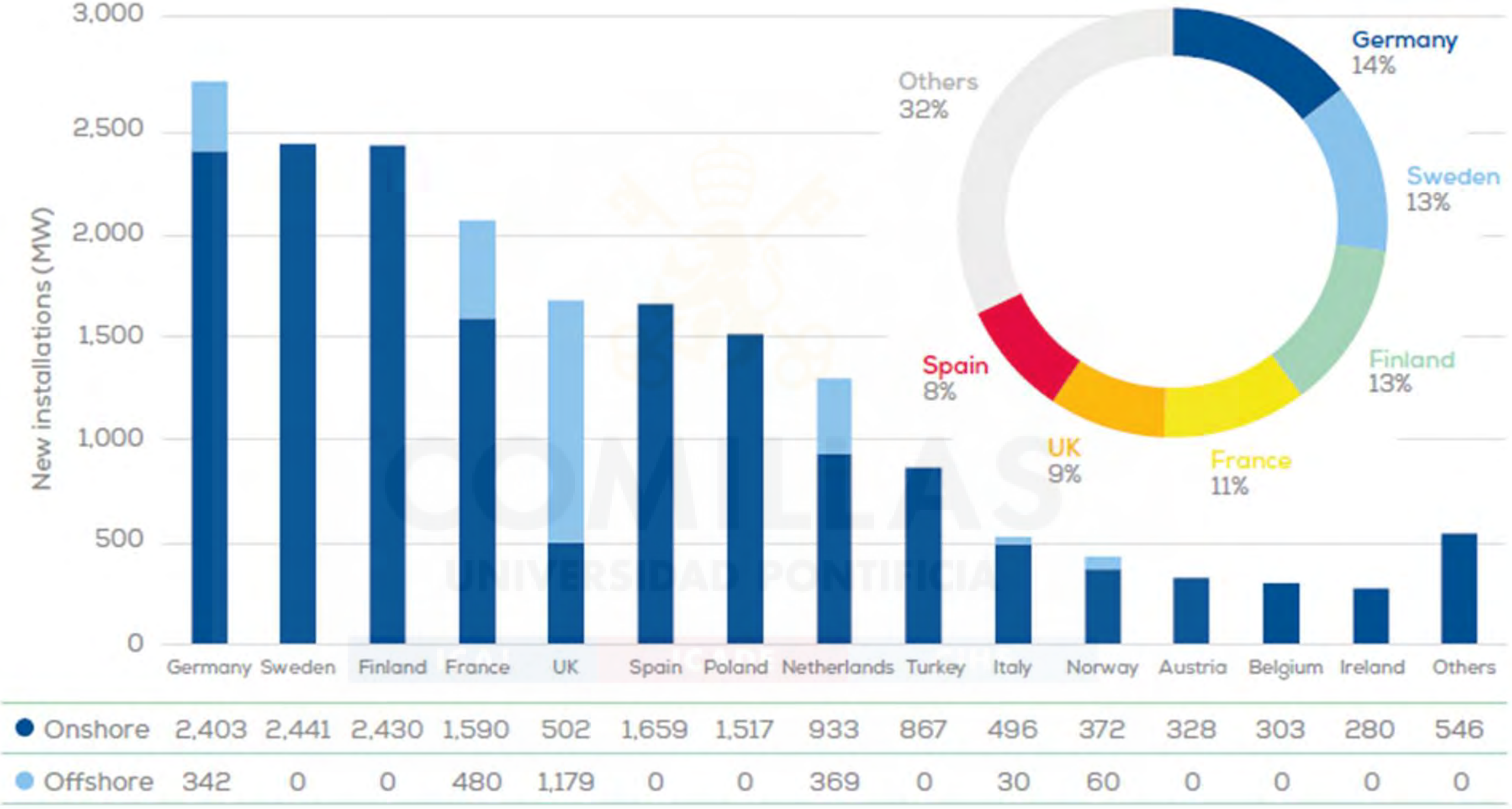
https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2022-statistics-and-the-outlook-for-2023-2027/

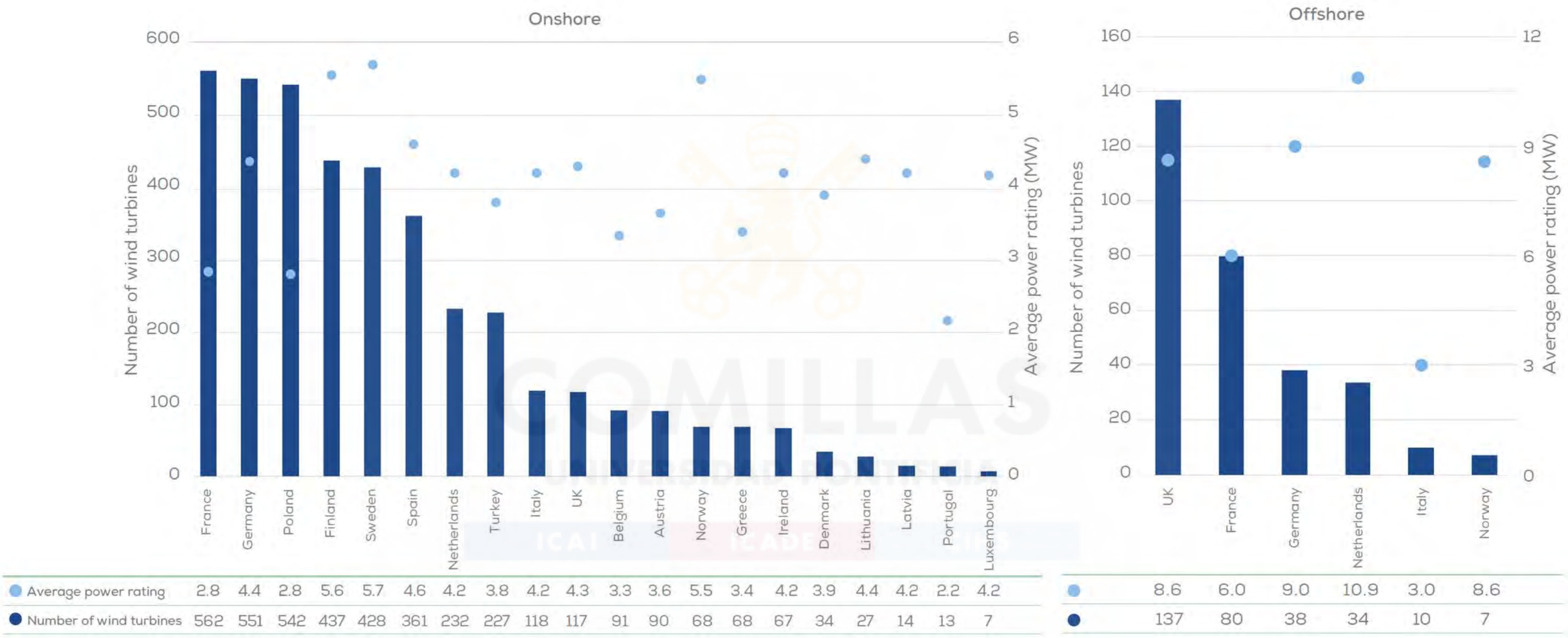
New wind installations in Europe per country in 2022



	Germany	Sweden	Finland	France	UK	Spain	Poland	Netherlands	Turkey	Italy	Norway	Austria	Belgium	Ireland	Others
● Onshore	2,403	2,441	2,430	1,590	502	1,659	1,517	933	867	496	372	328	303	280	546
● Offshore	342	0	0	480	1,179	0	0	369	0	30	60	0	0	0	0

WindEurope *Wind energy in Europe. 2022 Statistics and the outlook for 2023-2027* February 2023
https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2022-statistics-and-the-outlook-for-2023-2027/

Number of turbines installed in 2022 and their average power rating



Onshore

	France	Germany	Poland	Finland	Sweden	Spain	Netherlands	Turkey	Italy	UK	Belgium	Austria	Norway	Greece	Ireland	Denmark	Lithuania	Latvia	Portugal	Luxembourg
● Average power rating	2.8	4.4	2.8	5.6	5.7	4.6	4.2	3.8	4.2	4.3	3.3	3.6	5.5	3.4	4.2	3.9	4.4	4.2	2.2	4.2
● Number of wind turbines	562	551	542	437	428	361	232	227	118	117	91	90	68	68	67	34	27	14	13	7

Offshore

	UK	France	Germany	Netherlands	Italy	Norway
●	8.6	6.0	9.0	10.9	3.0	8.6
●	137	80	38	34	10	7

WindEurope *Wind energy in Europe. 2022 Statistics and the outlook for 2023-2027* February 2023
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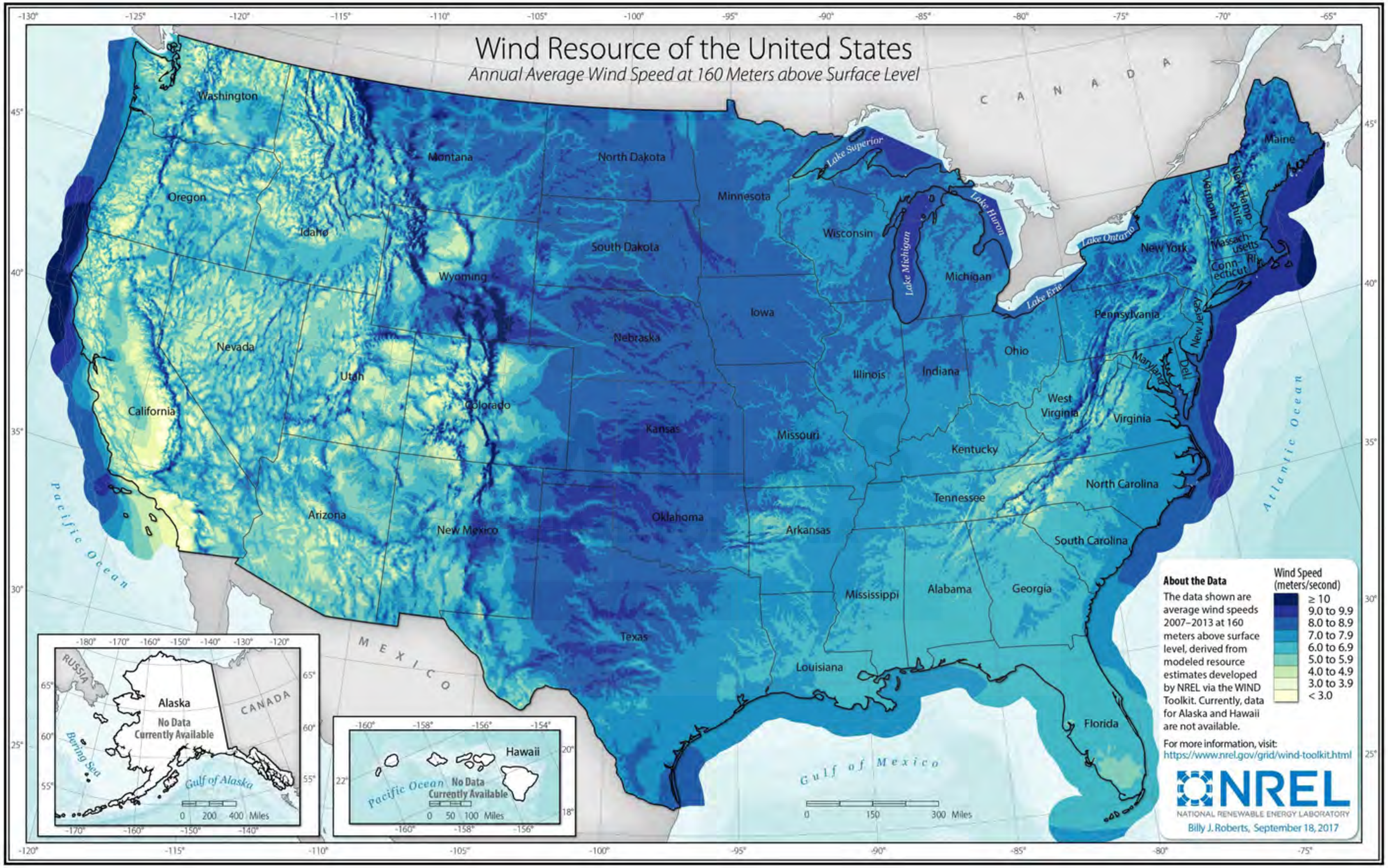
US Wind Speed at 100-Meters above Surface Level



Wind Resource of the United States

Annual Average Wind Speed at 160 Meters above Surface Level

About the Data

The data shown are average wind speeds 2007–2013 at 160 meters above surface level, derived from modeled resource estimates developed by NREL via the WIND Toolkit. Currently, data for Alaska and Hawaii are not available.

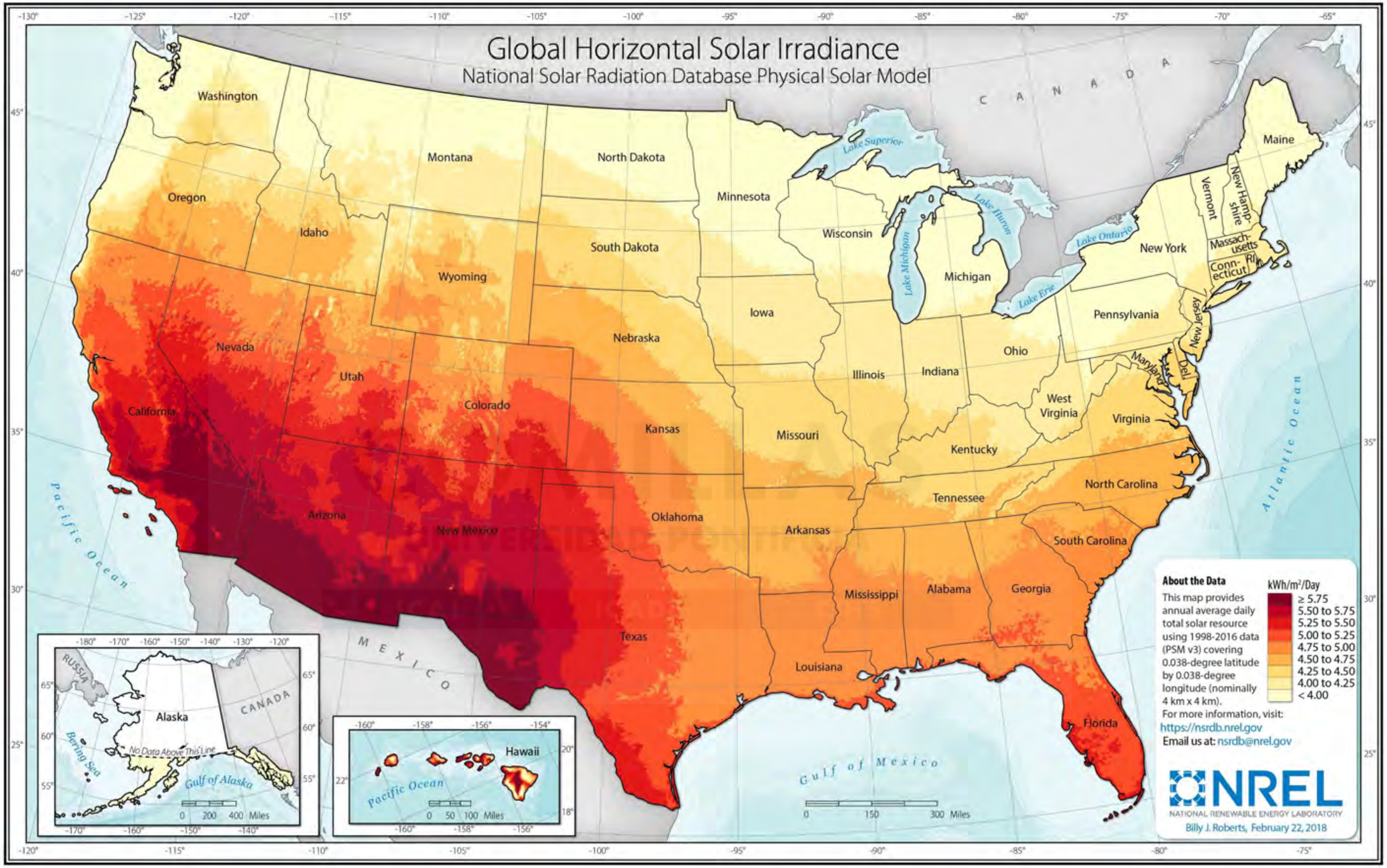
For more information, visit: https://www.nrel.gov/grid/wind-toolkit.html

NATIONAL RENEWABLE ENERGY LABORATORY

Billy J. Roberts, September 18, 2017

https://www.nrel.gov/gis/wind-resource-maps.html

US Global Horizontal Solar Irradiance



https://www.nrel.gov/gis/solar-resource-maps.html

US Offshore Wind Power Plans

U.S. Offshore Wind Power Plans

Along the East Coast, one of the world's richest wind resources, companies have leased vast areas of federal waters for developing wind power projects. Only one small wind farm, Block Island, is currently in operation.

SOURCE: Bureau of Ocean Energy Management

PAUL HORN / InsideClimate News

Source: Bureau of Ocean Energy Management (BOEM)

CECRE: Control Centre of Renewable Energies (video)

https://www.ree.es/en/press-office/video-library/corporate/cecre-control-centre

Observability

Controllability

CECRE: Control Centre of Renewable Energies (infograph)

Cecre (Control Centre of Renewable Energies)

In order to address the peculiarities of renewable energies, since 2006 in Spain we have counted on Cecre (Control Centre of Renewable Energies), a pioneering initiative set up by Red Eléctrica.

Its objective is to integrate into the electricity system the greatest quantity of renewable energy possible whilst maintaining the levels of quality and guaranteeing the security of the supply.

Cecre
Is the first centre in the world used for controlling and managing the electricity generation obtained from renewable energy producers, primarily wind farms.

CECRE is the first center in the world for controlling and managing the electricity generated from renewable energy producers, primarily wind farms, which makes it possible to integrate the maximum production of renewable energy into the electricity system while maintaining the levels of quality and guaranteeing the security of supply.

What has been the trick to integrate renewables in Spain?

- The integration into the system through generation control centers
  - Using 23 control centers (in 2010) of the generation companies, which act as interlocutors, CECRE receives every 12 seconds real-time information about each facility’s status of the grid connection, production, and voltage at the connection point. This data is used by a sophisticated tool that verifies whether the total generation obtained from renewable energies can be integrated at any moment into the electricity system without affecting the security of supply. Supervises and controls the production of renewable generation facilities or units larger than 5 MW
  - 36 centers in February 2021
  - Many of them can provide power control (secondary reserve)

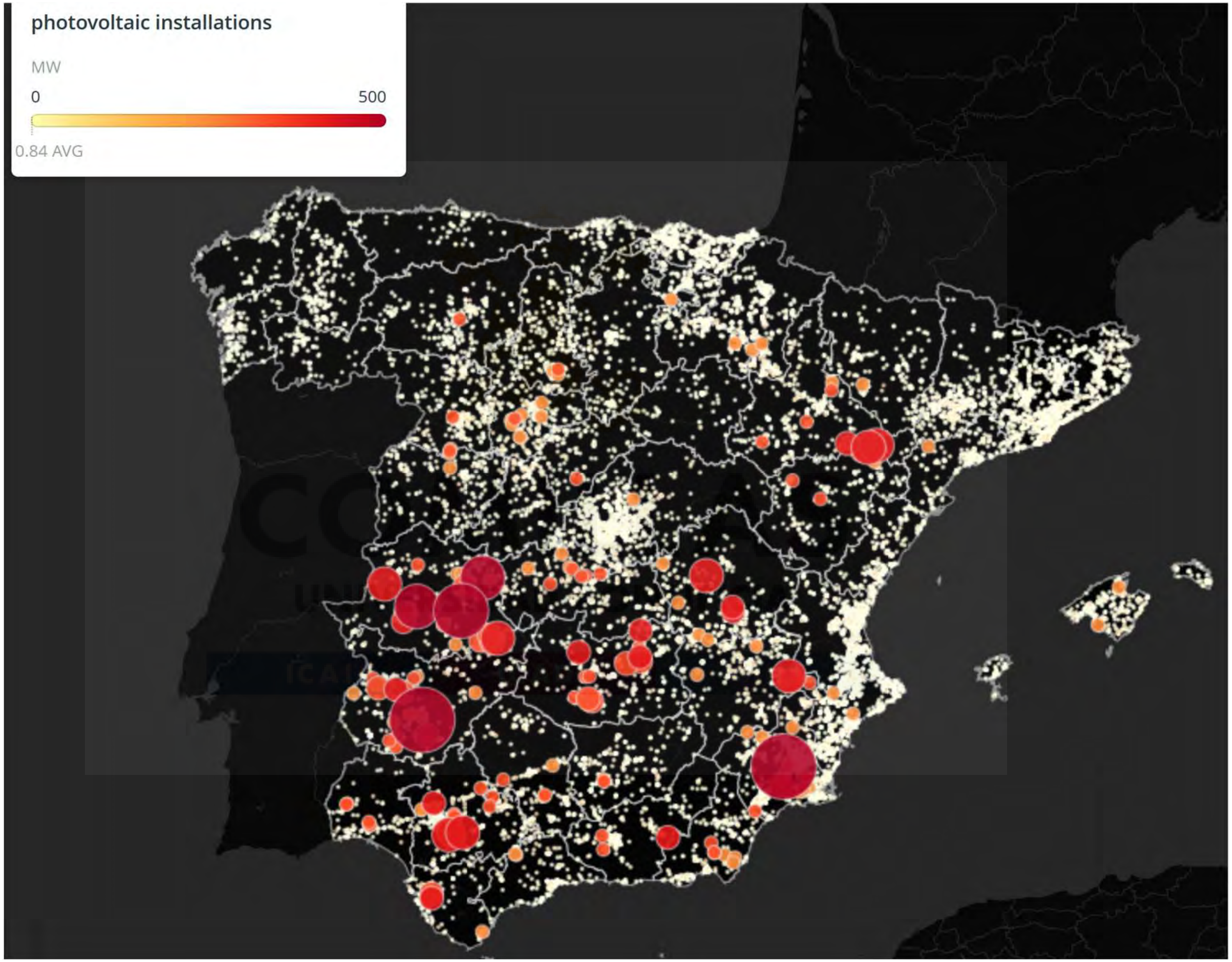
Wind farms in mainland Spain (October 2023)

https://www.esios.ree.es/en/interesting-maps/wind-installations-map

Solar thermal power plants in mainland Spain (October 2023)

https://www.esios.ree.es/en/interesting-maps/solar-thermal-installations-map

Solar PV power plants in mainland Spain (October 2023)

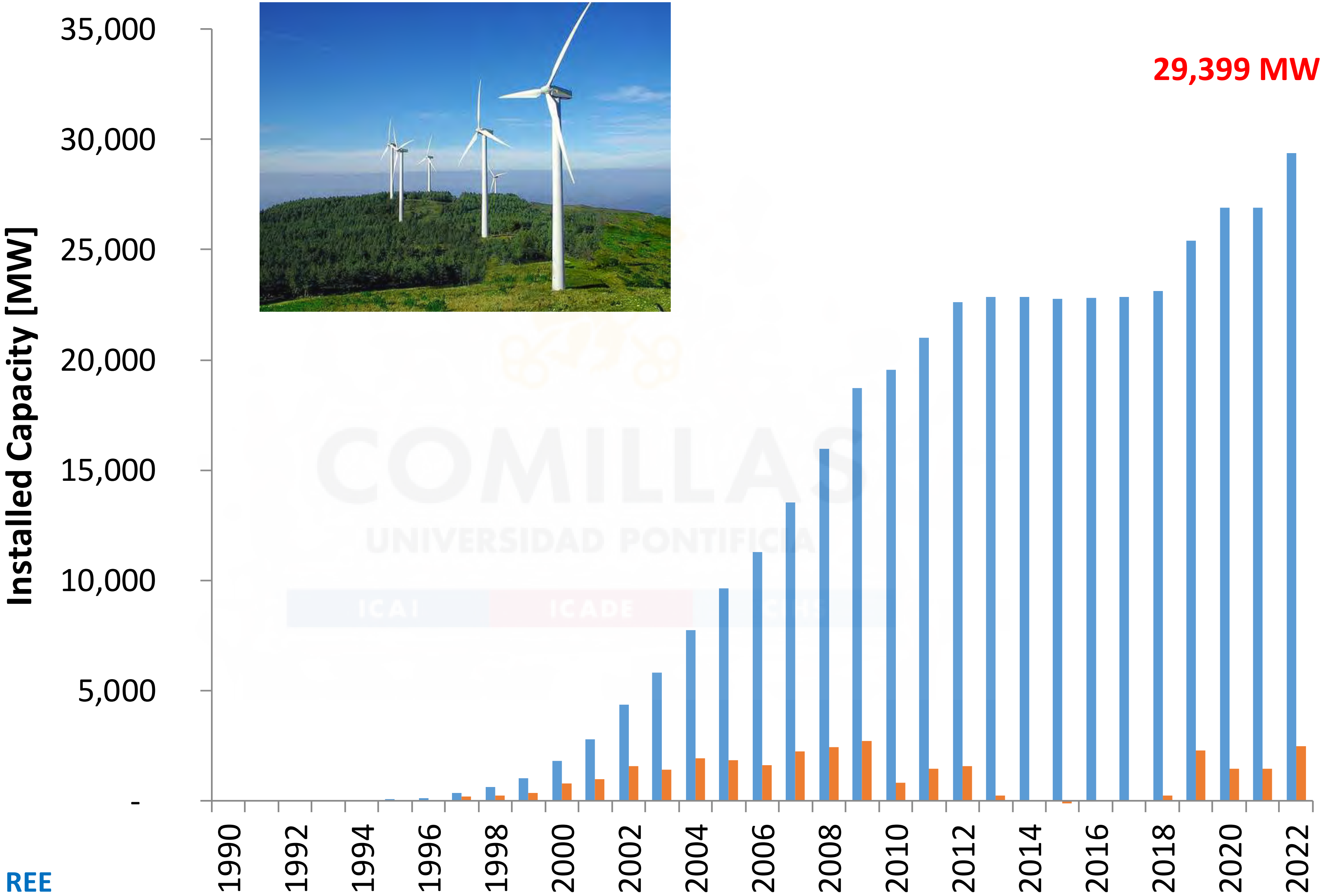


https://www.esios.ree.es/en/interesting-maps/solar-pv-installations-map

Renewable power plants time-lapse map (1998-2017)

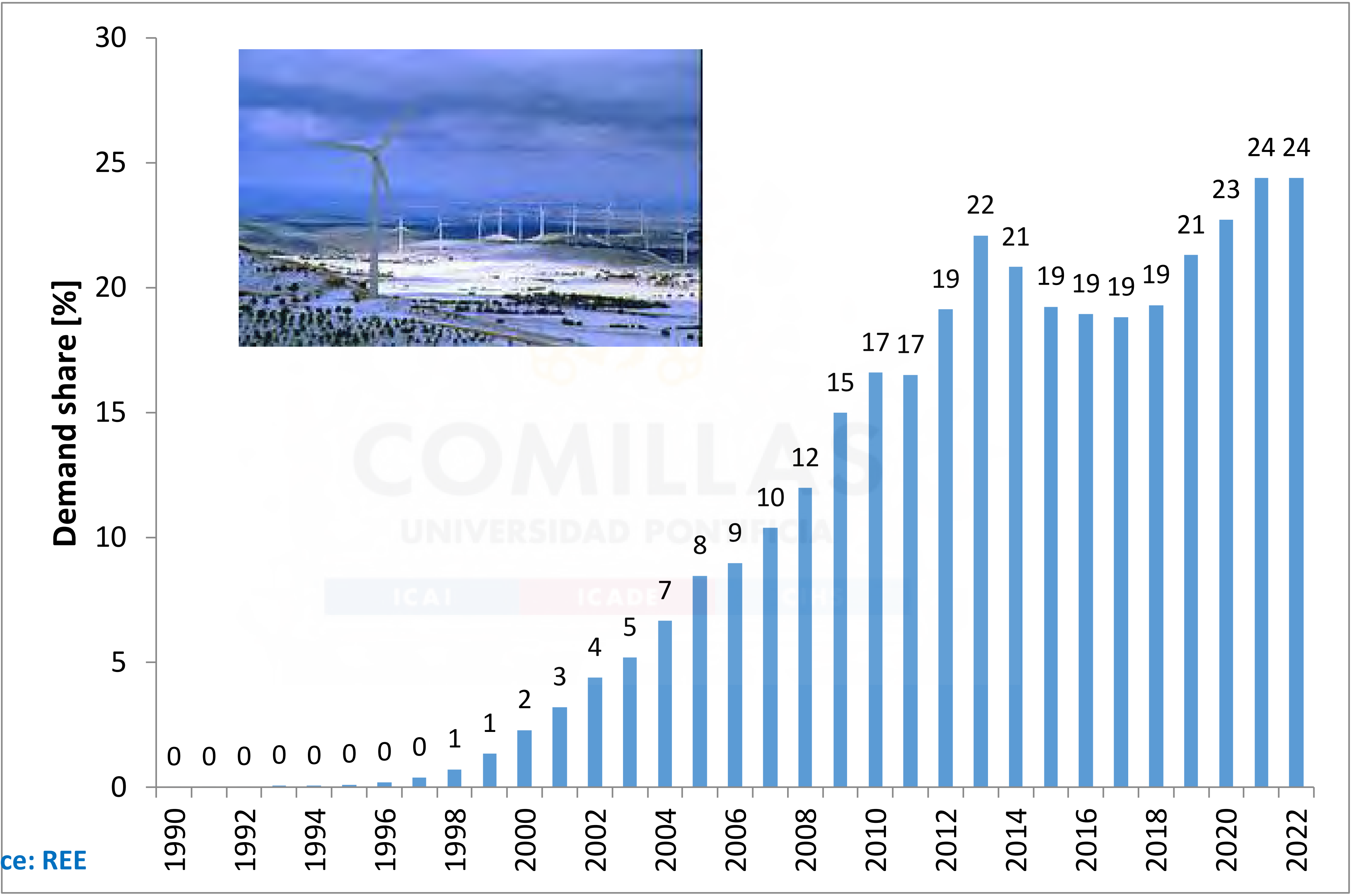
https://www.esios.ree.es/en/interesting-maps/renewable-installations-production-time-lapse-map

Installed capacity of WP



Source: REE

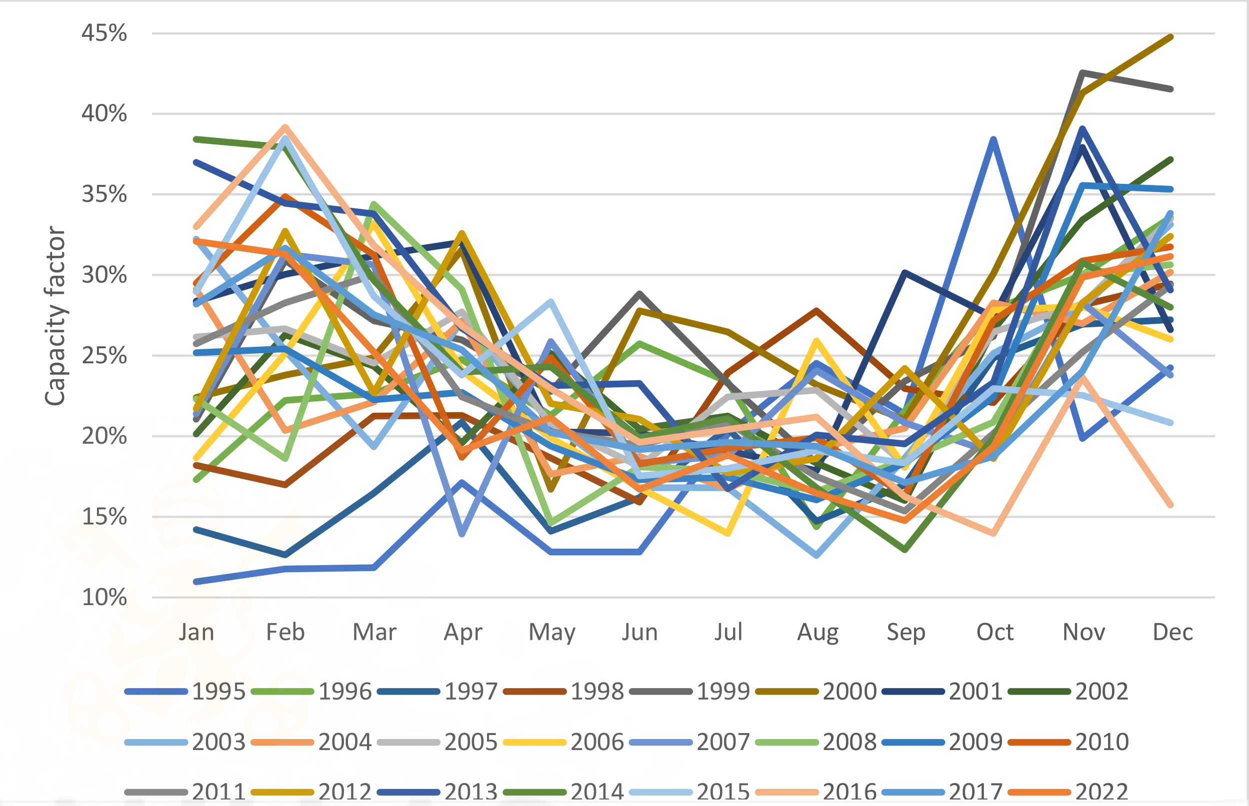
Demand share of WP

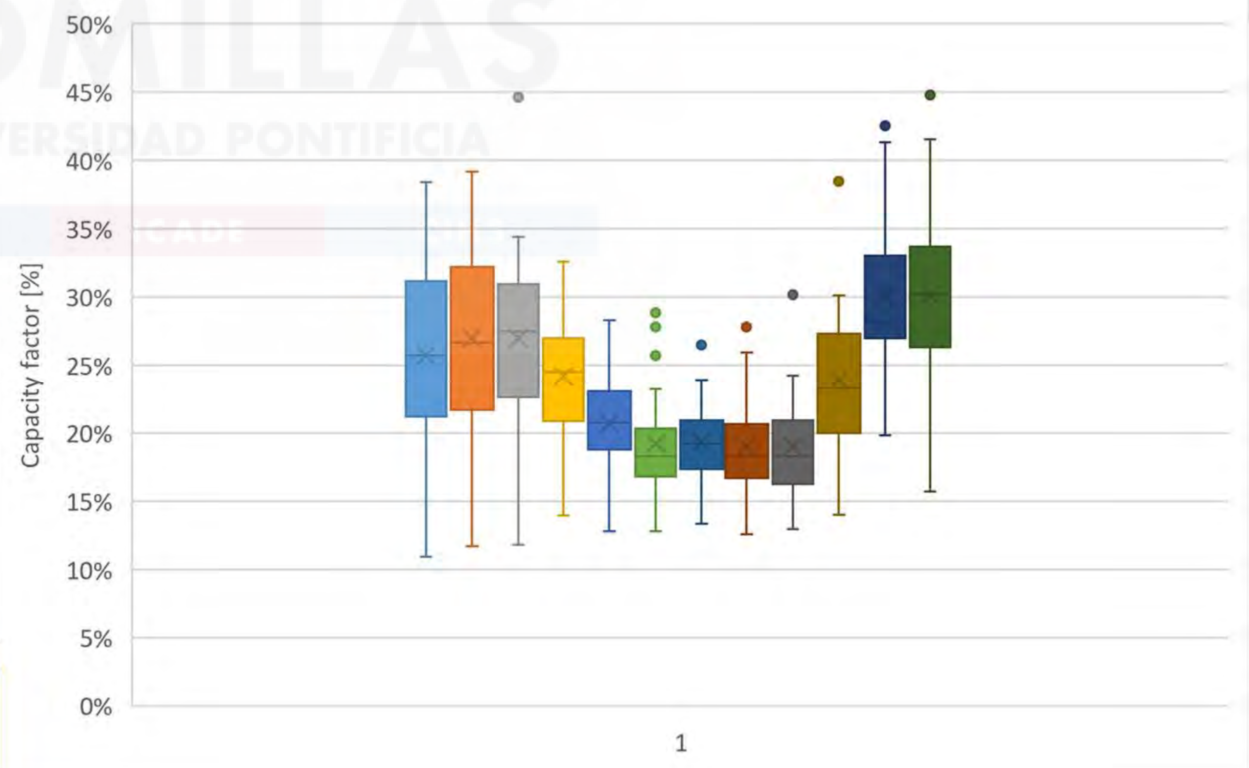


Source: REE

Monthly WP capacity factor

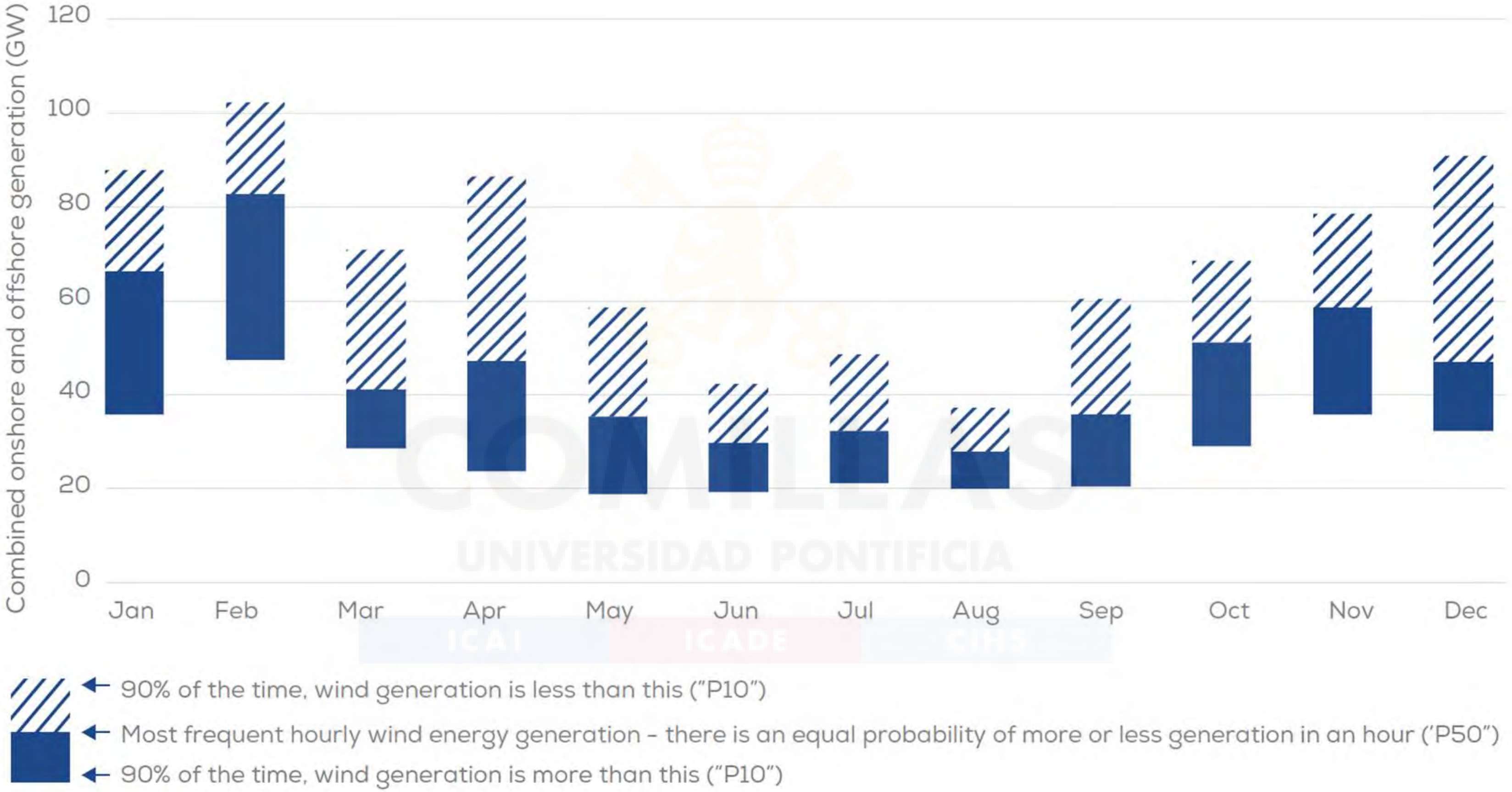
A Spanish saying:
Marzo ventoso y abril lluvioso sacan a mayo florido y hermoso
(March winds and April showers bring forth May flowers)





http://cvc.cervantes.es/lengua/refranero/ficha.aspx?Par=59017&L

Spread of hourly wind energy generation in the EU+UK in 2022



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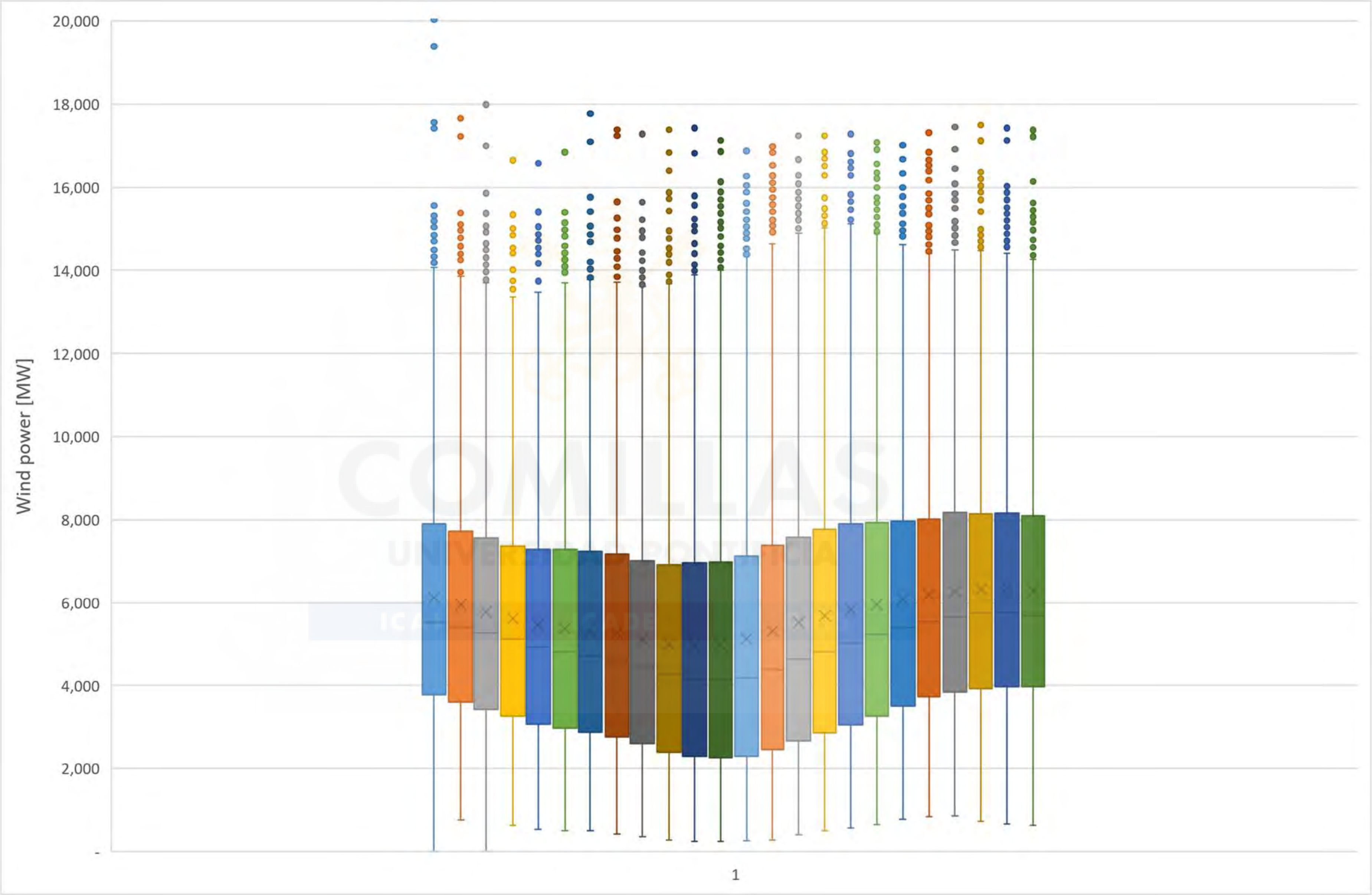
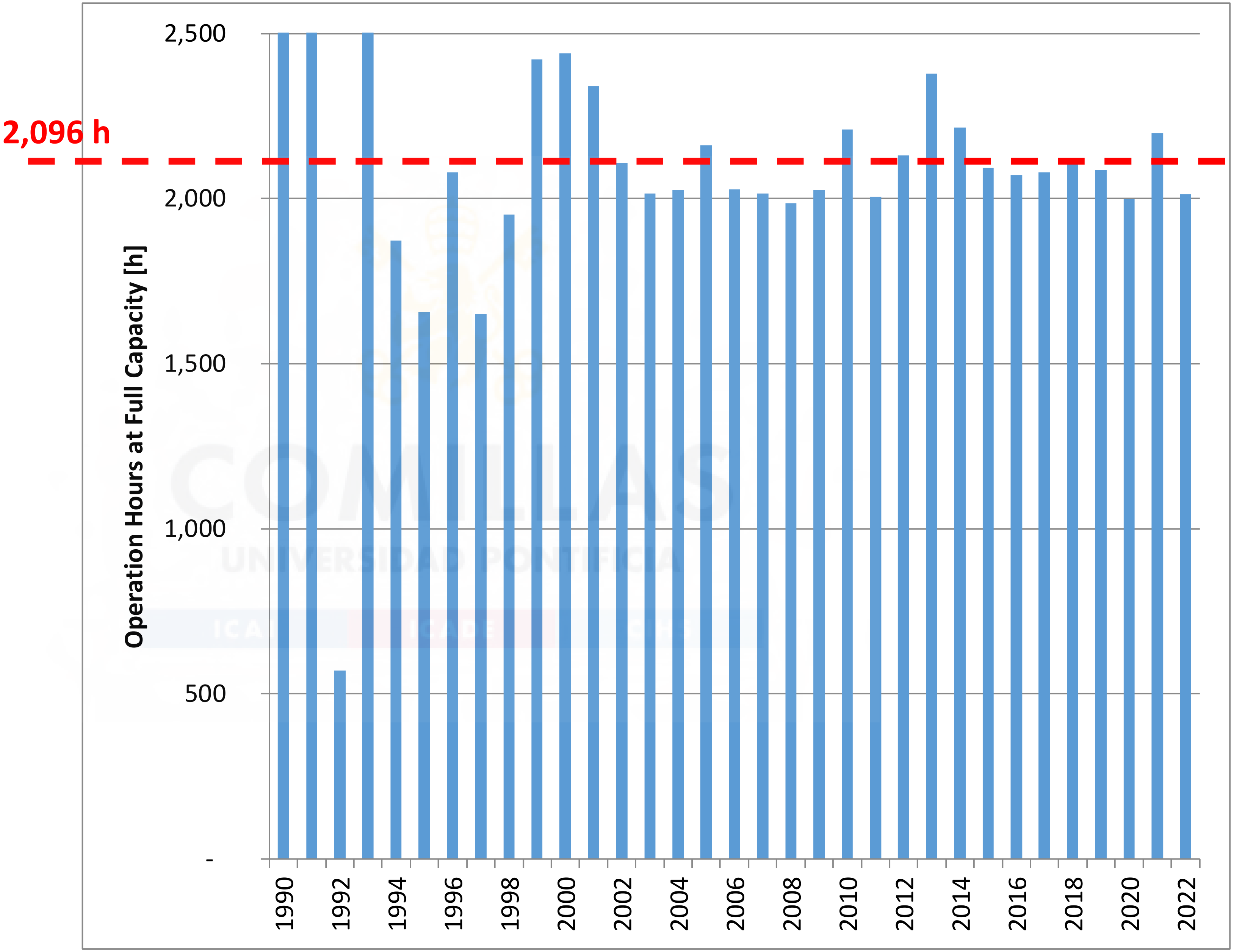
Hourly WP 2014-2022

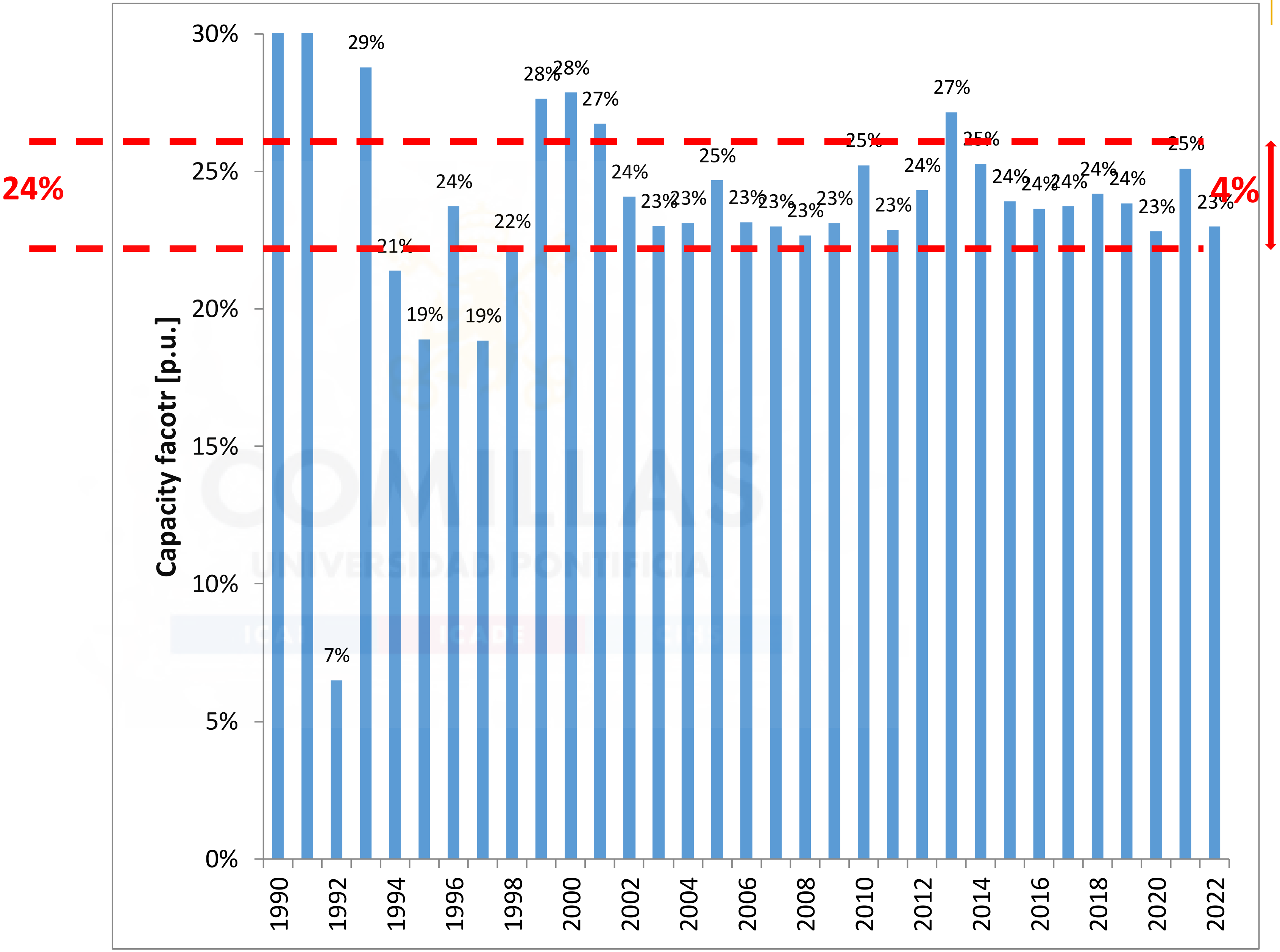


WP Operation hours at full capacity



Source: REE

Yearly WP Capacity factor



Source: REE

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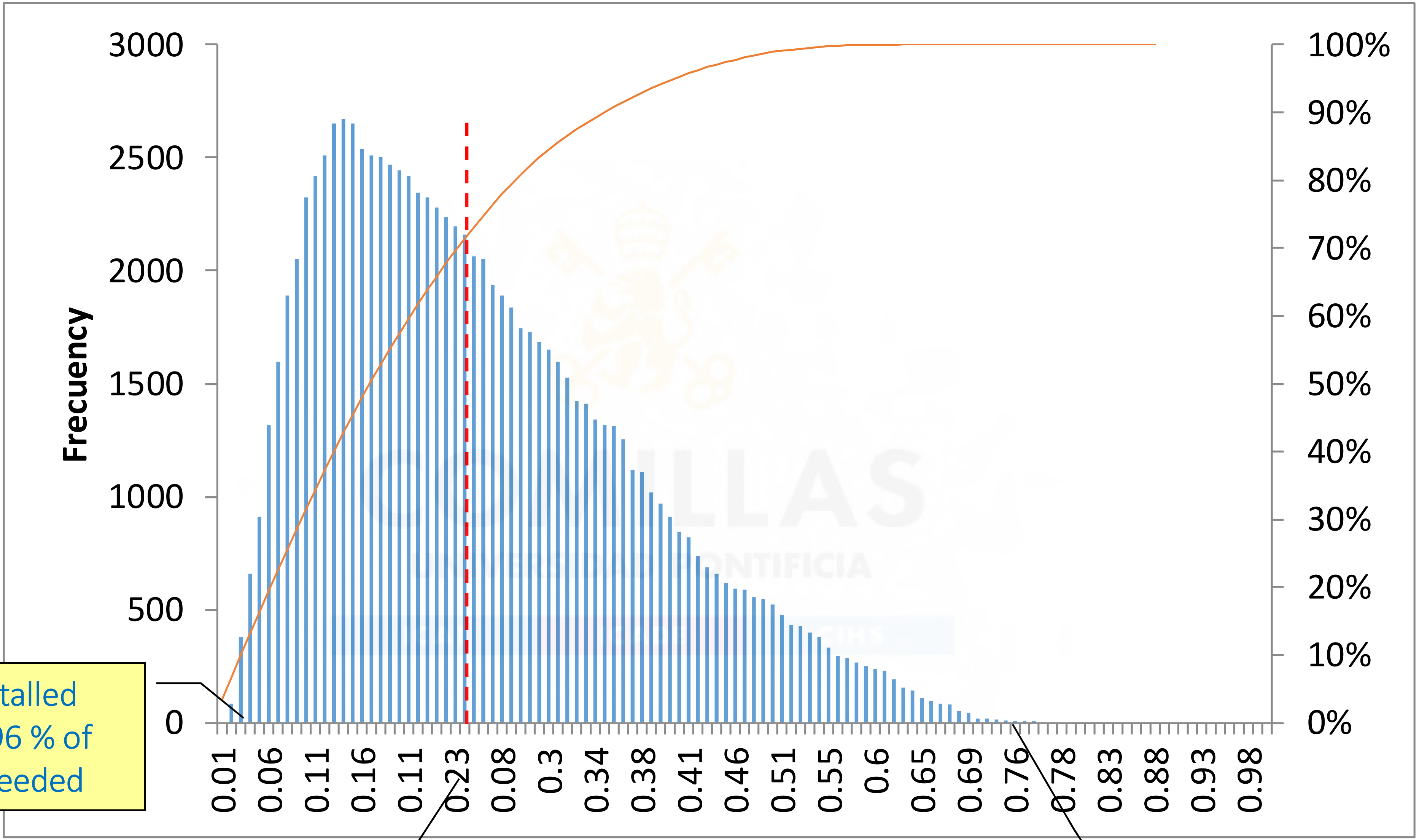
Impact of WP on medium and long-term planning

Probability distribution $f(x)$ and $F(x)$ (2014-2022 hourly data)



5 % of installed capacity 96 % of being exceeded

Mean value: 24 % of installed capacity

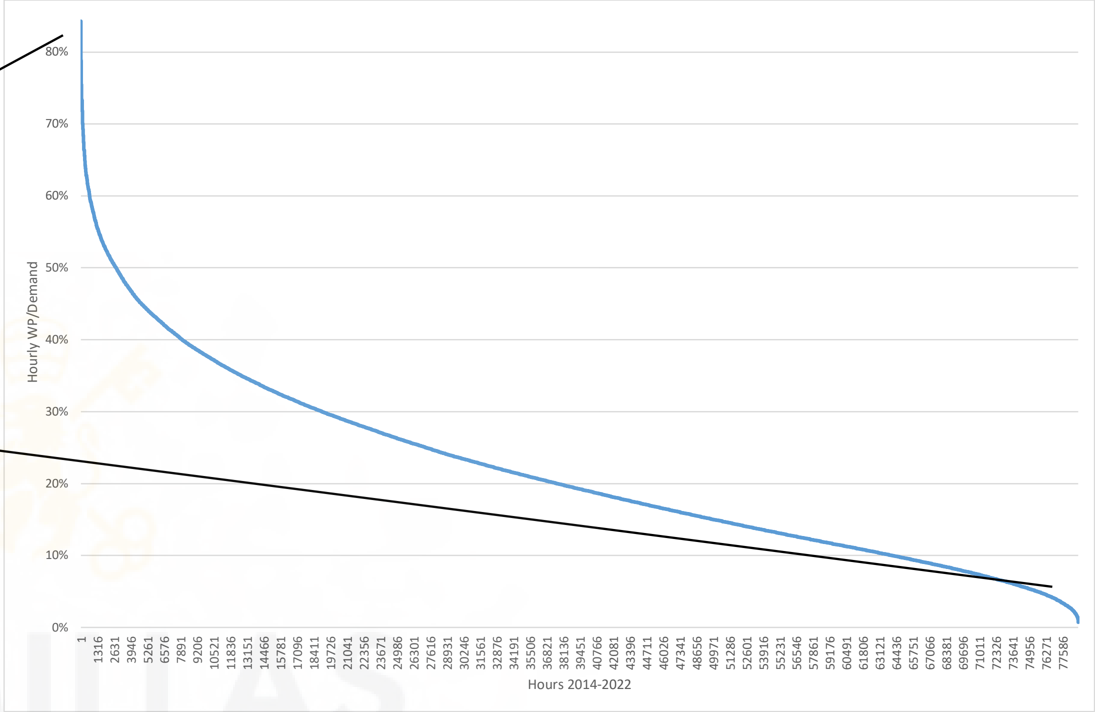
76 % of installed capacity never exceeded

Source: REE

WP Hourly and daily data 2014-2022

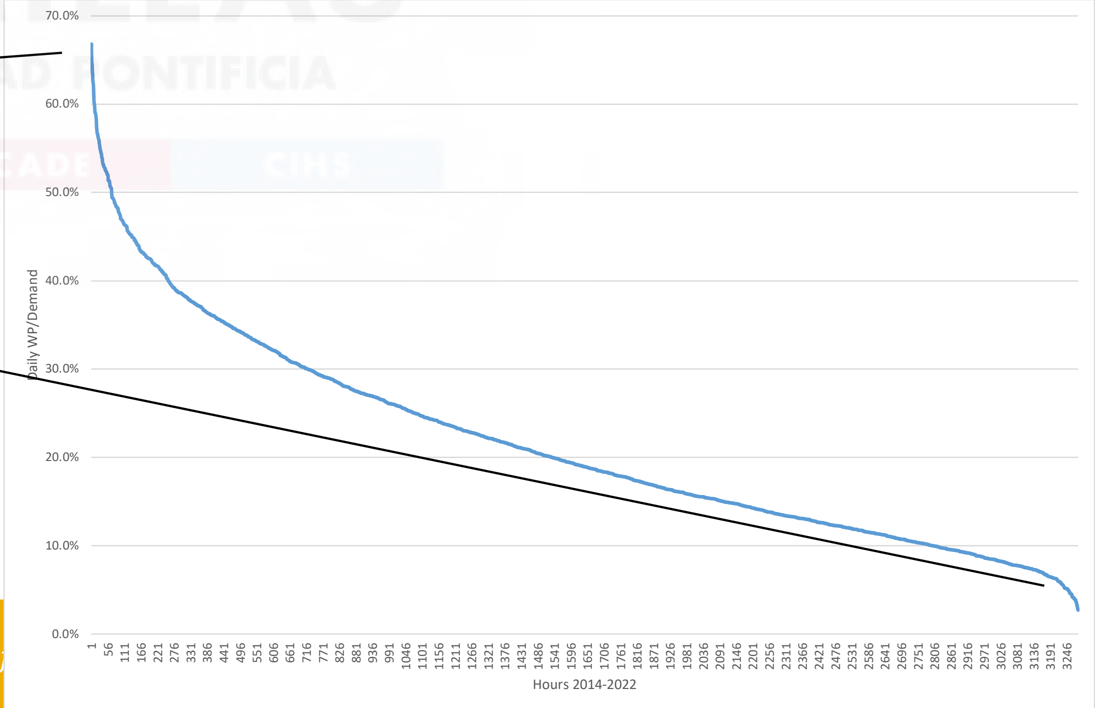
WP has reached 84 % of the hourly demand

4 % of the hours WP has produced < 5 % of the hourly demand

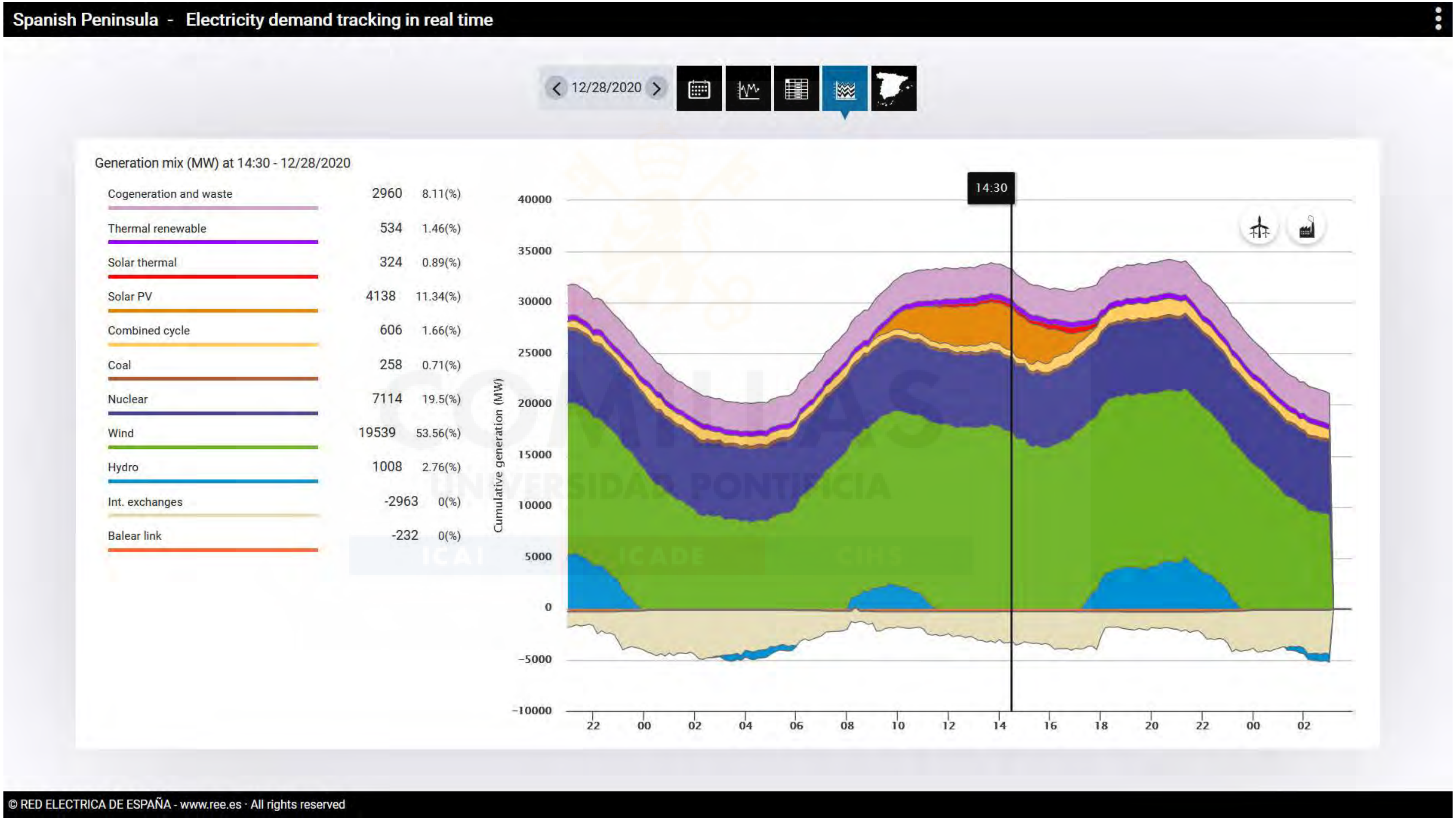


WP has reached 67 % of the daily demand

1 % of the days WP has produced < 5 % of the daily demand



Maximum hourly WP share (Monday, 2020-12-28)



Spanish Peninsula - Electricity demand tracking in real time

12/28/2020

Generation mix (MW) at 14:30 - 12/28/2020

Cogeneration and waste	2960	8.11(%)
Thermal renewable	534	1.46(%)
Solar thermal	324	0.89(%)
Solar PV	4138	11.34(%)
Combined cycle	606	1.66(%)
Coal	258	0.71(%)
Nuclear	7114	19.5(%)
Wind	19539	53.56(%)
Hydro	1008	2.76(%)
Int. exchanges	-2963	0(%)
Balear link	-232	0(%)

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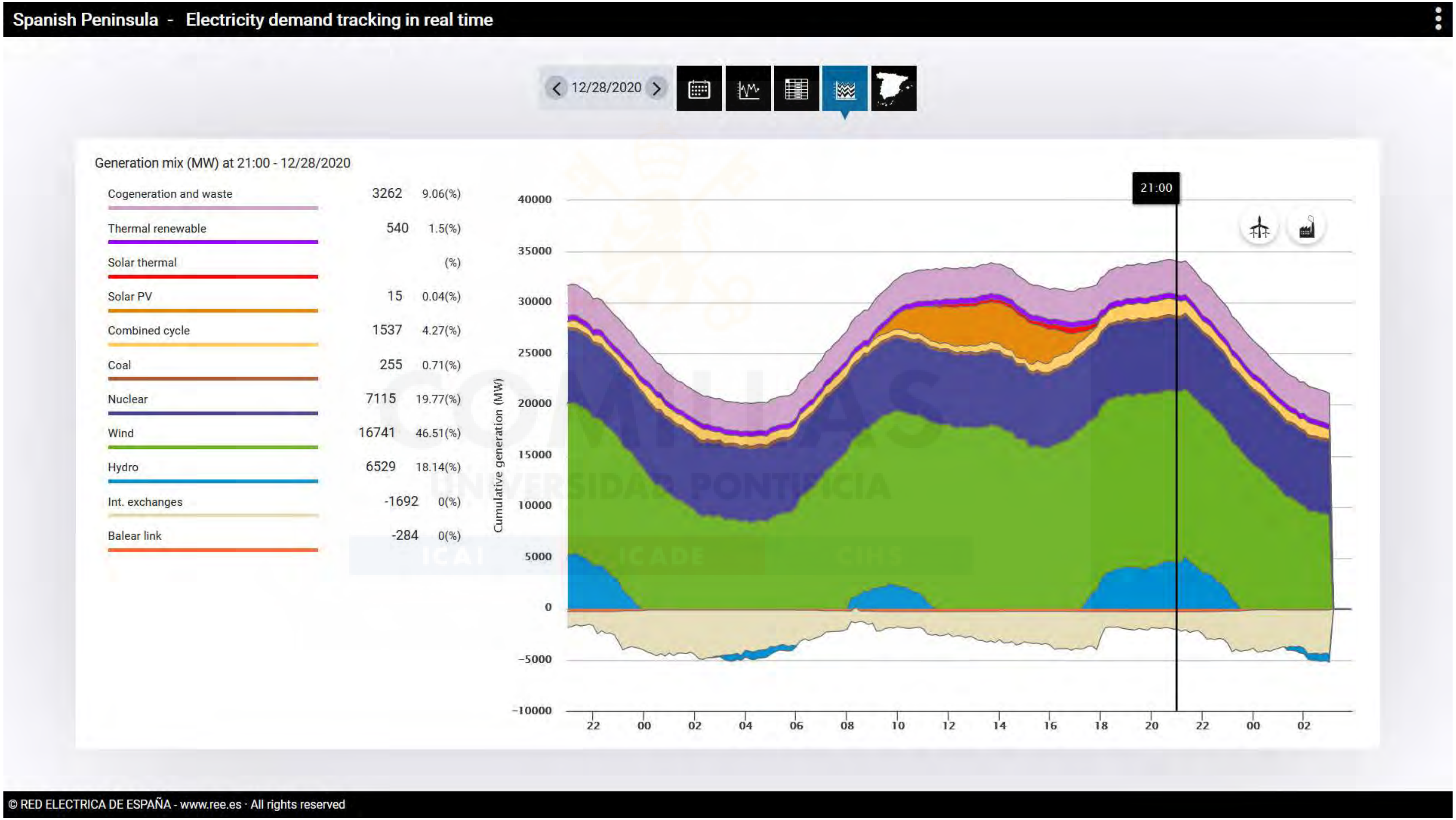
Maximum daily WP share (Monday, 2020-12-28)



Spanish Peninsula - Electricity demand tracking in real time

12/28/2020

Generation mix (MW) at 21:00 - 12/28/2020

Cogeneration and waste	3262	9.06(%)
Thermal renewable	540	1.5(%)
Solar thermal		(%)
Solar PV	15	0.04(%)
Combined cycle	1537	4.27(%)
Coal	255	0.71(%)
Nuclear	7115	19.77(%)
Wind	16741	46.51(%)
Hydro	6529	18.14(%)
Int. exchanges	-1692	0(%)
Balear link	-284	0(%)

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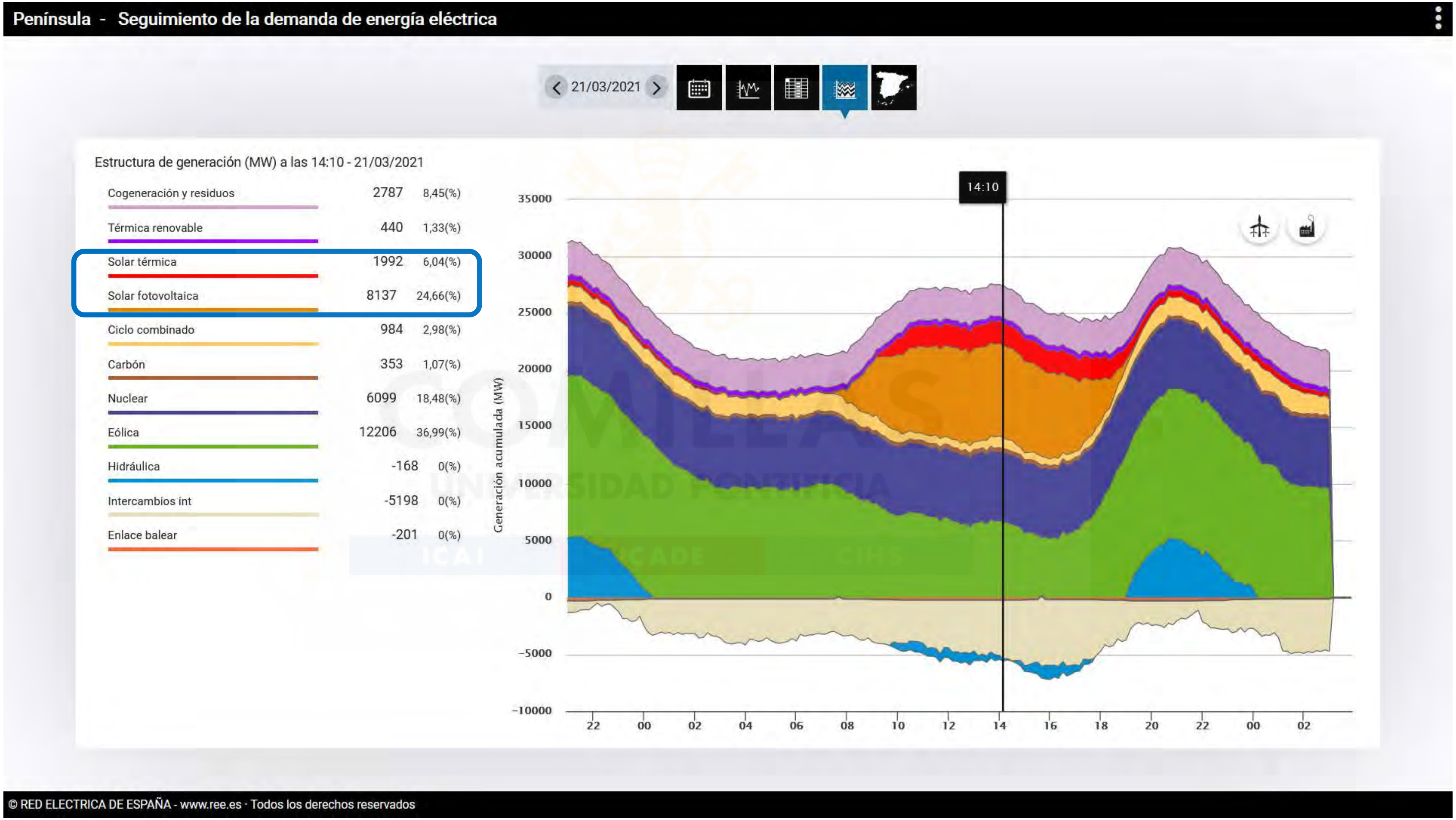
Maximum instantaneous solar output (2021-03-21)



Península - Seguimiento de la demanda de energía eléctrica

21/03/2021

Estructura de generación (MW) a las 14:10 - 21/03/2021

Cogeneración y residuos	2787	8,45(%)
Térmica renovable	440	1,33(%)
Solar térmica	1992	6,04(%)
Solar fotovoltaica	8137	24,66(%)
Ciclo combinado	984	2,98(%)
Carbón	353	1,07(%)
Nuclear	6099	18,48(%)
Eólica	12206	36,99(%)
Hidráulica	-168	0(%)
Intercambios int	-5198	0(%)
Enlace balear	-201	0(%)

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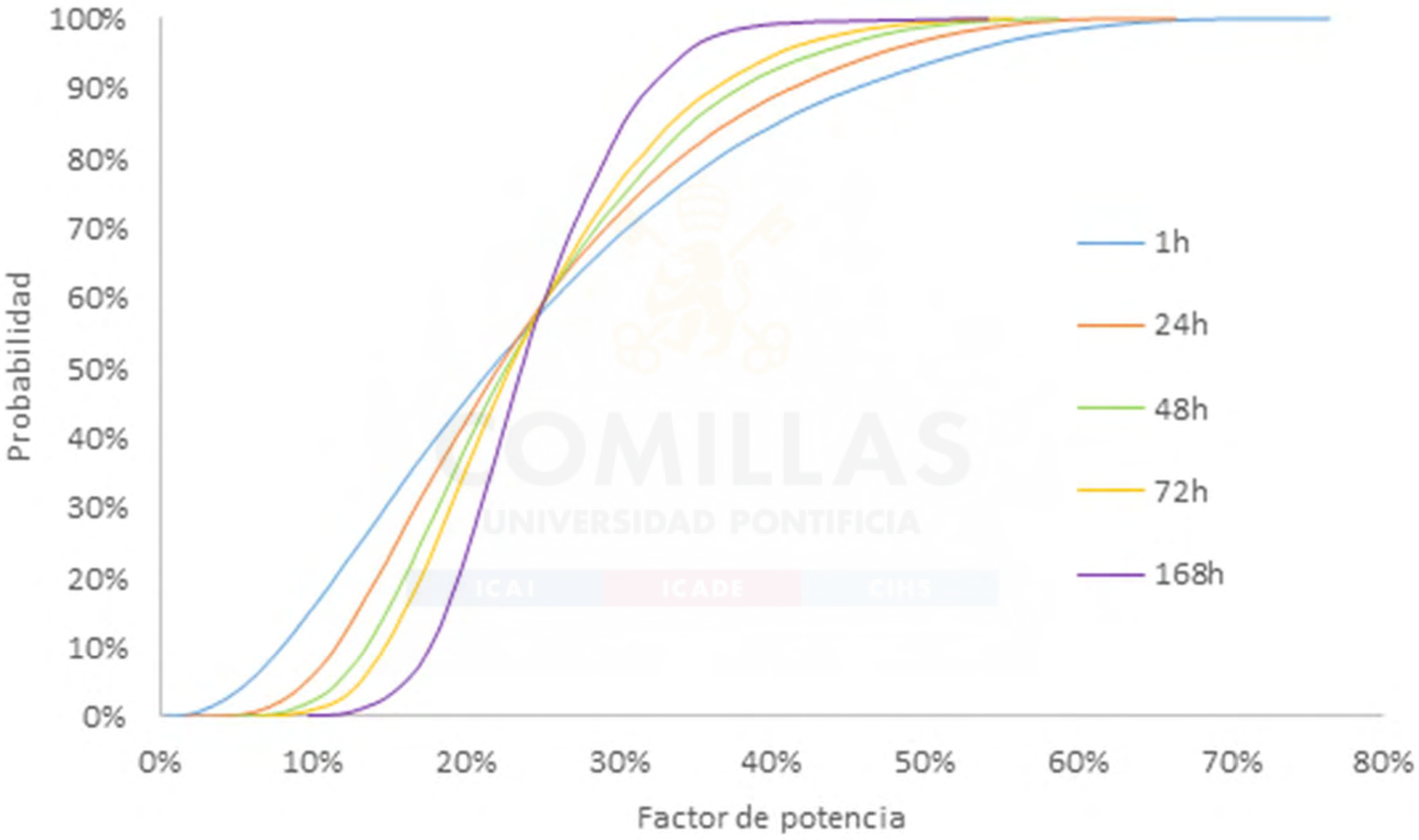
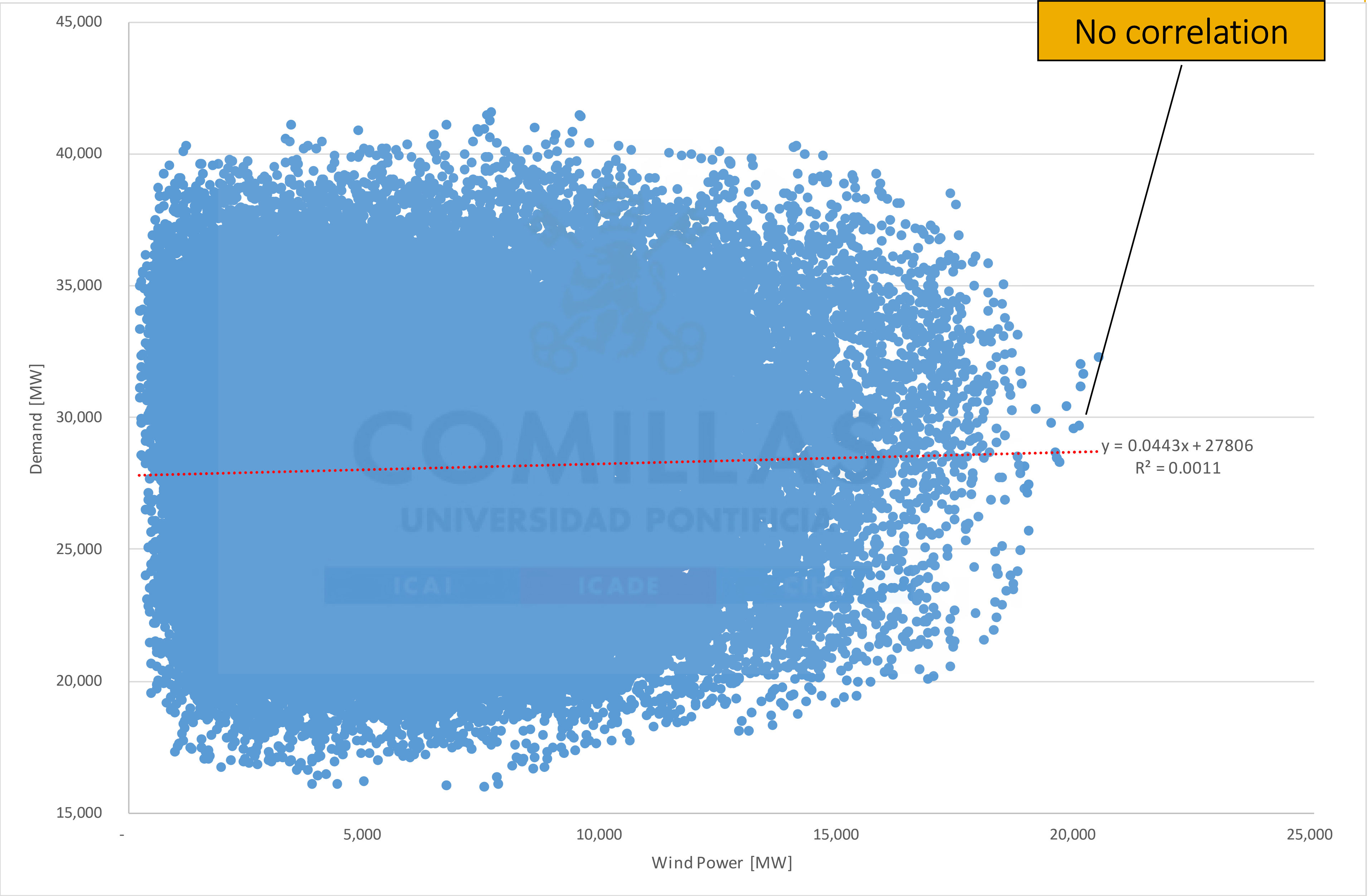
Cumulative distribution function (CDF) of WP



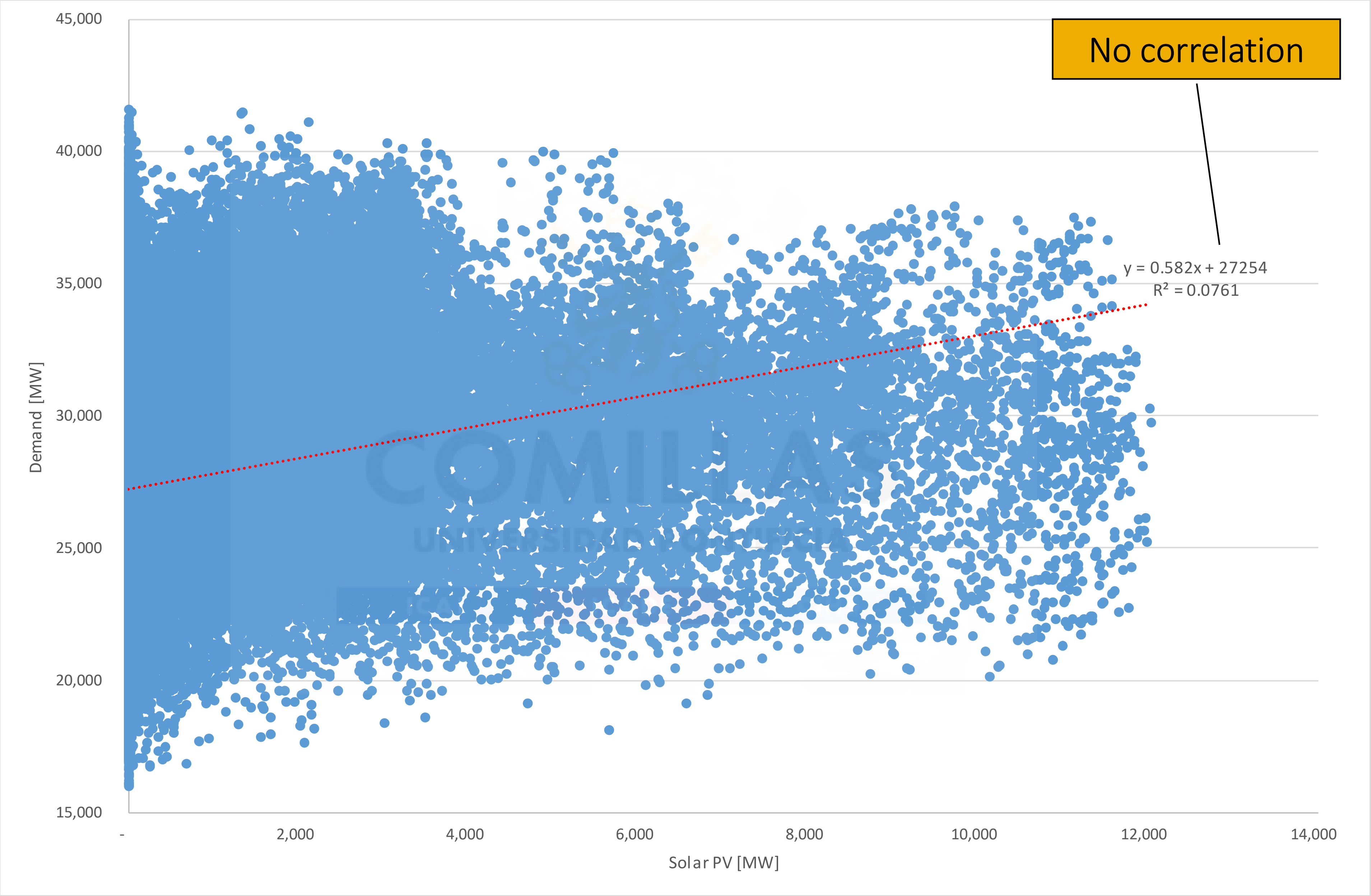
Installed capacity 27000 MW

Hourly Demand vs. Wind Power (2014-2022)



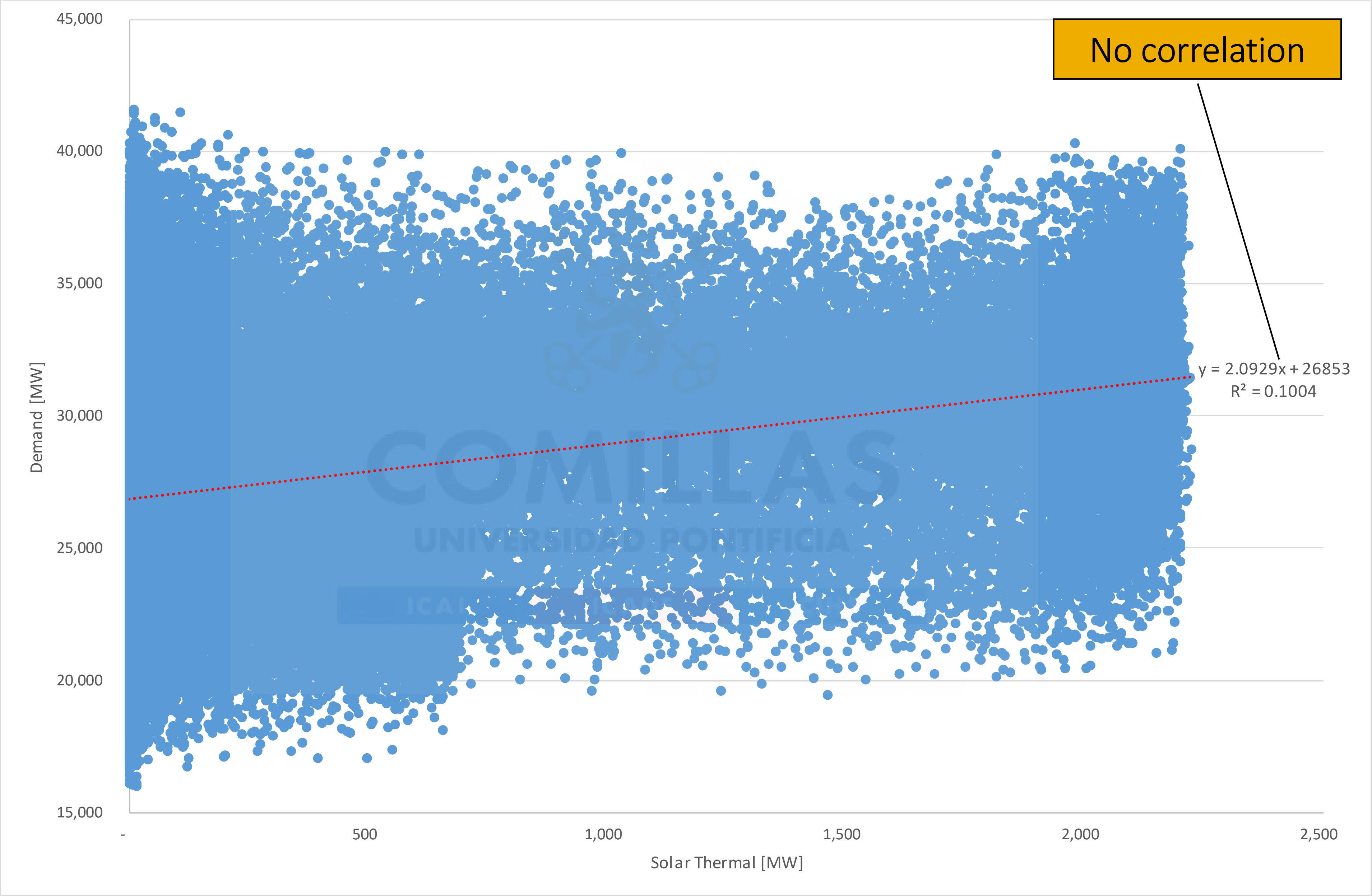
No correlation

Hourly Demand vs. Solar PV (2014-2022)

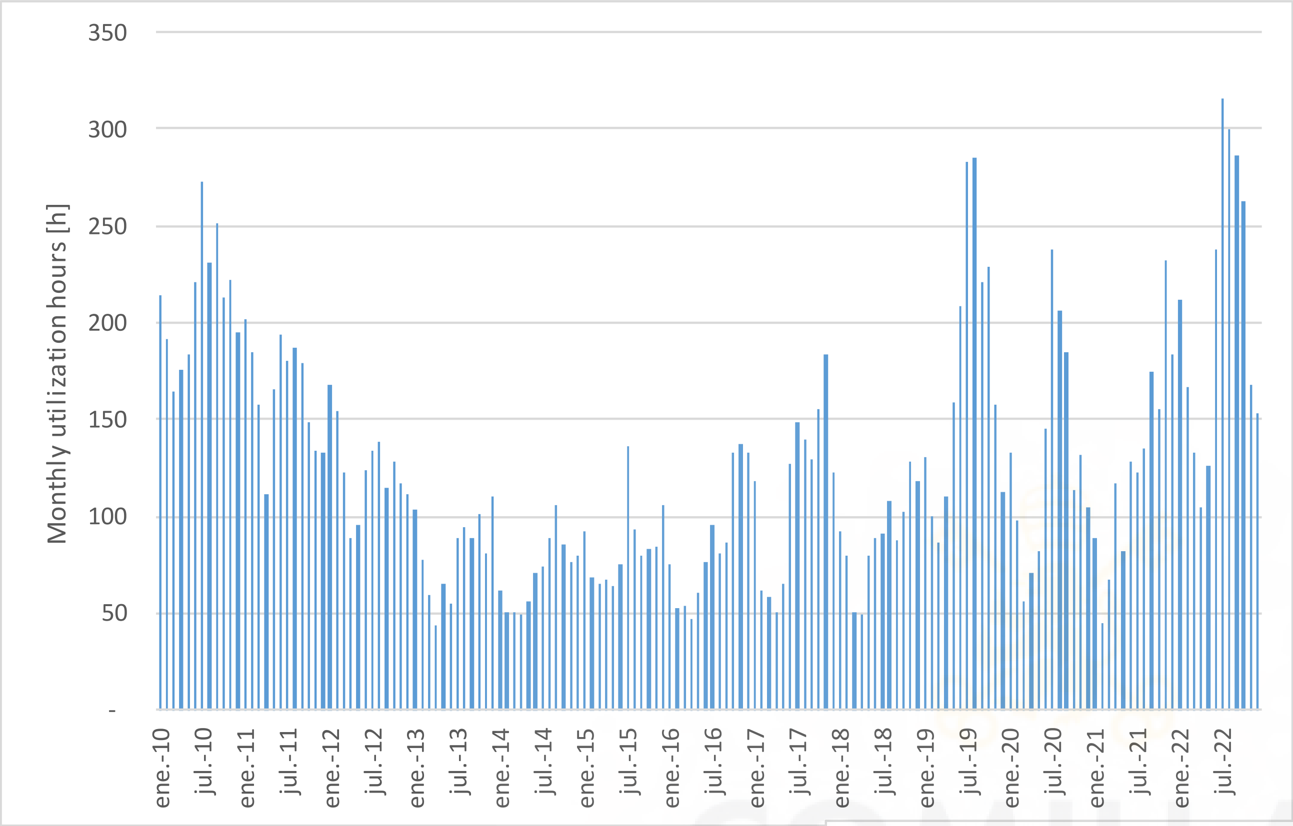


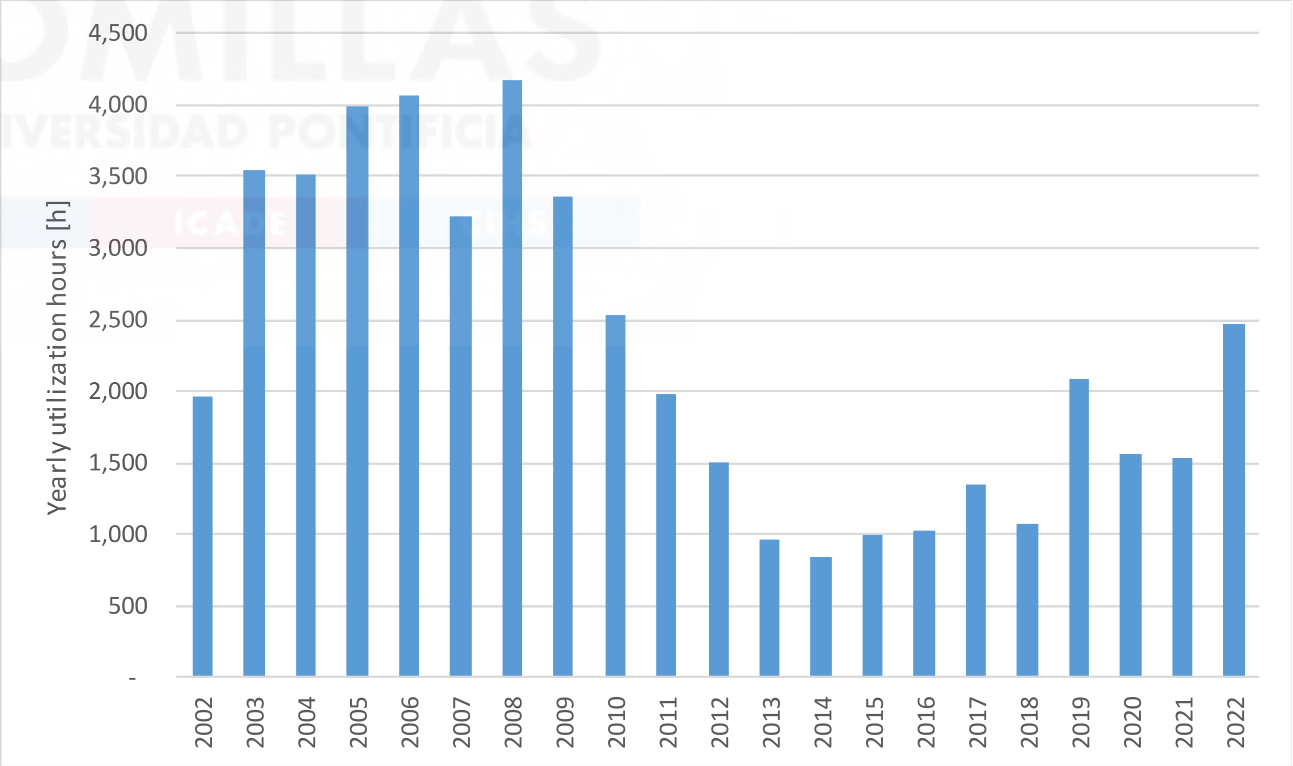
No correlation

Hourly Demand vs. Solar Thermal (2014-2022)

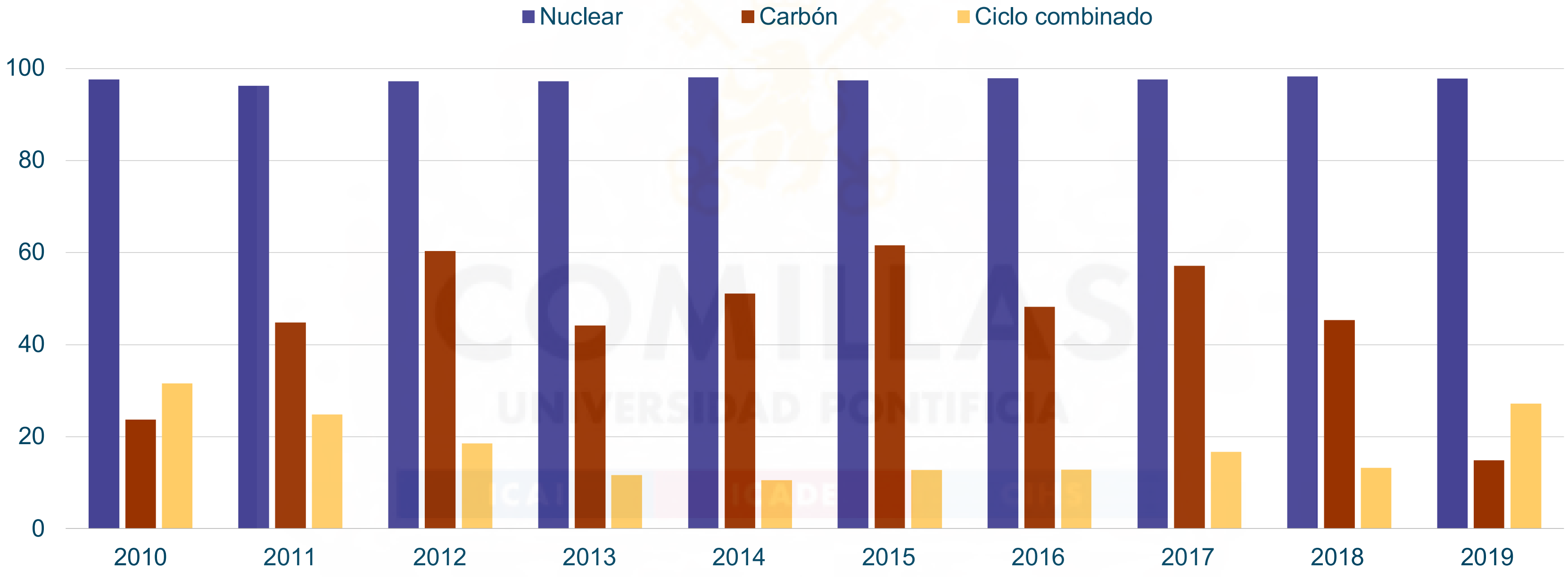


Utilization hours of CCGT in Spain





Capacity factor



Impact of WP on medium and long-term planning

- Reliability assessment (i.e., security of supply)
  - Low coincidence with yearly peak loads (January and July)
  - Almost no dispatchability of WP
  - NEED FOR BACKUP UNITS (i.e., firm capacity, capacity payments)

  - Will there be enough generation to meet peak loads, including WP? Assessed by some system adequacy reliability measures of the system: reserve margin

    Capacity credit: WP contribution to the system reliability.

Wind power

Impact of WP on medium and long-term planning

Impact of WP on short-term planning

Impact of WP on real-time operation

Stochastic UC

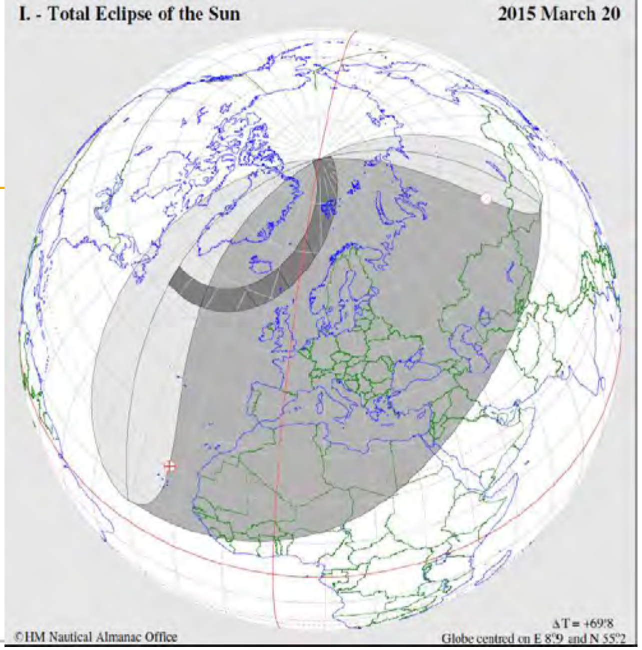
Prototype stochastic UC. Mathematical formulation

Prototype stochastic UC. Computer implementation

3

Impact of WP on short-term planning

Max expected hourly ramp rates in solar eclipse (March 20th, 2015)

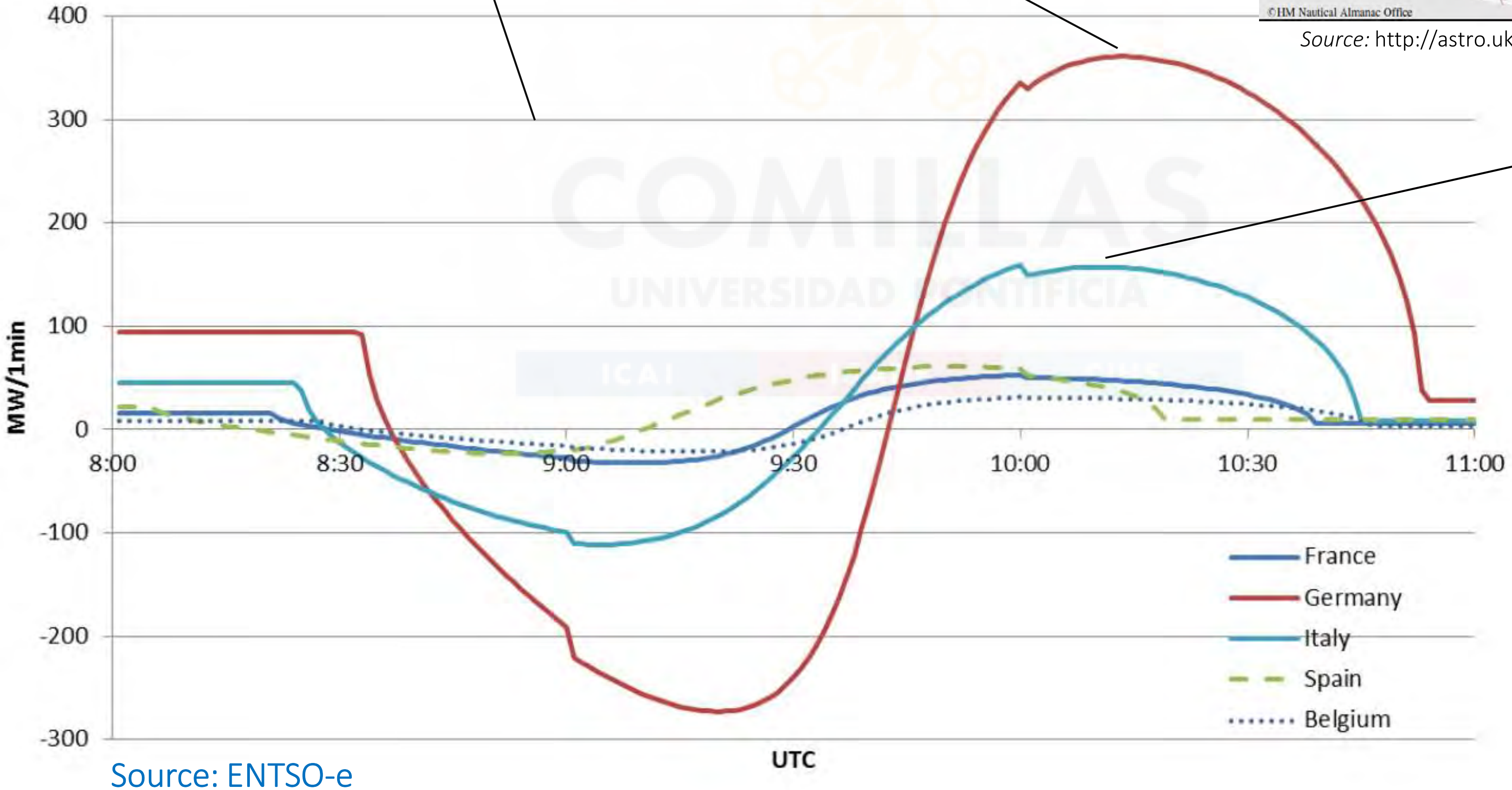


Source: http://astro.ukho.gov.uk/eclipse/0112015/

18000 MW/h

21600 MW/h

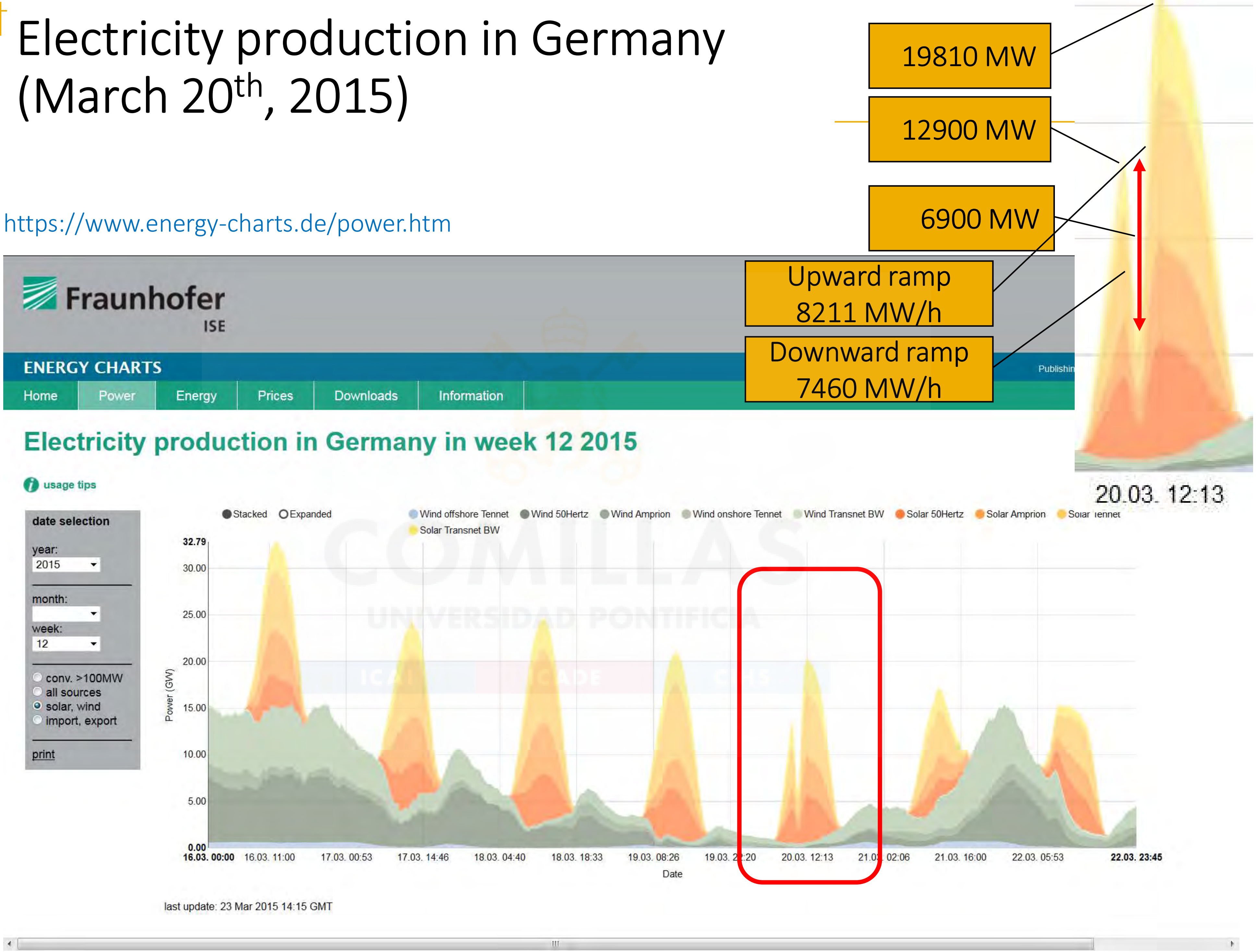
9600 MW/h



Source: ENTSO-e

Electricity production in Germany (March 20th, 2015)

https://www.energy-charts.de/power.htm



Electricity production in Germany in week 12 2015

usage tips

date selection

year: 2015

month:

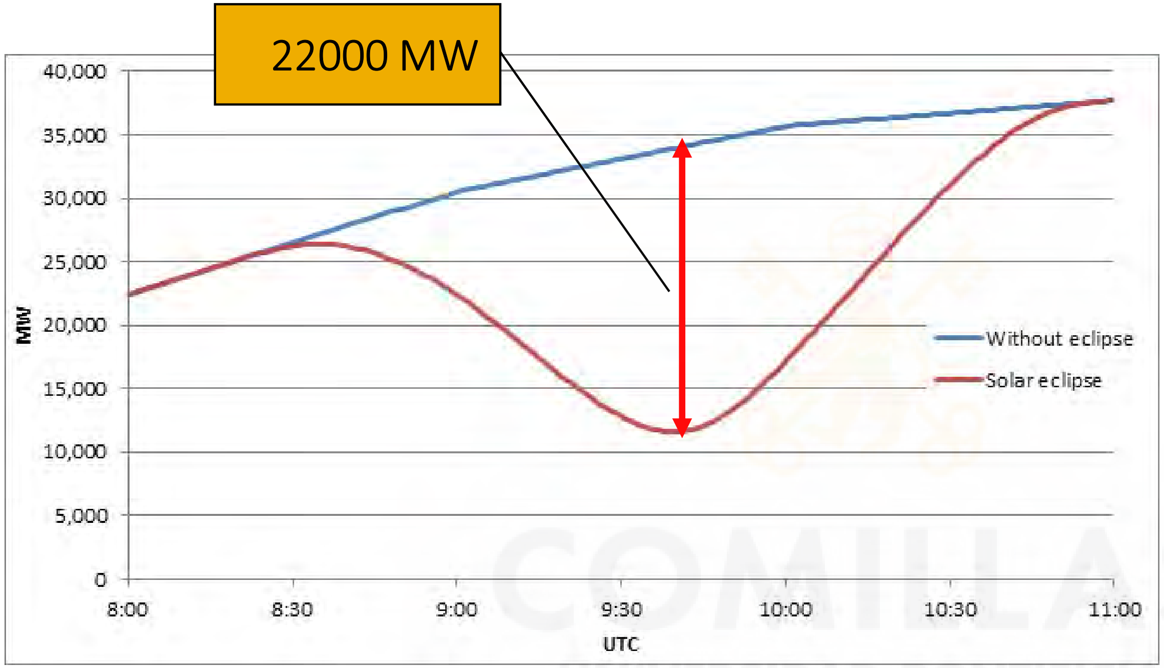
week: 12

○ conv. >100MW
○ all sources
● solar, wind
○ import, export

print

last update: 23 Mar 2015 14:15 GMT

Solar PV generation in Europe (March 20th, 2015)

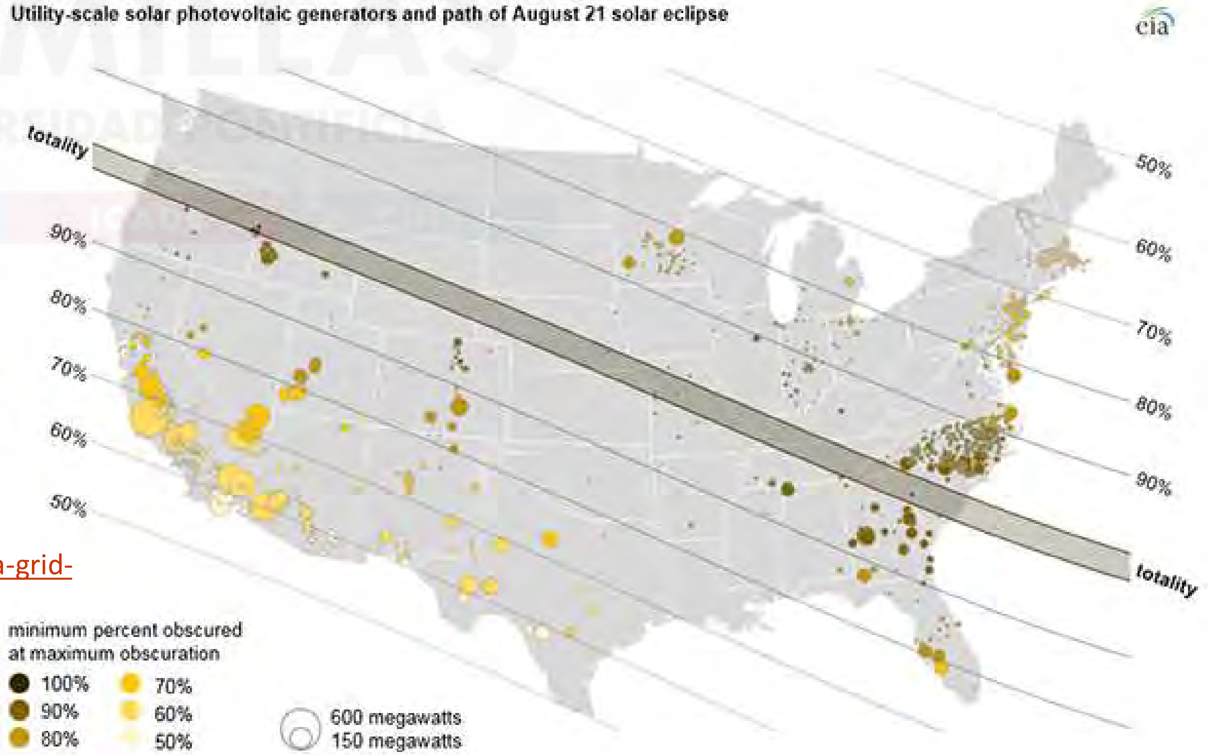


22000 MW

Source: ENTSO-e

How California Grid Operators Managed the Eclipse (2017-08-21)

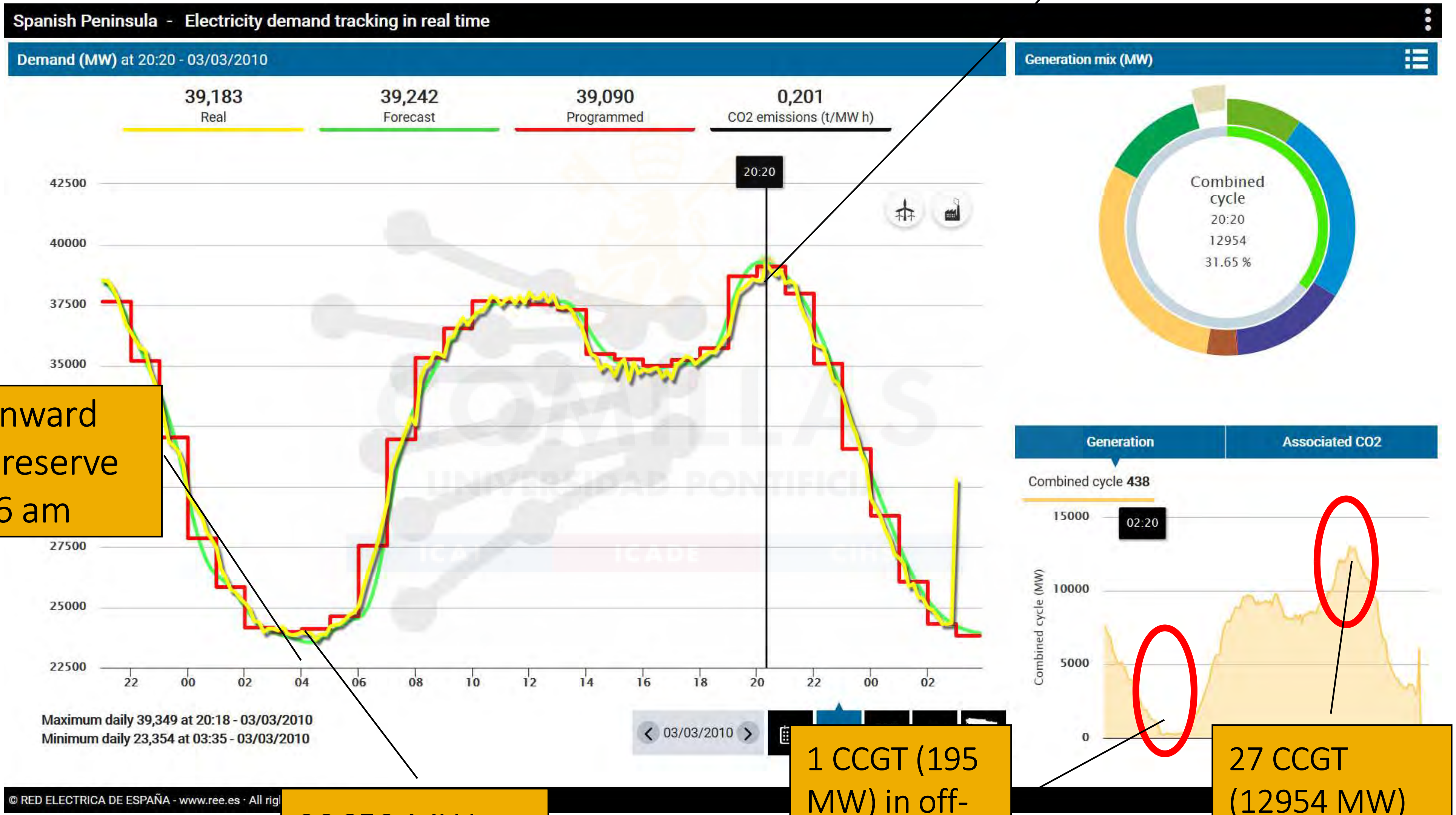
- California faced the biggest challenge. It is not in the path of totality, but the 56- to 78-percent blockage of sunlight will have a big impact thanks to 18 gigawatts worth of solar panels deployed at utility-scale power plants and across rooftops—more than any other state. California's Independent System Operator (CAISO), which manages most of the state's power grid, projected this morning that the eclipse would knock out about 4,300 megawatts (MW) of utility-scale solar and another 1,300 MW of rooftop generation. The utility-scale solar loss, traced on the CAISO website after 9 am Pacific time until the eclipse's California peak at 10:22 am, was actually 3,400 MW.



Utility-scale solar photovoltaic generators and path of August 21 solar eclipse

https://spectrum.ieee.org/energywise/green-tech/solar/how-california-grid-operators-managed-the-eclipse

Load demand (Wednesday, 2010-03-03)



Spanish Peninsula - Electricity demand tracking in real time

Demand (MW) at 20:20 - 03/03/2010

39,183	39,242	39,090	0,201
Real	Forecast	Programmed	CO2 emissions (t/MW h)

Maximum daily 39,349 at 20:18 - 03/03/2010
Minimum daily 23,354 at 03:35 - 03/03/2010

Generation mix (MW)

Combined cycle
20:20
12954
31.65 %

Generation | **Associated CO2**

Combined cycle **438**

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39183 MW

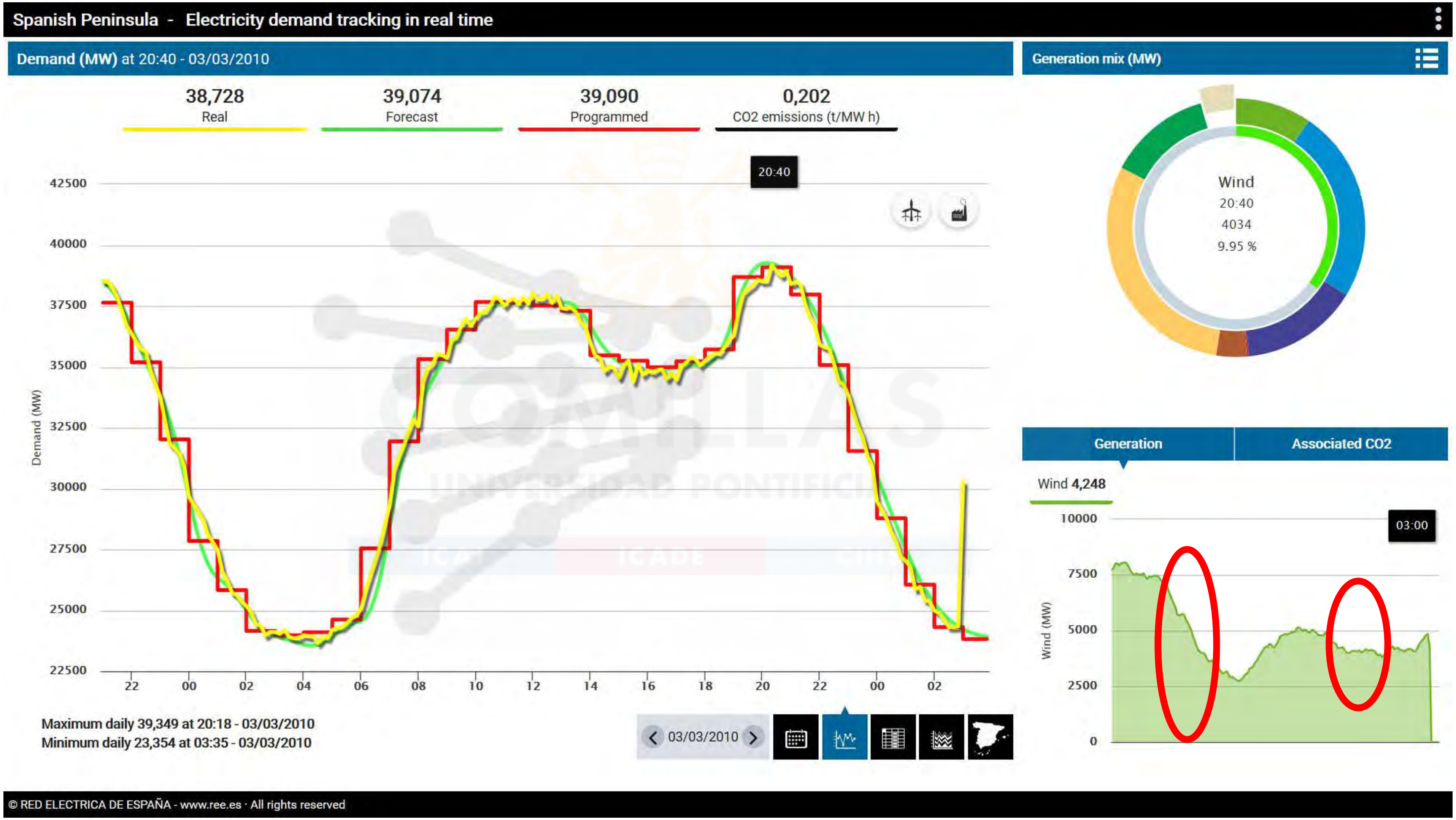
No downward tertiary reserve from 2-6 am

23653 MW

1 CCGT (195 MW) in off-peak hours

27 CCGT (12954 MW) in peak hours

Load demand (Wednesday, 2010-03-03)



Spanish Peninsula - Electricity demand tracking in real time

Demand (MW) at 20:40 - 03/03/2010

38,728	39,074	39,090	0,202
Real	Forecast	Programmed	CO2 emissions (t/MW h)

Maximum daily 39,349 at 20:18 - 03/03/2010
Minimum daily 23,354 at 03:35 - 03/03/2010

Generation mix (MW)

Wind
20:40
4034
9.95 %

Generation | **Associated CO2**

Wind **4,248**

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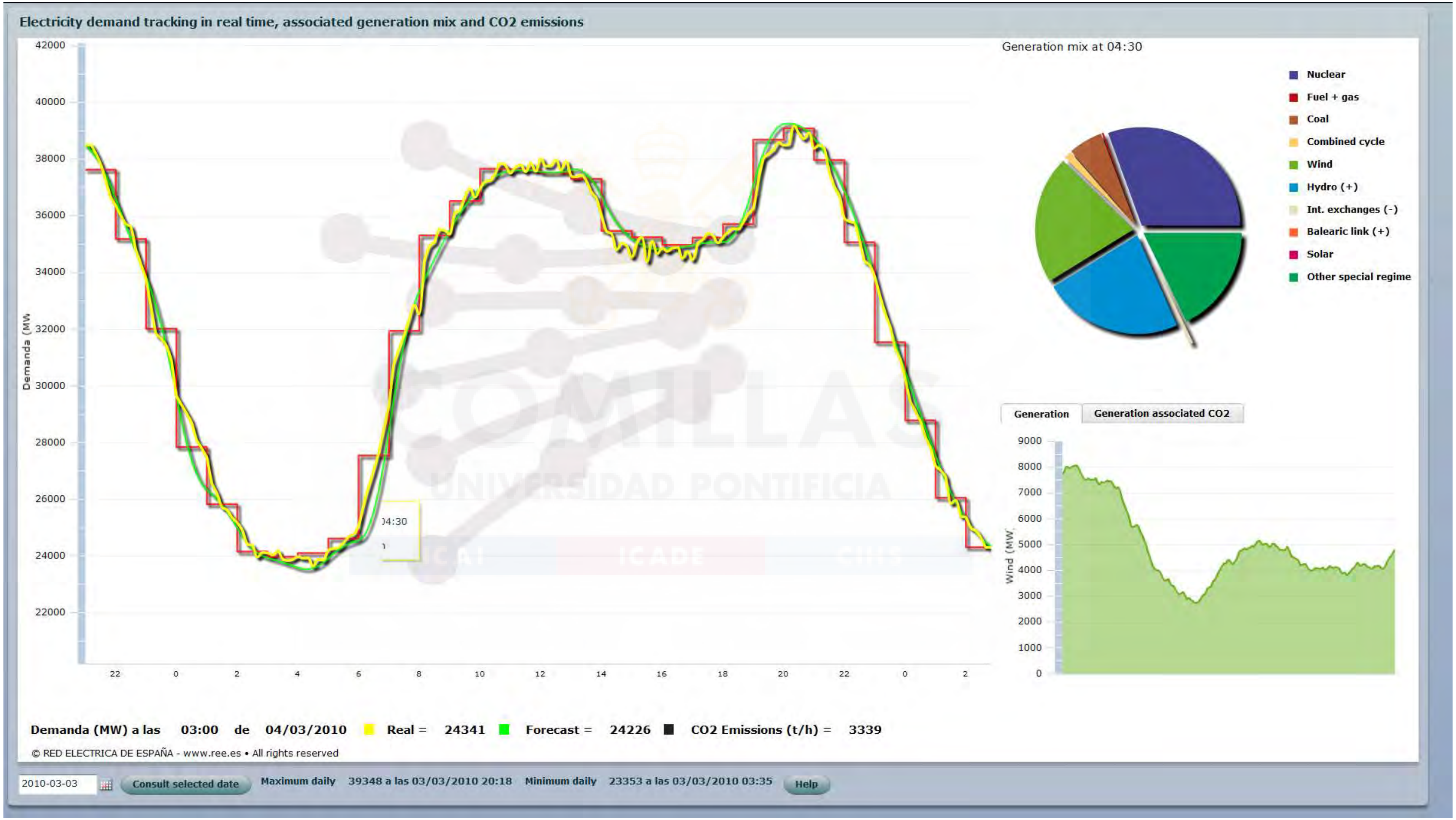
Load demand (Wednesday, 2010-03-03, 4:30 h)



Demanda (MW) a las 03:00 de 04/03/2010 🟨 **Real = 24341** 🟩 **Forecast = 24226** ■ **CO2 Emissions (t/h) = 3339**

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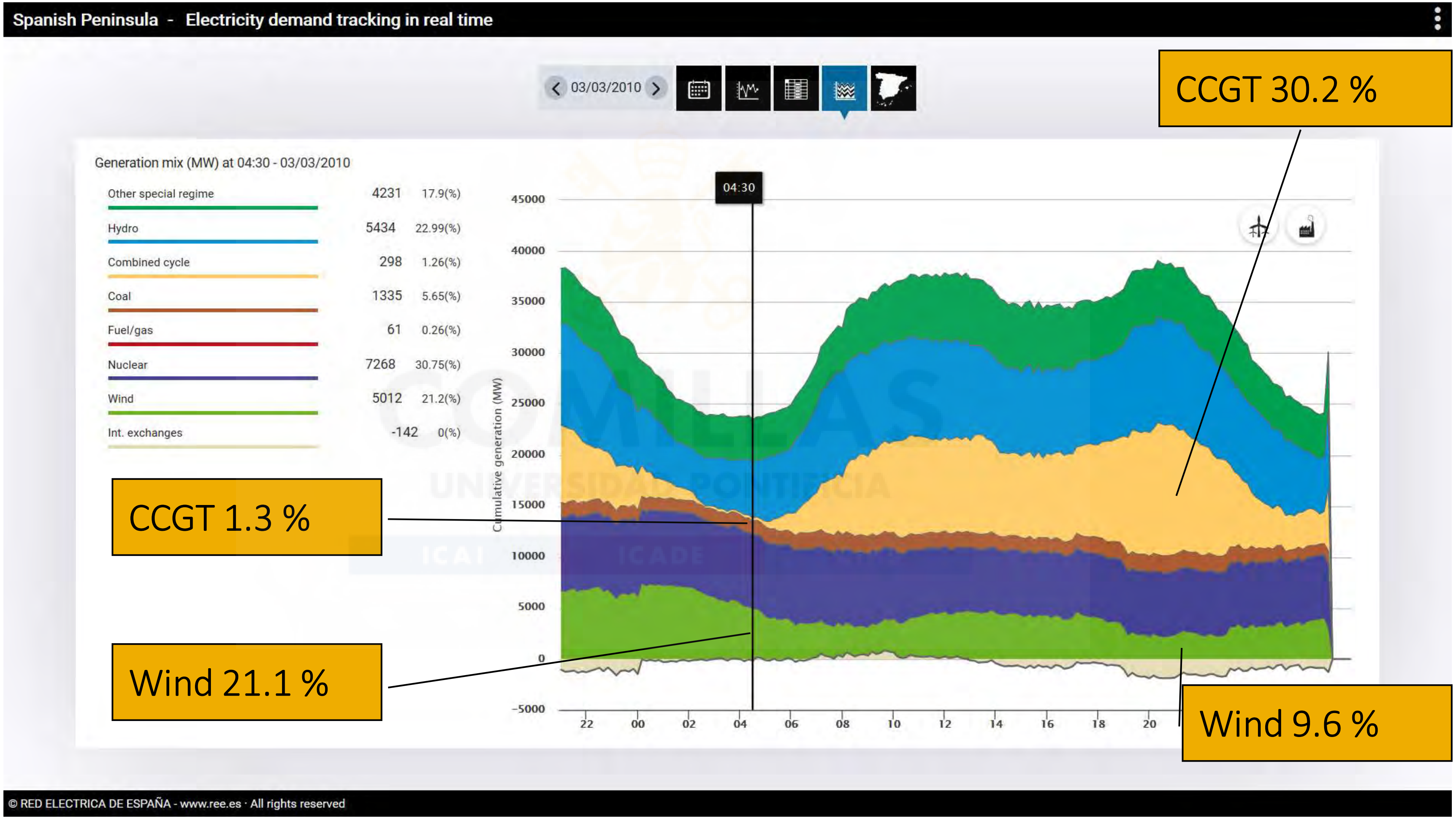
Maximum daily 39348 a las 03/03/2010 20:18 **Minimum daily** 23353 a las 03/03/2010 03:35

Load demand (Wednesday, 2010-03-03)



Spanish Peninsula - Electricity demand tracking in real time

03/03/2010

Generation mix (MW) at 04:30 - 03/03/2010

Other special regime	4231	17.9(%)
Hydro	5434	22.99(%)
Combined cycle	298	1.26(%)
Coal	1335	5.65(%)
Fuel/gas	61	0.26(%)
Nuclear	7268	30.75(%)
Wind	5012	21.2(%)
Int. exchanges	-142	0(%)

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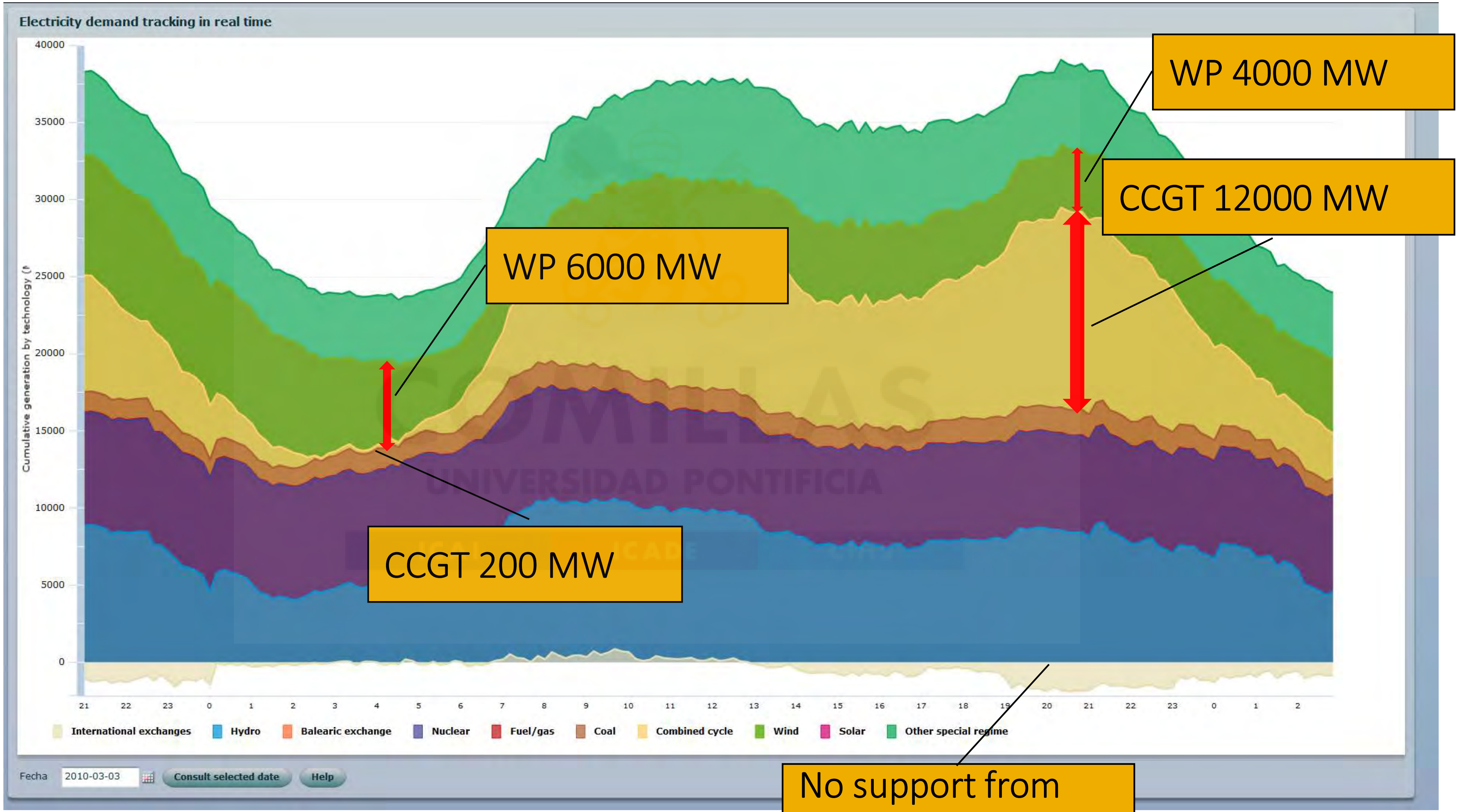
CCGT 30.2 %

CCGT 1.3 %

Wind 21.1 %

Wind 9.6 %

Load demand (Wednesday, 2010-03-03)



WP 4000 MW

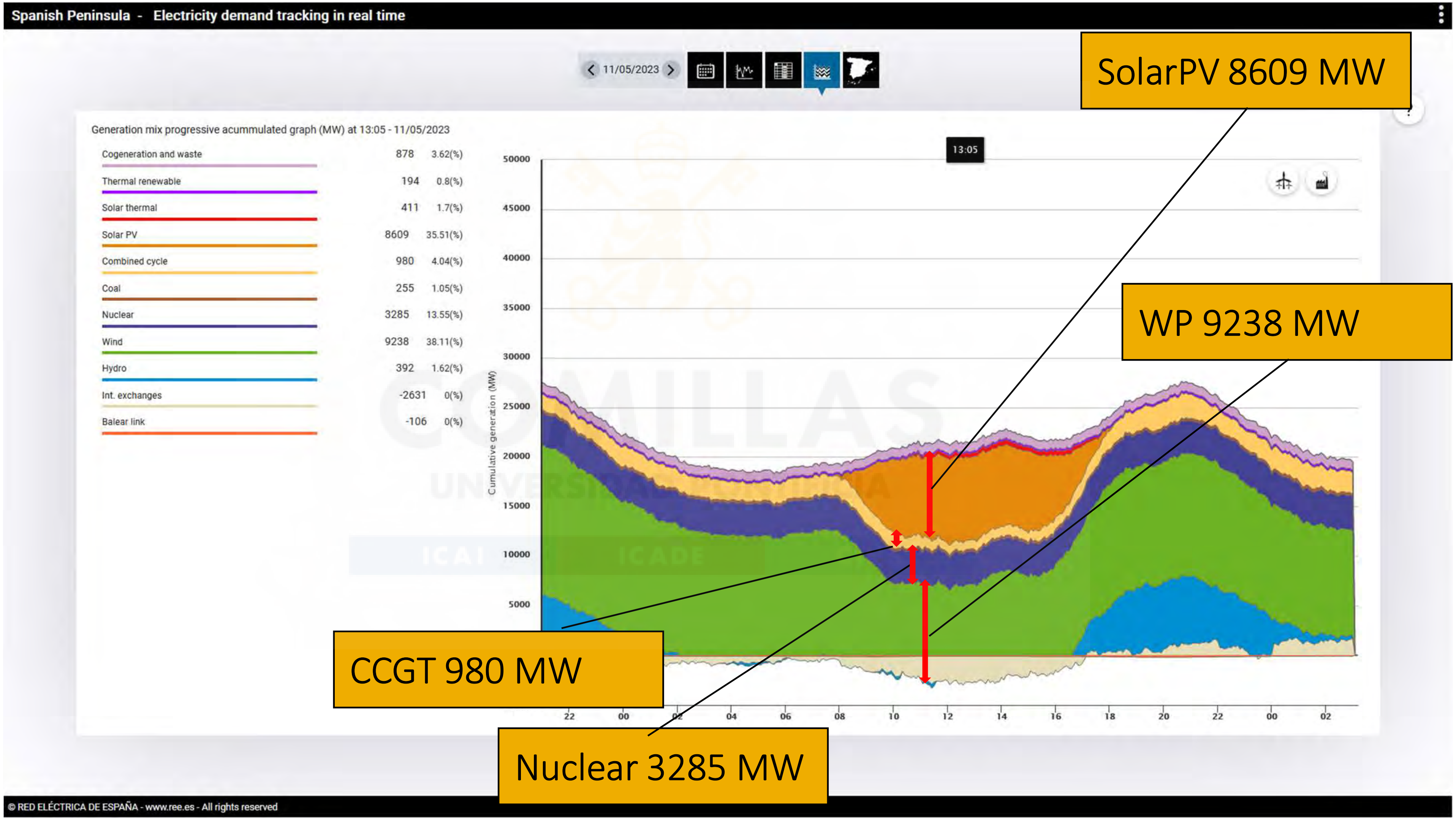
CCGT 12000 MW

WP 6000 MW

CCGT 200 MW

No support from neighbors

Generation operation (Sunday 2023-11-05)



Spanish Peninsula - Electricity demand tracking in real time

11/05/2023

Generation mix progressive acummulated graph (MW) at 13:05 - 11/05/2023

Cogeneration and waste	878	3.62(%)
Thermal renewable	194	0.8(%)
Solar thermal	411	1.7(%)
Solar PV	8609	35.51(%)
Combined cycle	980	4.04(%)
Coal	255	1.05(%)
Nuclear	3285	13.55(%)
Wind	9238	38.11(%)
Hydro	392	1.62(%)
Int. exchanges	-2631	0(%)
Balear link	-106	0(%)

SolarPV 8609 MW

WP 9238 MW

CCGT 980 MW

Nuclear 3285 MW

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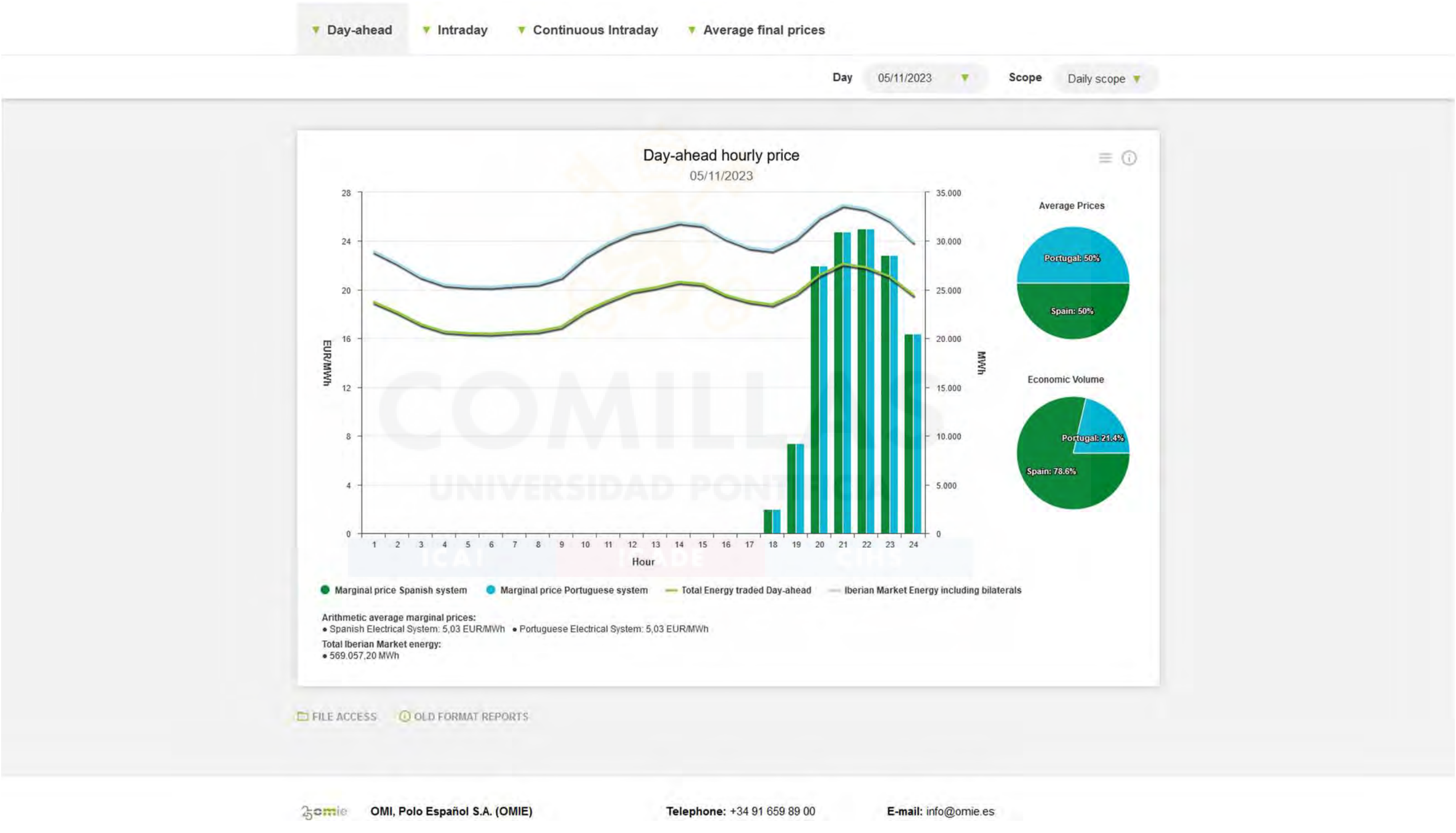
Day-ahead hourly price (Sunday 2023-11-05)

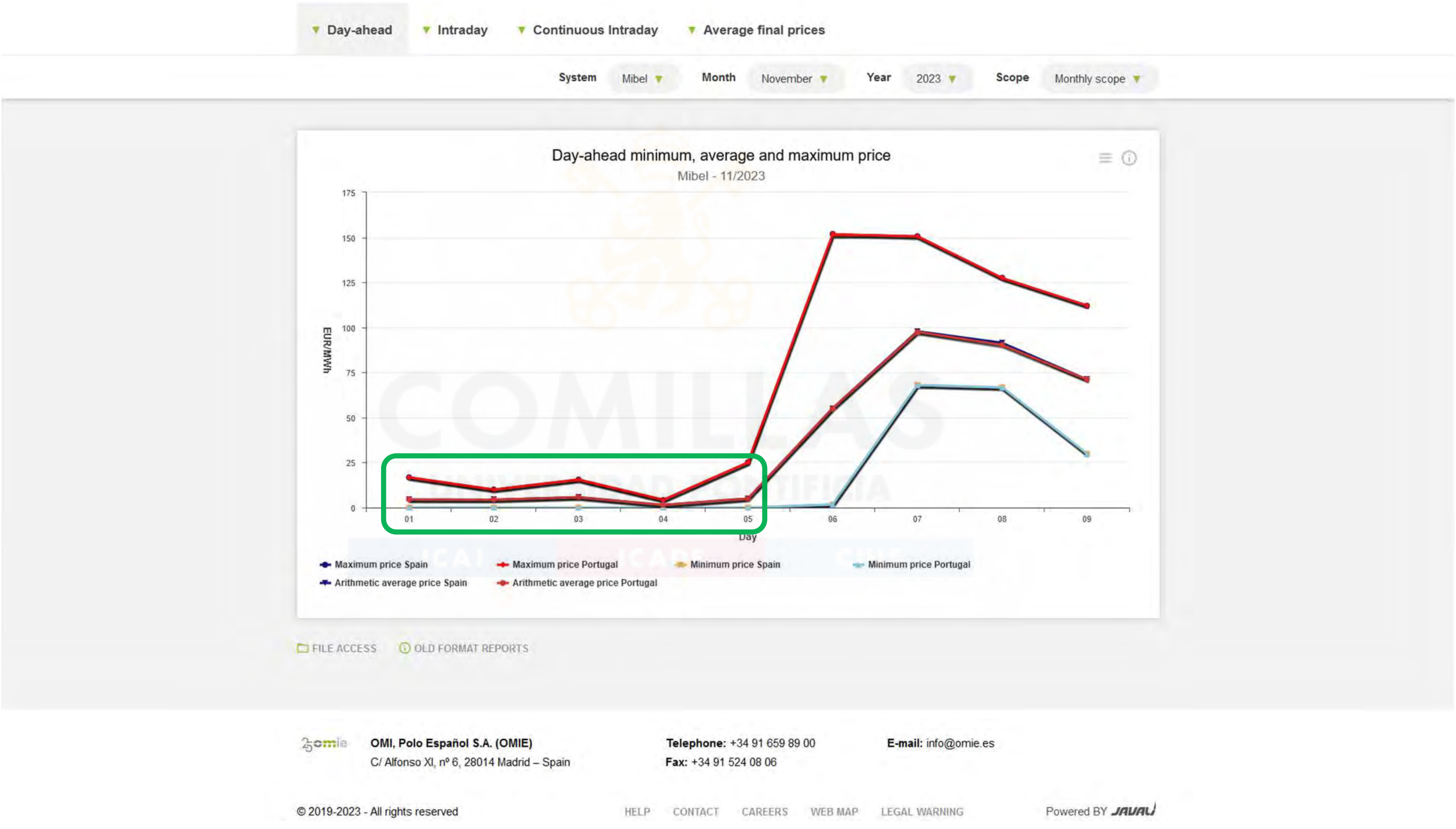


Arithmetic average marginal prices:
- Spanish Electrical System: 5,03 EUR/MWh
- Portuguese Electrical System: 5,03 EUR/MWh

Total Iberian Market energy:
- 569.057,20 MWh

OMI, Polo Español S.A. (OMIE) **Telephone:** +34 91 659 89 00 **E-mail:** info@omie.es

Day-ahead price (Sunday 2023-11-05)



System Mibel
Month November
Year 2023
Scope Monthly scope

OMI, Polo Español S.A. (OMIE)
C/ Alfonso XI, nº 6, 28014 Madrid – Spain

Telephone: +34 91 659 89 00
Fax: +34 91 524 08 06

E-mail: info@omie.es

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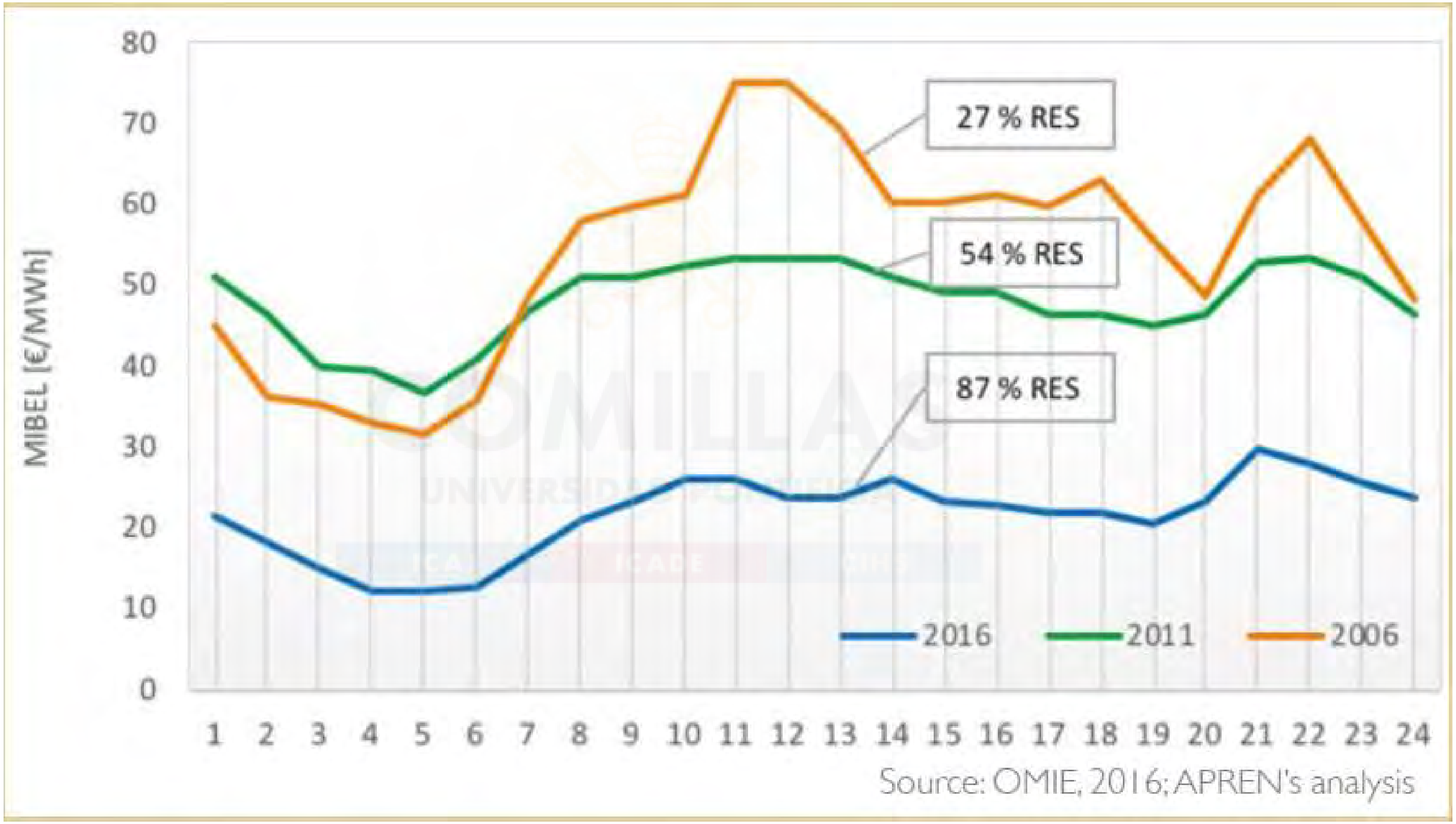
MIBEL average hourly spot price for an April's working days

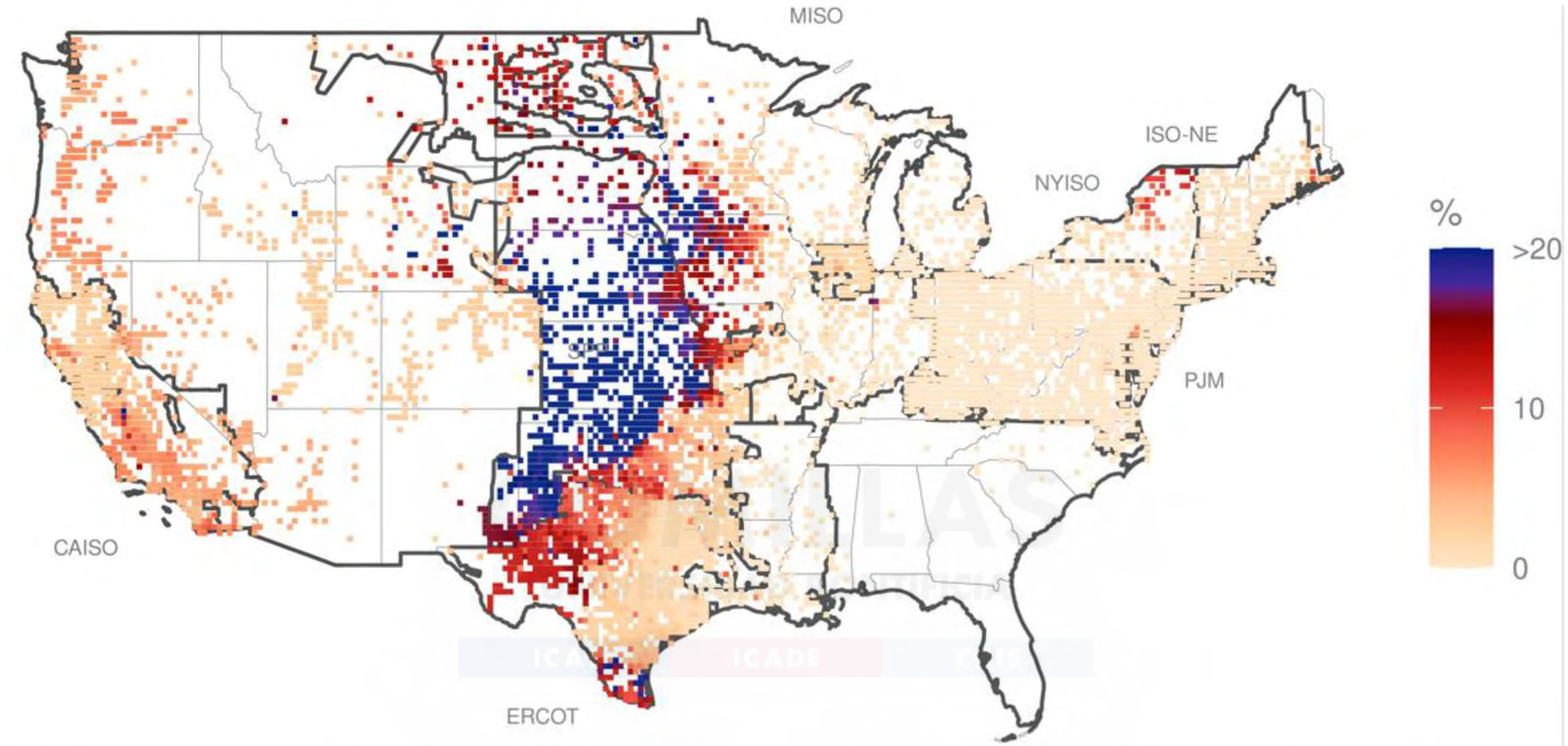
- Price inversely related to the RES share



Source: OMIE, 2016; APREN's analysis

J. Medeiros Pinto, S. Serôdio *"Brief characterization of the electricity sector in Portugal and Challenges"* Cuadernos de Energía 56, Oct 2018

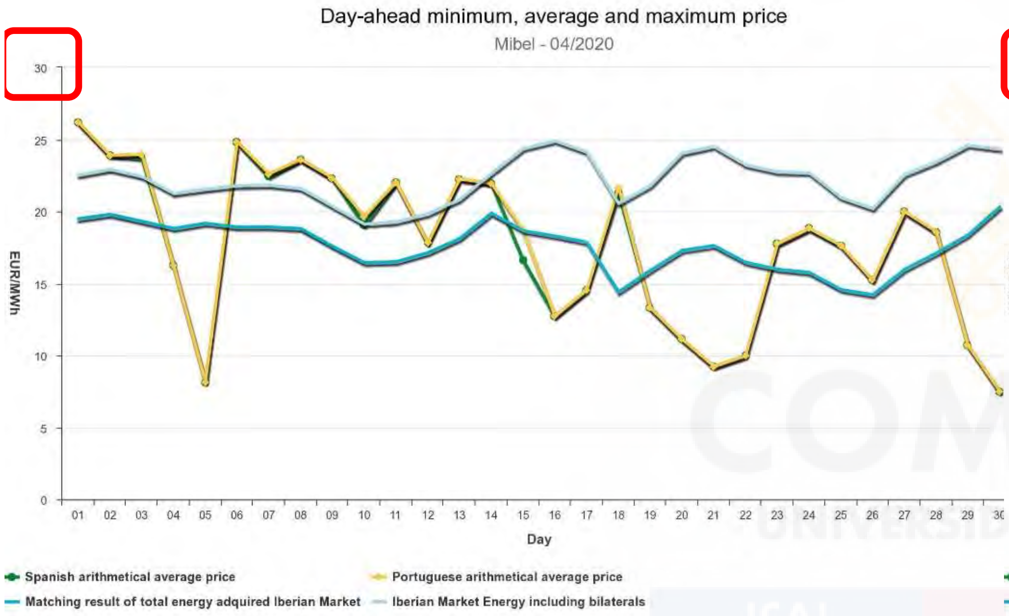
Frequency of Negative Electricity Prices in 2022 in the USA



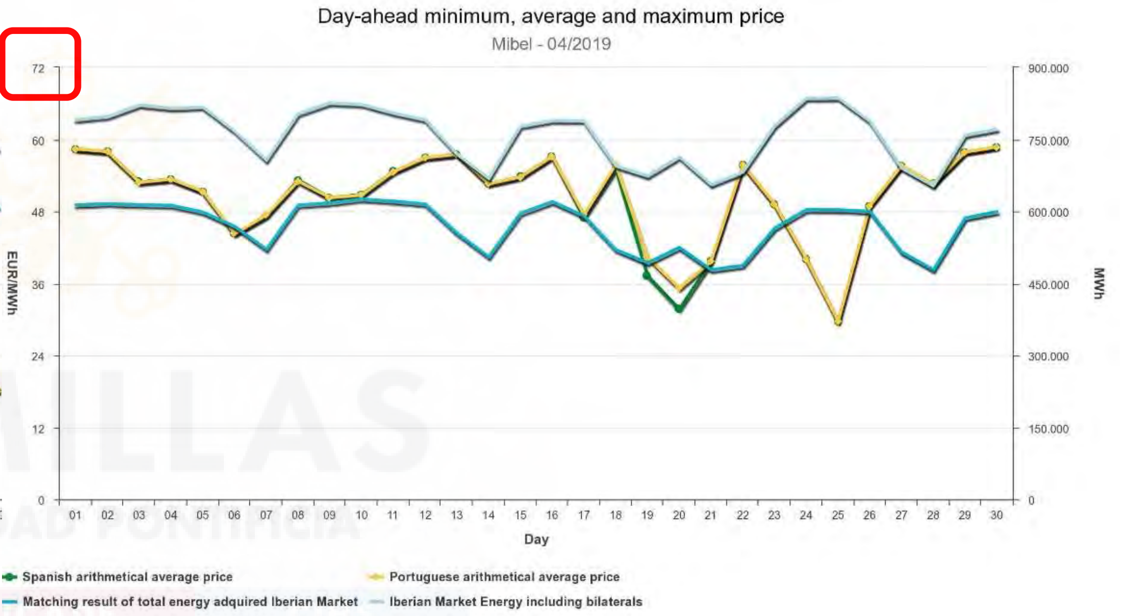
Note: This figure was reproduced with permission from Millstein et al (2023). The figure plots the frequency of negative local marginal electricity prices during all hours in 2022. The underlying price data in the ReWEP tool was compiled through the commercial product "Velocity Suite" based on prices from over 50,000 individual local nodes across the seven major US independent system operators. To verify the map, we spot-checked the negative price frequency at hundreds of locations in MISO and SPP (roughly, North Dakota to Michigan to Oklahoma) using hourly wholesale market price data.

L. Davis, C. Hausman, and N. Rose "Transmission Impossible? Prospects for Decarbonizing the US Grid" Energy Institute at HAAS WP 338. June 2023

April 2019 and 2020. Covid-19 impact


Day-ahead minimum, average and maximum price

Mibel - 04/2020


Day-ahead minimum, average and maximum price

Mibel - 04/2019

Impact of WP on short-term planning

- Operation planning
  - Strong variability of WP over the day
  - Opposite behavior with respect to the demand in specific periods
  - NEED FOR FLEXIBLE UNITS

  - Unit Commitment
  - Detailed modeling of ramps, minimum load, startups, and shutdowns of thermal units
  - Reduce unit time step
  - Introduce WP scenarios → Stochastic Unit Commitment

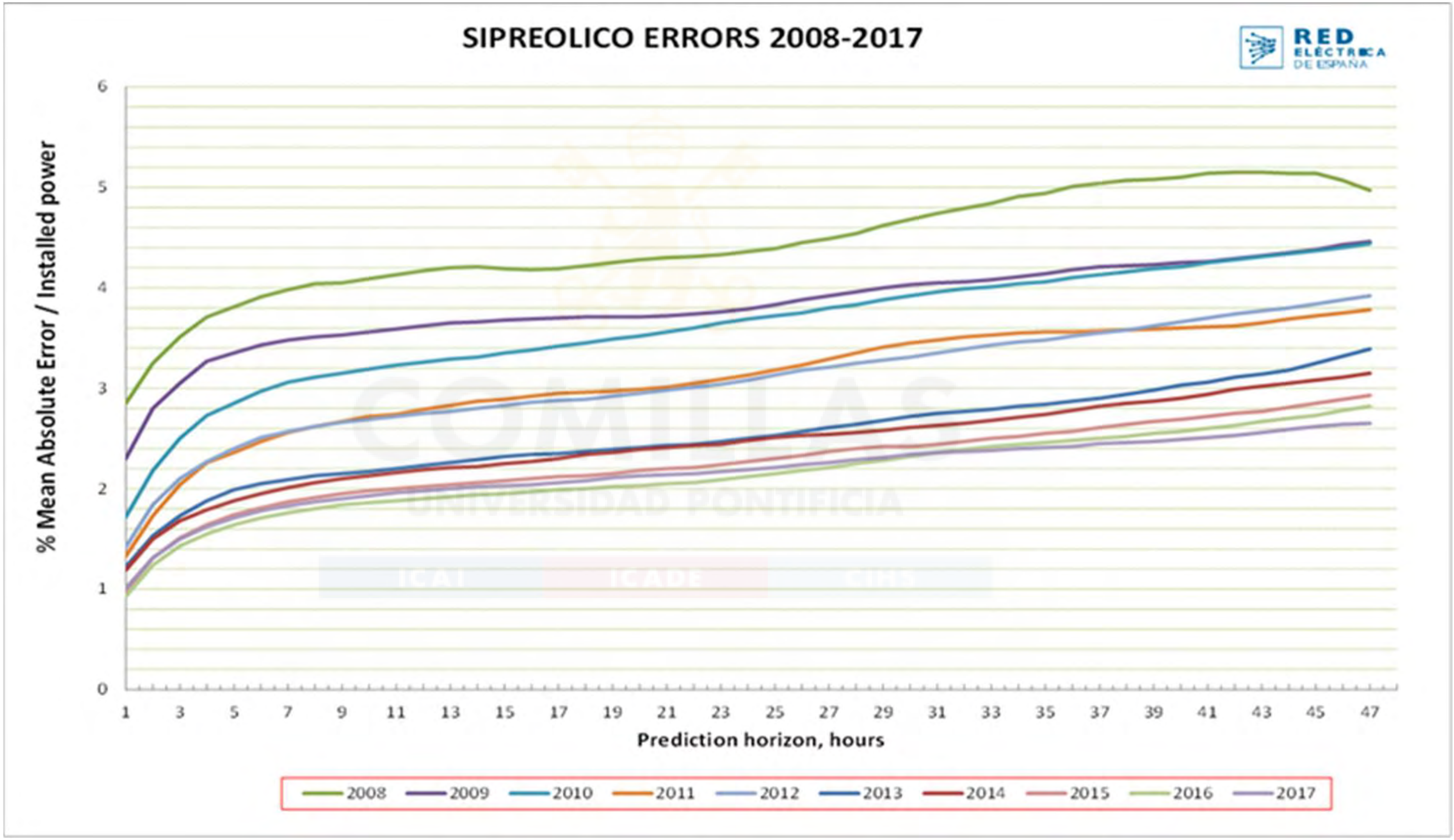
NERC "Flexibility Requirements and Metrics for Variable Generation: Implications for System Planning Studies." Special Report. August 2010. www.nerc.com/files/ivgtf_task_1_4_final.pdf

4

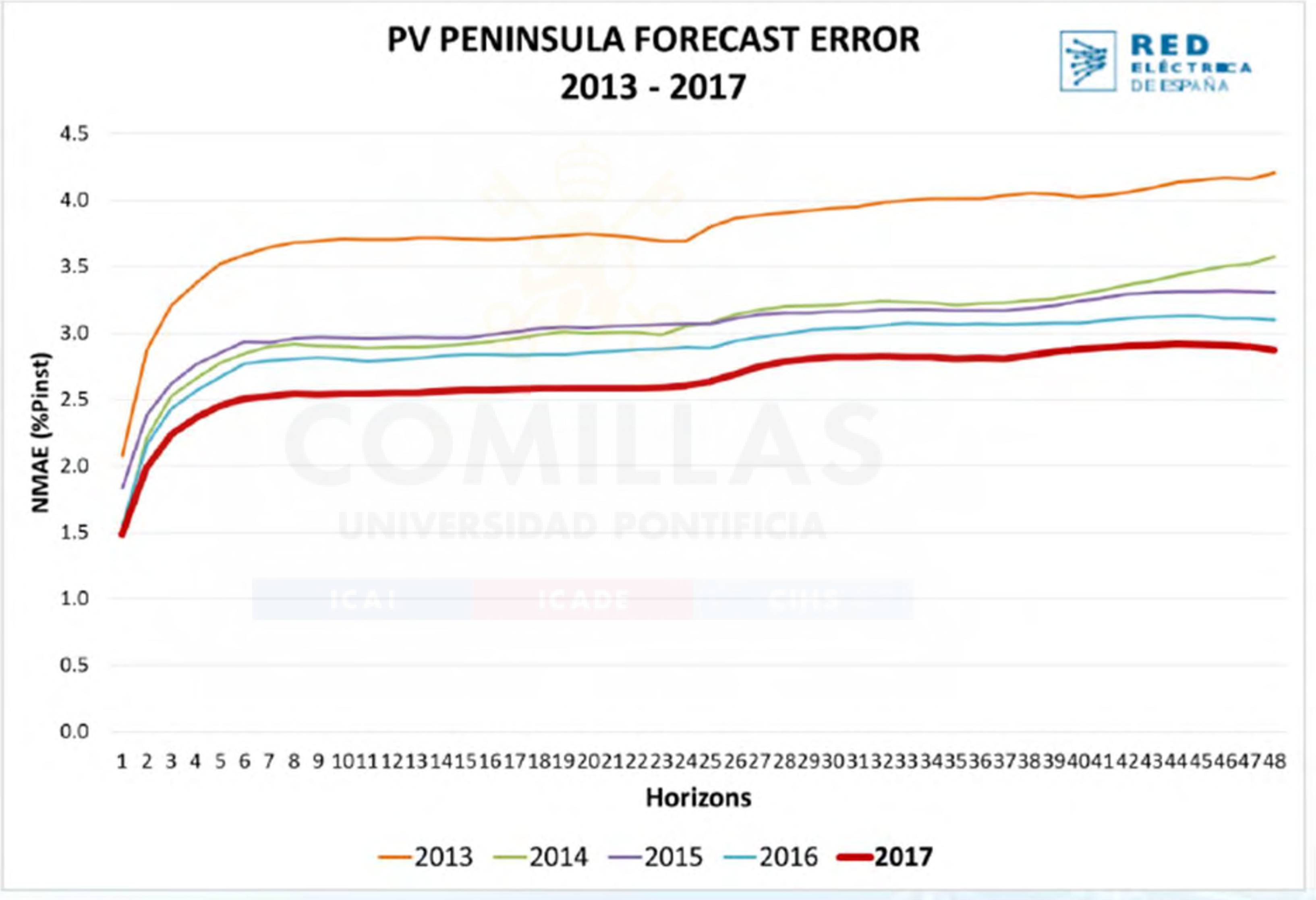
- Wind power
- Impact of WP on medium and long-term planning
- Impact of WP on short-term planning
- Impact of WP on real-time operation
- Stochastic UC
- Prototype stochastic UC. Mathematical formulation
- Prototype stochastic UC. Computer implementation

Impact of WP on real-time operation

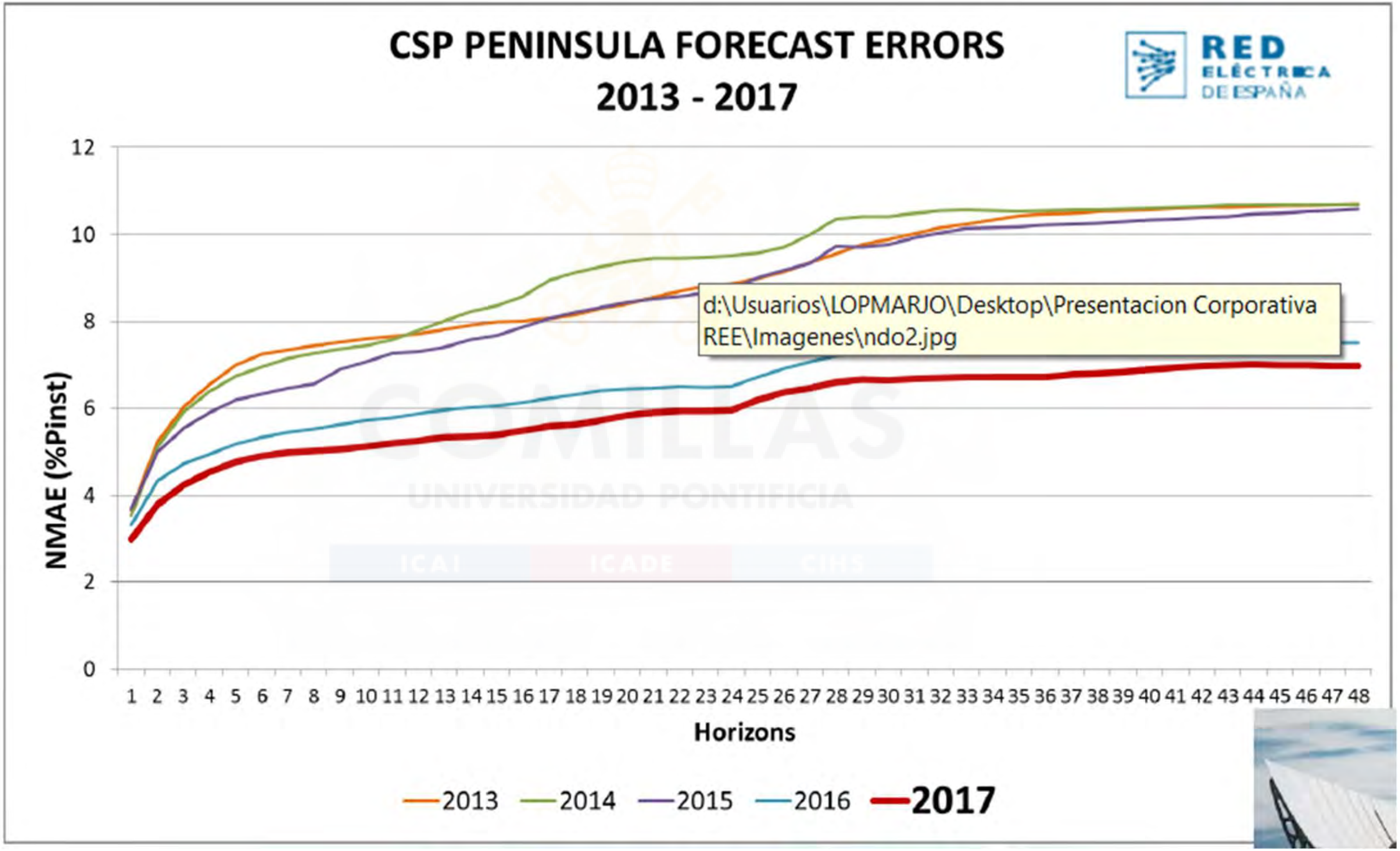
WP Forecast error



Solar PV forecast error



Solar CSP forecast error



WP Forecast error. Location aggregation in Germany

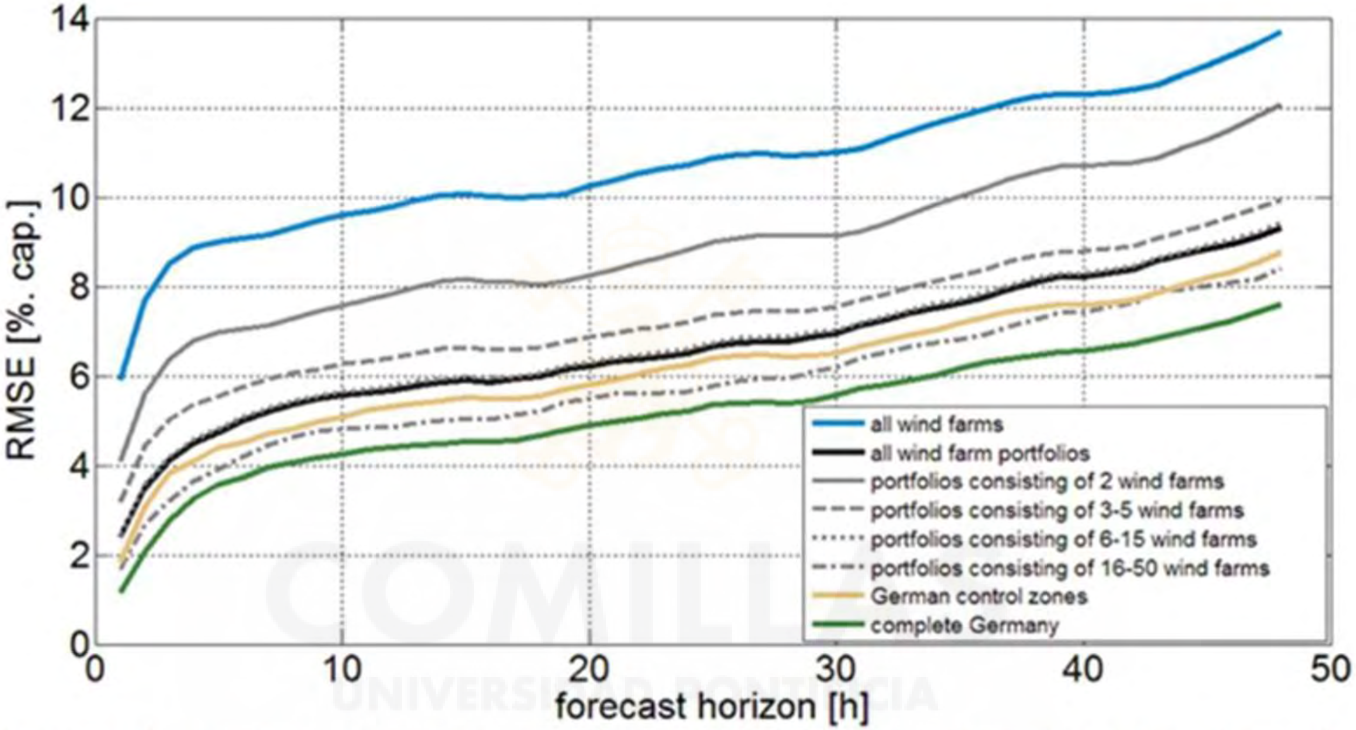


Figure 4. Forecast accuracy depending on the forecast horizon (as root-mean-square-error RMSE in percent of the installed wind power capacity). The lines present different aggregation levels ranging from single wind power plants (blue) up to complete Germany (green). The forecast accuracy has been averaged over several relevant wind power plants, wind power plant portfolios and over all 20 different weather forecasts [6].

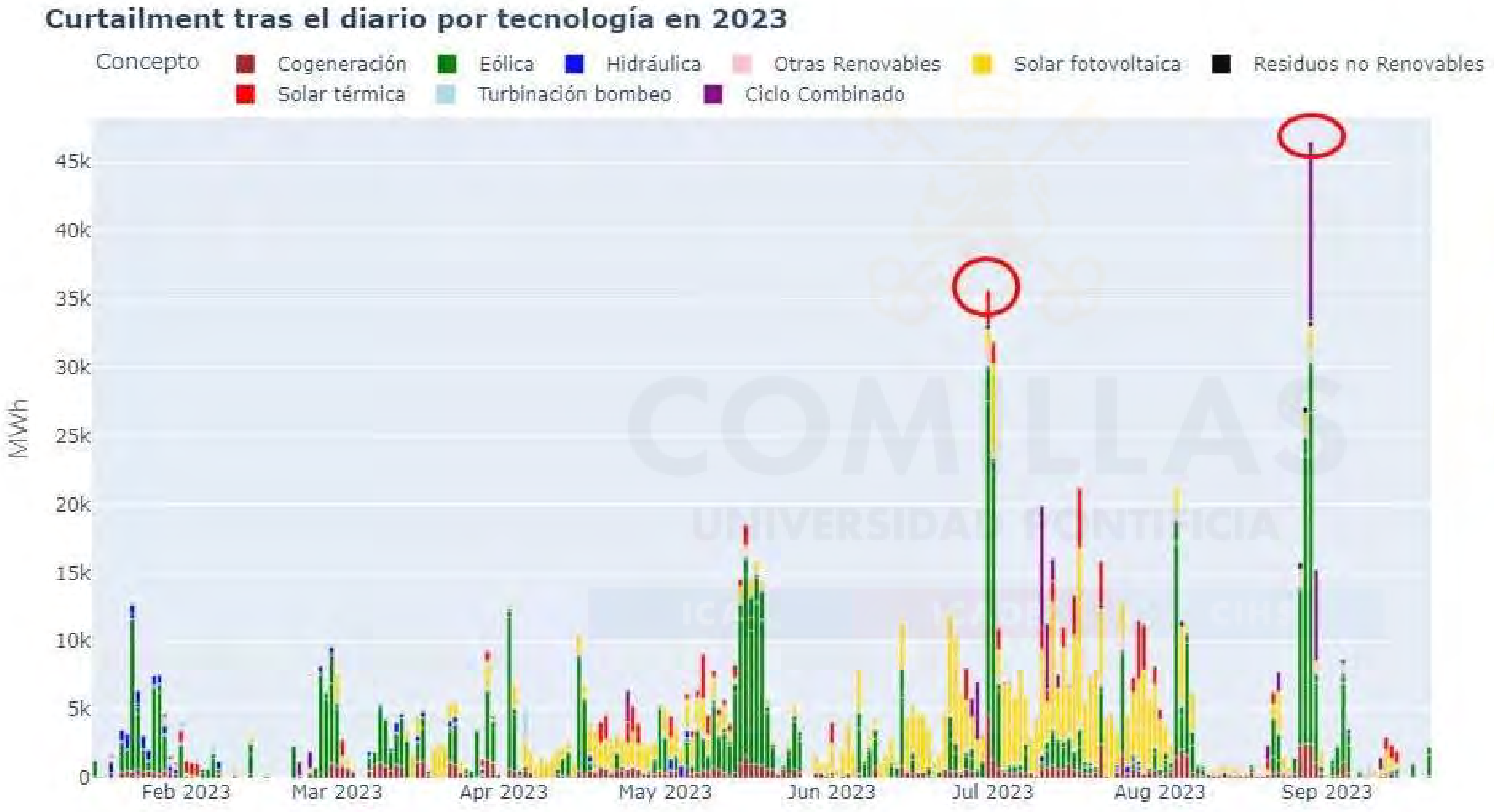
H. Holttinen *EA Wind Task 25 - summary of experiences and studies for wind integration* WIW2016 Workshop Vienna, 15 Nov 2016

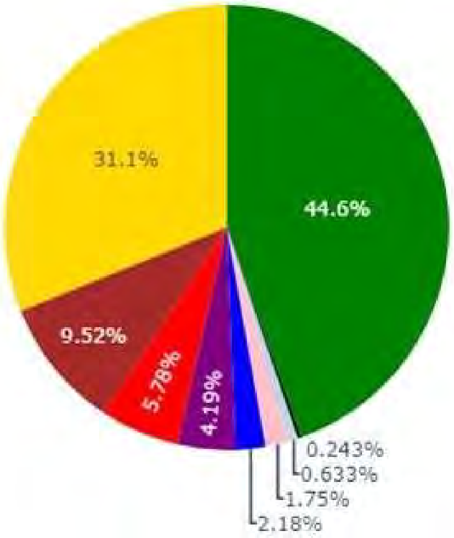
Wind forecast error in Portugal

Source: REN

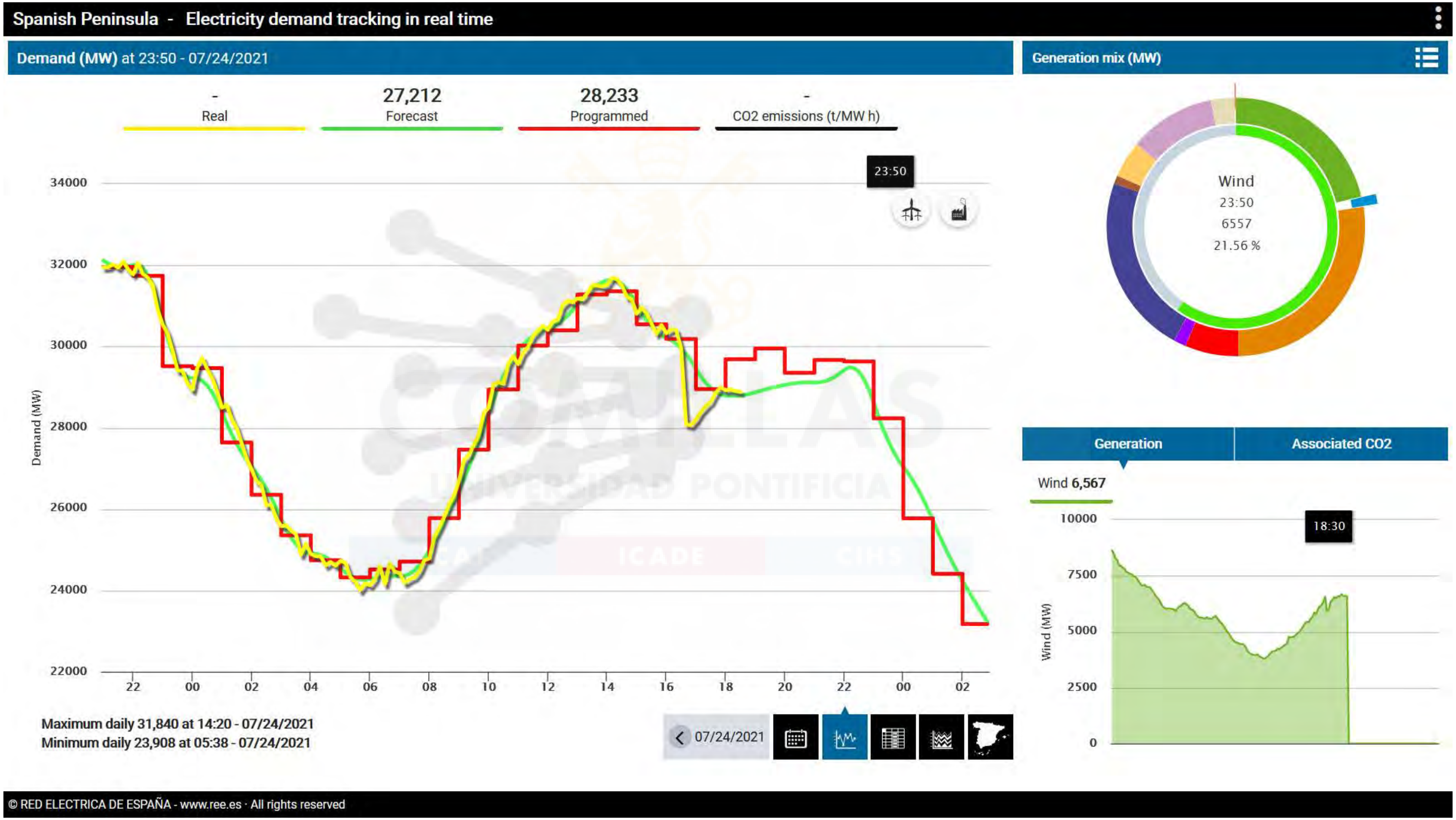
RMSE Root-Mean-Square Error

Curtailment in 2023





Load shedding (July 24, 2021) by an incident in the French power grid



Spanish Peninsula - Electricity demand tracking in real time

Demand (MW) at 23:50 - 07/24/2021

Real	Forecast	Programmed	CO2 emissions (t/MW h)
-	27,212	28,233	-

Maximum daily 31,840 at 14:20 - 07/24/2021
Minimum daily 23,908 at 05:38 - 07/24/2021

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UK National Grid Control Center deals with 1,500,000 kettles

https://youtu.be/WCAzalhldg8

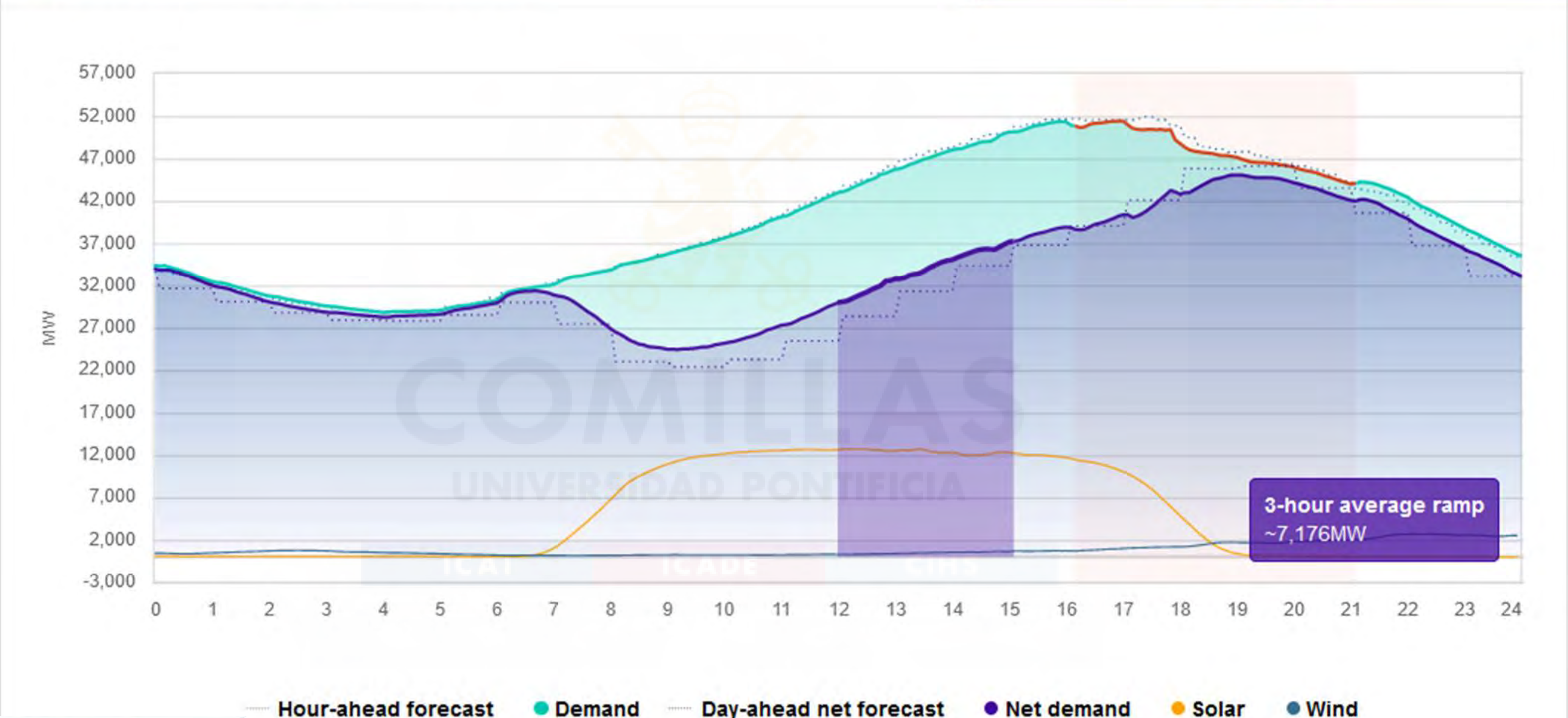
Record high temperatures across California (September 2022)

https://energyathaas.wordpress.com/2022/09/12/how-high-did-californias-electricity-prices-get/


California ISO

Extended: Statewide Flex Alert

Sept. 6 from 4 p.m. – 9 p.m.



http://www.caiso.com/TodaysOutlook/Pages/default.aspx


Tuesday, September 6

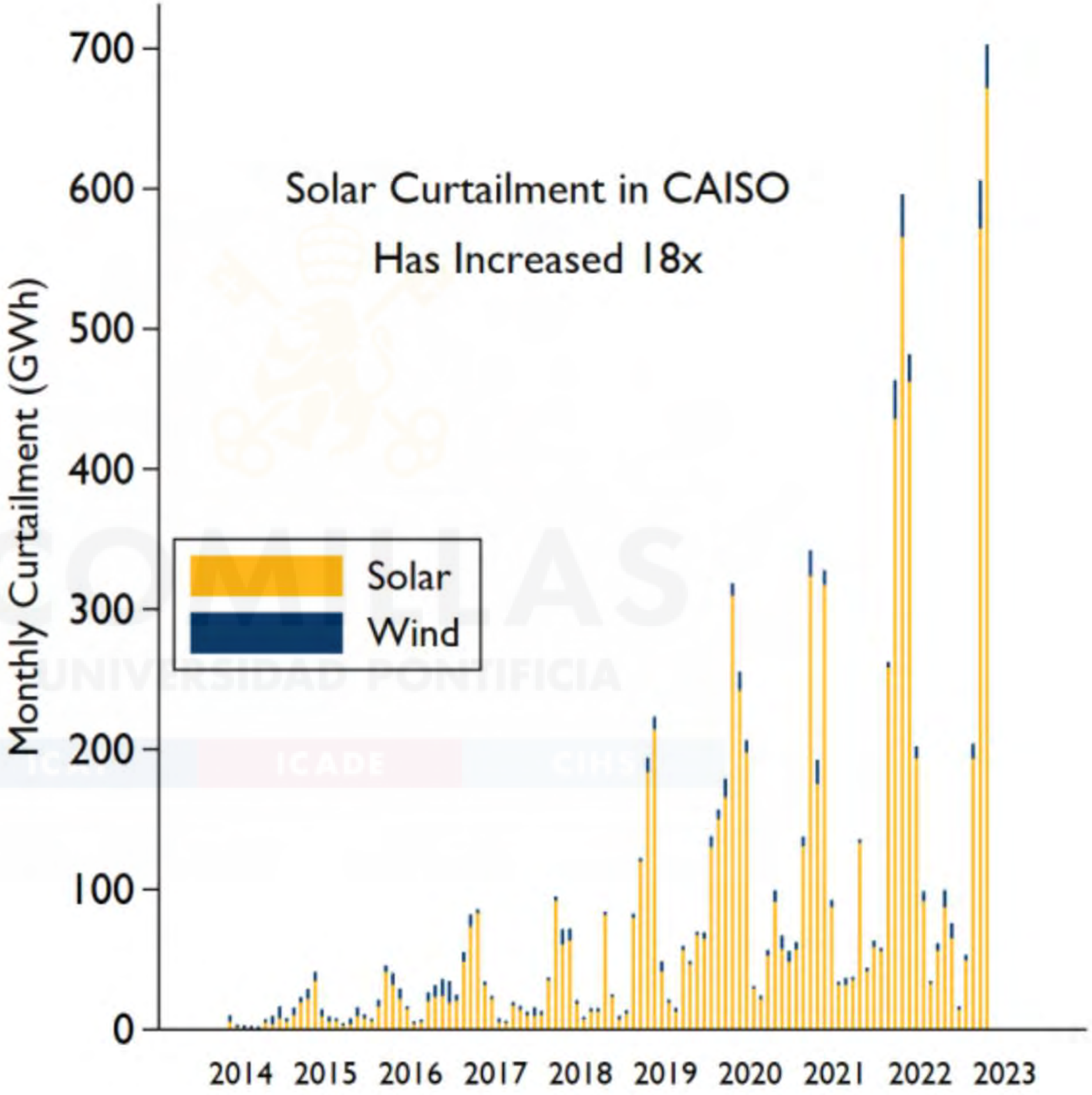
5:48

Emergency Alert now

CalOES, Conserve energy now to protect public health and safety. Extreme heat is straining the state energy grid. Power interruptions may occur unless you take action. Turn off or reduce nonessential power if health allows, now until 9pm.

Curtailment of Renewables at California

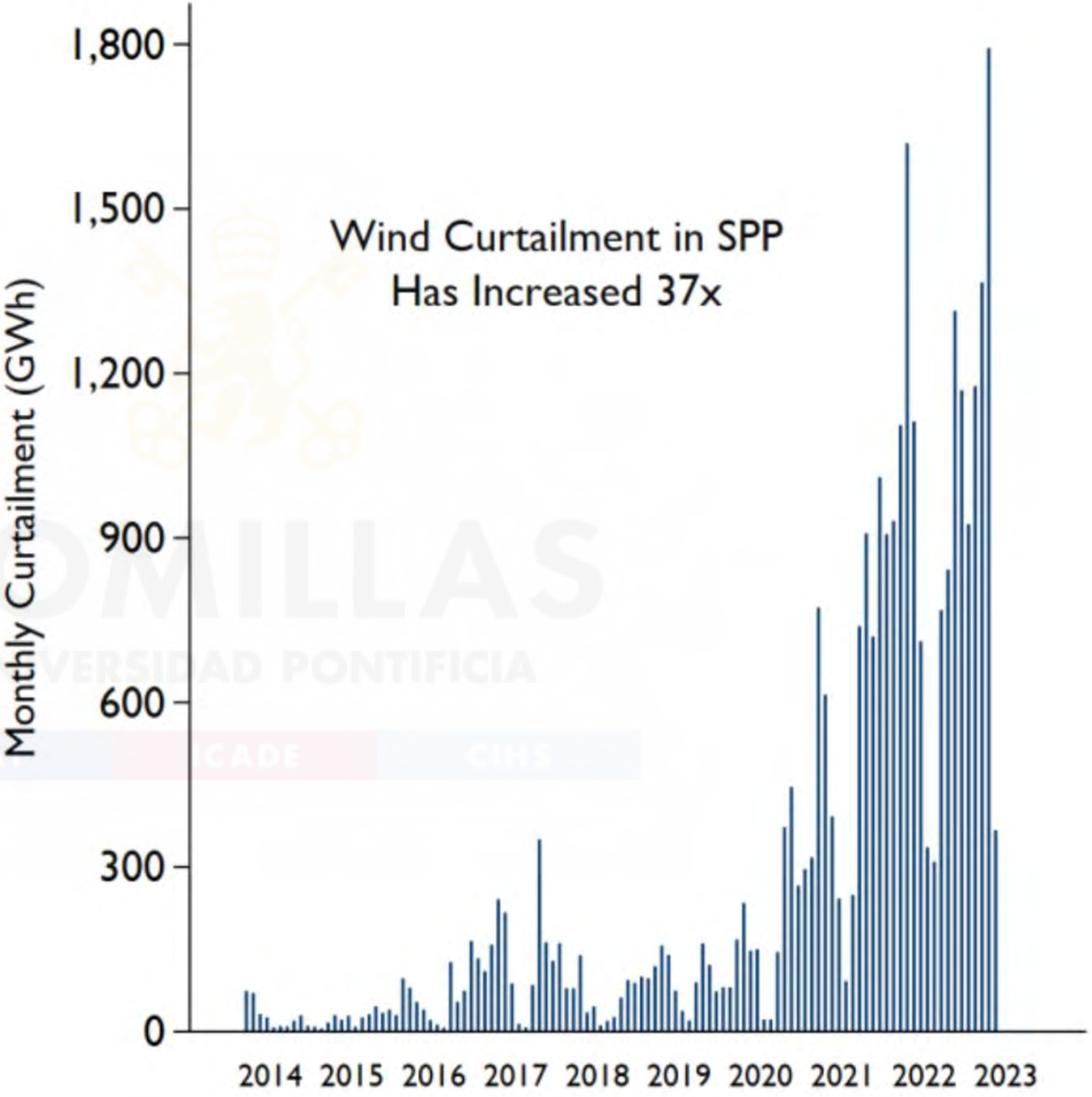
Total solar curtailment in CAISO in 2022 was 1,734 GWh, equivalent to 4.4 % of total solar generation.



L. Davis, C. Hausman, and N. Rose "Transmission Impossible? Prospects for Decarbonizing the US Grid" Energy Institute at HAAS WP 338. June 2023

Curtailment of Renewables at Southwest Power Pool

Total wind curtailment in SPP in 2022 was 11,124 GWh, equivalent to 10.3 % of total wind generation.

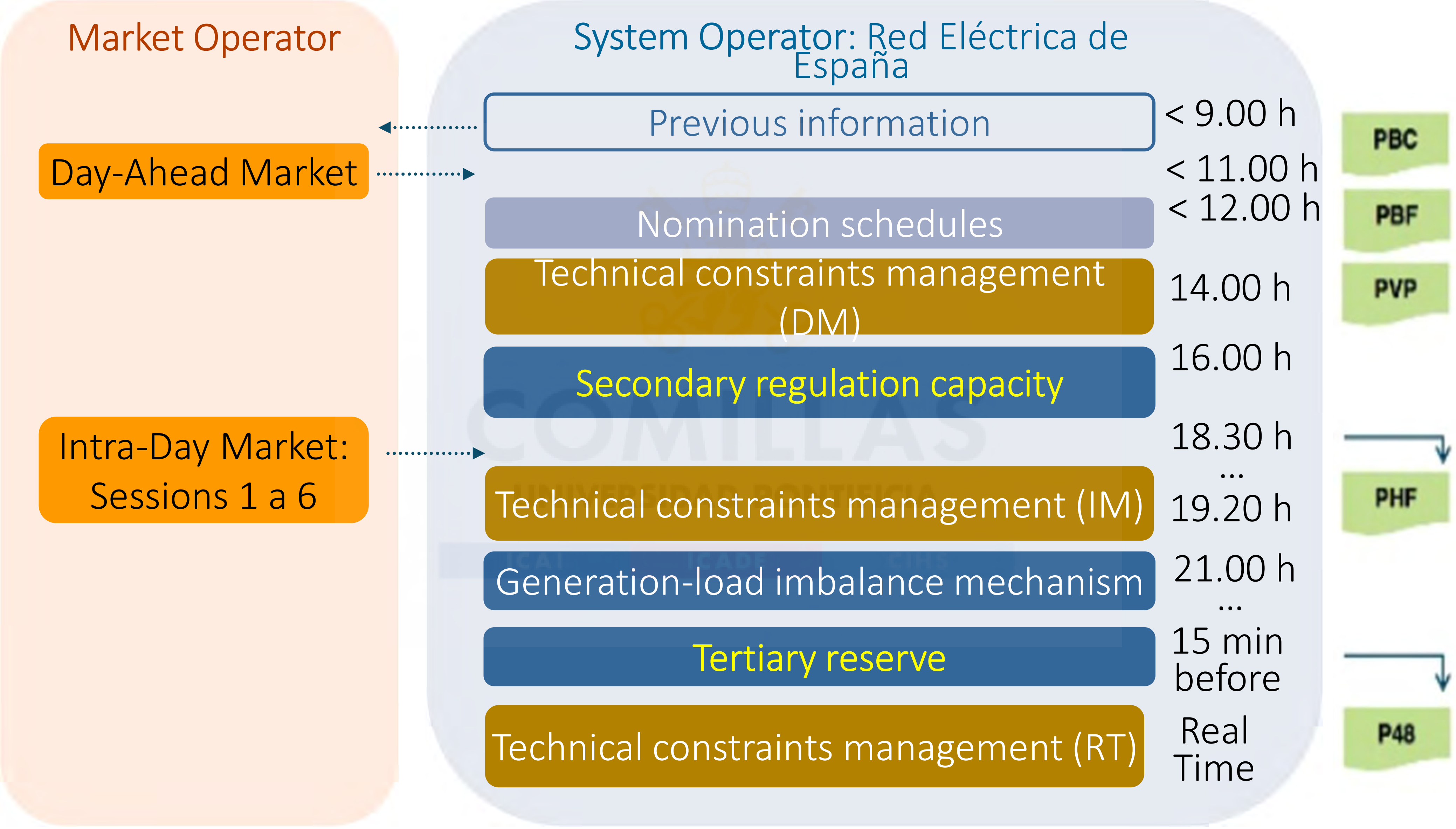


L. Davis, C. Hausman, and N. Rose "Transmission Impossible? Prospects for Decarbonizing the US Grid" Energy Institute at HAAS WP 338. June 2023

Impact of WP on real-time operation

- Predictability. Forecast error. Operating reserves. Wind curtailment
  - Limited predictability or uncertainty: errors increasing with a forecast horizon
  - Critical time horizons are 24 or 36 hours in advance for D-1 operating reserve assessment and 6 hours for real-time unit commitment.
  - NEED FOR OPERATING RESERVES
  - Rapid dynamic adjustments (automatic and manual reserve) to fix WP forecast errors.

Market-based short-term operation scheduling



Market Operator

Day-Ahead Market

Intra-Day Market: Sessions 1 a 6

System Operator: Red Eléctrica de España

Previous information — < 9.00 h

< 11.00 h

< 12.00 h

Nomination schedules

Technical constraints management (DM) — 14.00 h

Secondary regulation capacity — 16.00 h

18.30 h
…

Technical constraints management (IM) — 19.20 h

Generation-load imbalance mechanism — 21.00 h
…

Tertiary reserve — 15 min before

Technical constraints management (RT) — Real Time

Source: M. de la Torre, J. Paradinas *Integration of renewable generation. The case of Spain*

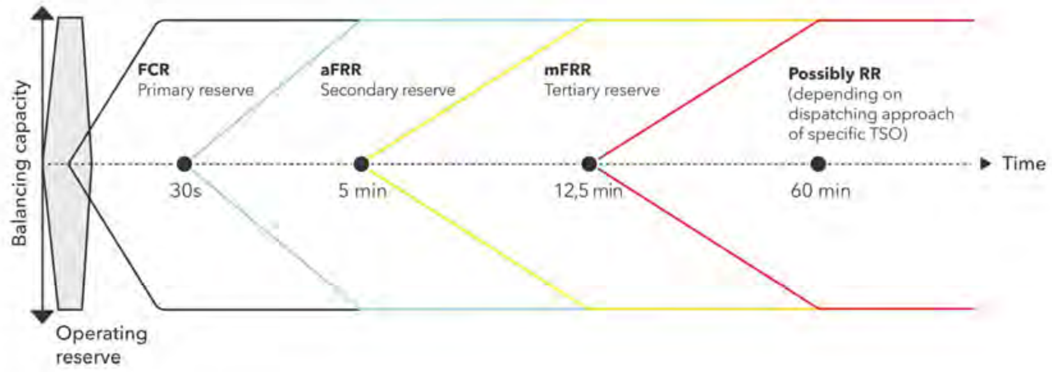
Operating reserves in the Iberian market

- Secondary reserve
  - Offered and cleared one day in advance (at 16 h D-1)
  - Can be asked for at any time
  - Must be deployed in less than 15 min
- Tertiary reserve
  - Offered one day in advance (at 23 h D-1) and updated continuously
  - Asked 10 min in advance
- Can the WP contribute to these operating reserves?
  - One single wind farm can only guarantee approximately 30 % of the installed capacity one day in advance
  - The whole system may have a 15-20 % of forecast error of the output one day in advance

ENTSO-e operating reserves

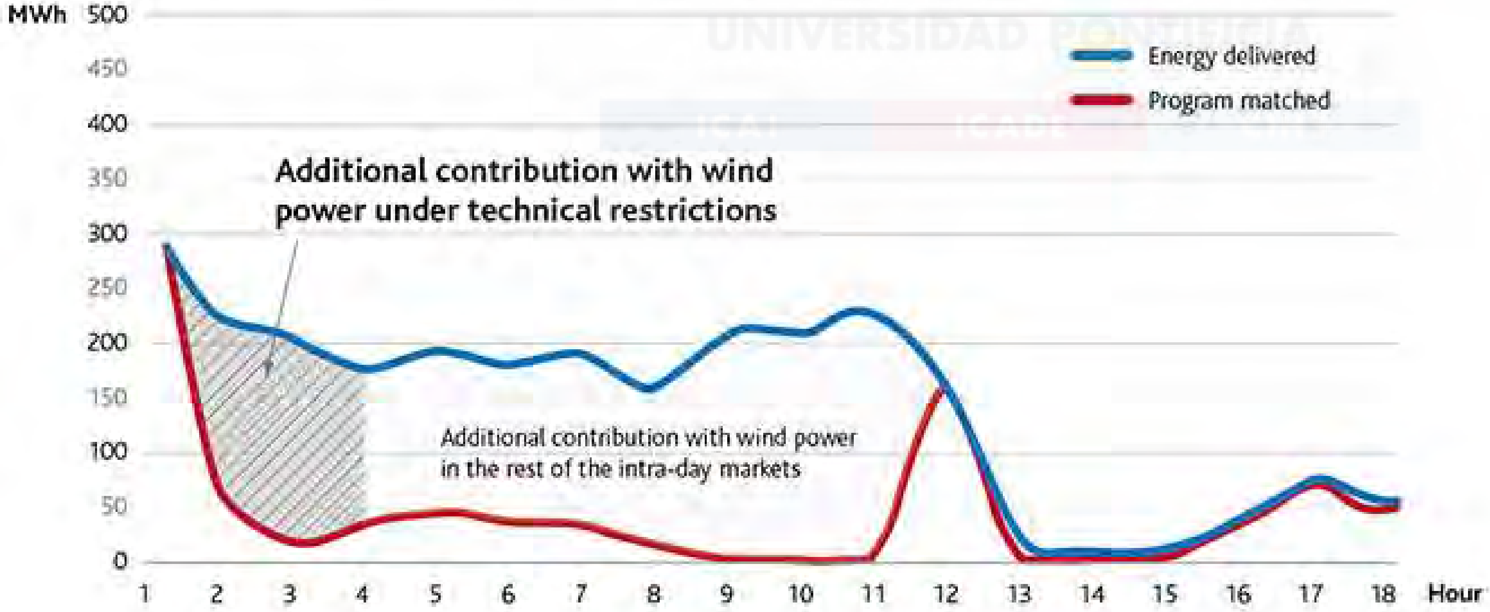
- Frequency Containment Reserves (FCR) (Primary Control)
  - Reserves activated to contain System Frequency after the occurrence of an imbalance
- Frequency Restoration Reserves (FRR)
  - Active Power Reserves activated to restore System Frequency to the Nominal Frequency and for Synchronous Area consisting of more than one LFC Area power balance to the scheduled value
  - Automatic (aFRR) (Secondary Control) or Manual (mFRR) (Tertiary Control)
- Replacement Reserves (RR) (Tertiary Control)
  - Reserves used to restore/support the required level of FRR to be prepared for additional system imbalances. This category includes operating reserves with activation time from Time to Restore Frequency up to hours

Balancing Services According to the System Envisaged by ENTSO-E



ACCIONA Energía, pioneer in providing electric power system adjustment only using wind power

https://www.acciona.com/news/acciona-energia-pioneer-providing-electric-power-system-adjustment-only-using-wind-power/



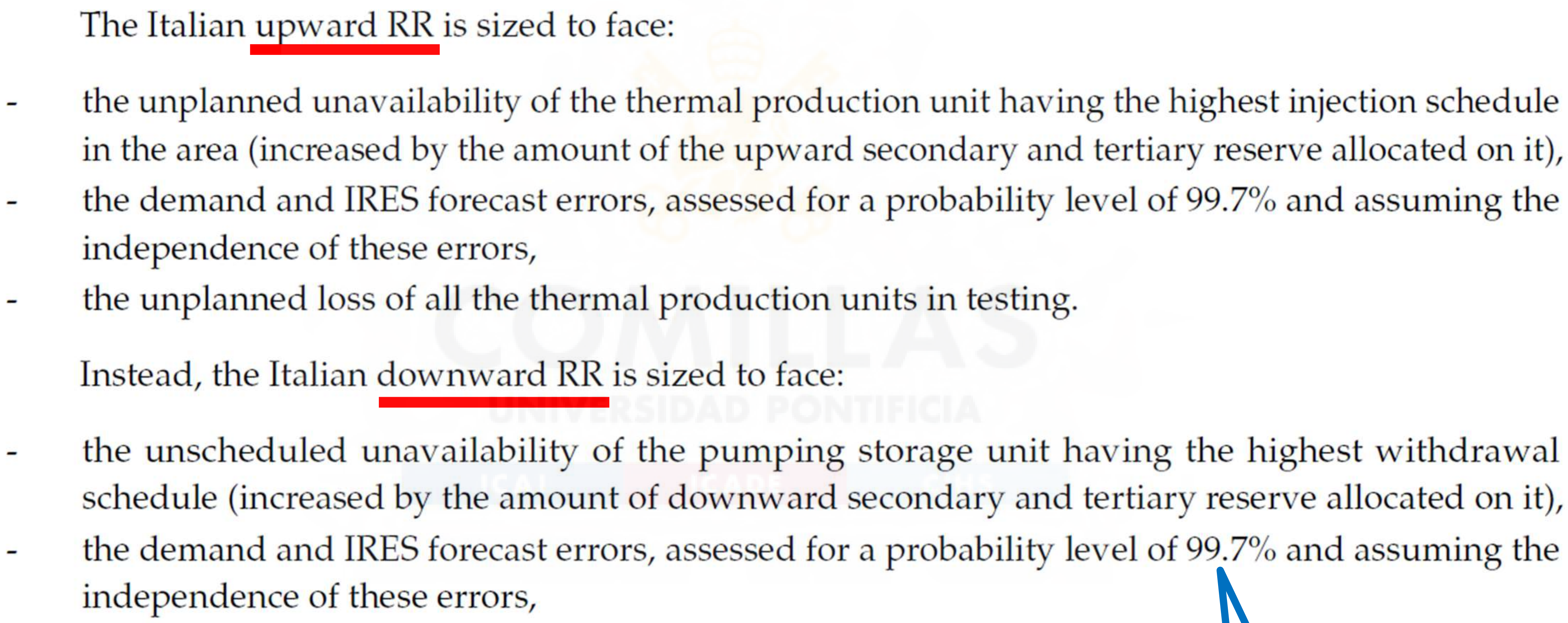
ACCIONA'S CONTRIBUTION TO THE ADJUSTMENT OF THE ELECTRIC POWER SYSTEM IN SPAIN ON 28.02.16

Deterministic criterion for procuring operating reserves in Portugal

- Upward replacement reserve (RR)
  - 2 % of the load
  - 10 % of wind power
  - Largest thermal generator

- Downward replacement reserve (RR)
  - 2 % of the load
  - 10 % of wind power
  - Largest pumped hydro

Upward and Downward Replacement Reserve (Tertiary) in Italy



The Italian upward RR is sized to face:

- the unplanned unavailability of the thermal production unit having the highest injection schedule in the area (increased by the amount of the upward secondary and tertiary reserve allocated on it),
- the demand and IRES forecast errors, assessed for a probability level of 99.7% and assuming the independence of these errors,
- the unplanned loss of all the thermal production units in testing.

Instead, the Italian downward RR is sized to face:

- the unscheduled unavailability of the pumping storage unit having the highest withdrawal schedule (increased by the amount of downward secondary and tertiary reserve allocated on it),
- the demand and IRES forecast errors, assessed for a probability level of 99.7% and assuming the independence of these errors,

3σ

M. Caprabianca, M.C. Falvo, L. Papi, L. Promutico, V. Rossetti and F. Quaglia *Replacement Reserve for the Italian Power System and Electricity Market* Energies 2020, 13(11), 2916; 10.3390/en13112916

Impact of WP at different time scopes

- Medium and long-term planning. Reliability assessment
  - Will there be enough generation to meet peak loads? Determine some system adequacy reliability measures for the system. NEED FOR BACKUP UNITS
- Short-term operation planning. Unit commitment
  - Strong variability of WP over the day. Opposite behavior for the demand in specific periods. Ramps, minimum load, startups, and shutdowns. NEED FOR FLEXIBLE UNITS
- Real-time operation. Operating reserves
  - Limited predictability or uncertainty: errors increasing with a forecast horizon
  - Critical time horizons are 24 or 36 hours in advance for D-1 reserve evaluation and 6 hours for real-time unit commitment.
  - Rapid dynamic adjustments to fix WP forecast errors. Balancing mechanisms, operating reserves. NEED FOR OPERATING RESERVES

5

Wind power

Impact of WP on medium and long-term planning

Impact of WP on short-term planning

Impact of WP on real-time operation

Stochastic UC

Prototype stochastic UC. Mathematical formulation

Prototype stochastic UC. Computer implementation

Stochastic Unit Commitment

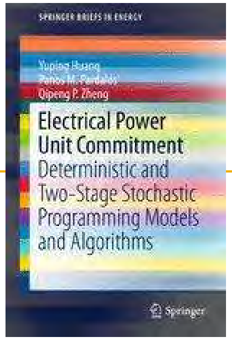
UC in a market framework

- Market surveillance/monitoring
- Assess market power
- Assess operating reserves
- Modifications
  - Price-taker. Self unit commitment
    - Dispatch a single company to maximize profits assuming know market price
  - Price-maker. Strategic unit commitment
    - Dispatch a single company to maximize profits, assuming a residual demand curve to represent competitors’ behavior

Introduction

- Deterministic Unit Commitment (UC)
  - Given load forecasts and available generators, decide when to start up and shut down generators to minimize costs and maintain reliability.
- Stochastic Unit Commitment
  - Some parameters are uncertain. Only their distribution is known
  - Protection against uncertainty
  - Some scenarios may cause “catastrophic” consequences (ENS)
- Sources of uncertainty
  - Generation
    - Intermittent generation (wind, solar)
    - Failure of connected units (security-constrained UC)
  - Demand

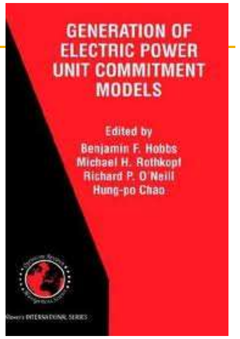
References (i)


SPRINGER BRIEFS IN ENERGY

Yuping Huang
Panos M. Pardalos
Qipeng P. Zheng

Electrical Power Unit Commitment
Deterministic and Two-Stage Stochastic Programming Models and Algorithms

Springer


GENERATION OF ELECTRIC POWER UNIT COMMITMENT MODELS

Edited by
Benjamin F. Hobbs
Michael H. Rothkopf
Richard P. O'Neill
Hung-po Chao

Kluwer's INTERNATIONAL SERIES

- M.F. Anjos, A.J. Conejo *Unit Commitment in Electric Energy Systems* Now, 2017
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- Tight: small integrality gap, initial LP relaxation close to the final MIP solution
- Compact: small optimization problem, few constraints and variables

6

- Wind power
- Impact of WP on medium and long-term planning
- Impact of WP on short-term planning
- Impact of WP on real-time operation
- Stochastic UC
- Prototype stochastic UC. Mathematical formulation
- Prototype stochastic UC. Computer implementation

Prototype Stochastic UC. Mathematical Formulation

Mathematical formulation

- Objective function
  - Minimize the total expected variable costs plus penalties for energy not served
- Variables
  - BINARY: commitment, startup, and shutdown of thermal units
  - Hydro and thermal output
- Operation constraints
  - Load balance and operating reserve
  - Hydro and thermal operation constraints
  - Energy inventory in water reservoirs
- Mixed integer linear programming (MIP)

Indices

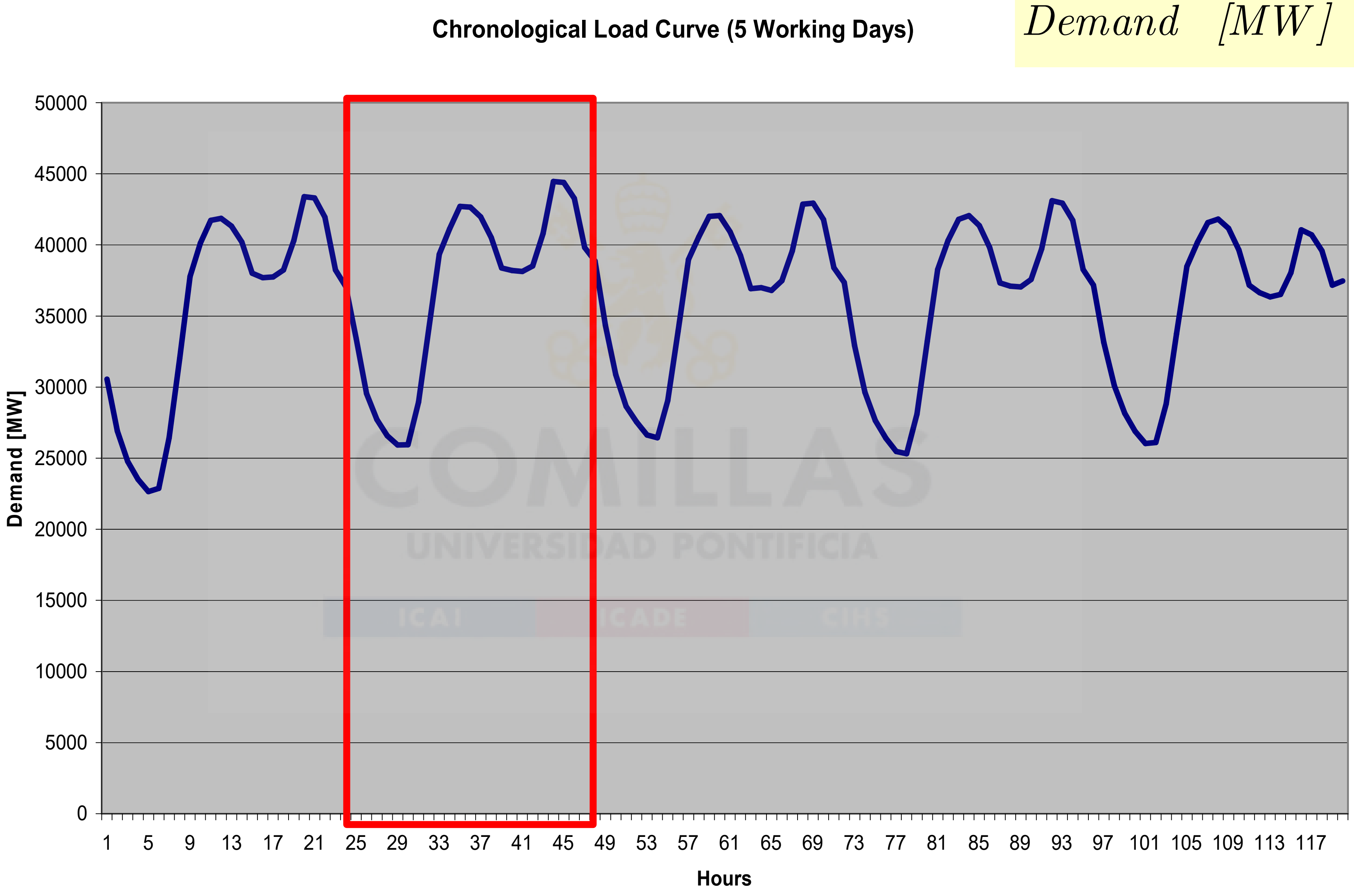
- Time scope
  - 1 day
- Period
  - 1 hour
- Scenario

$Hour \quad n$

$Scenario \quad \omega$

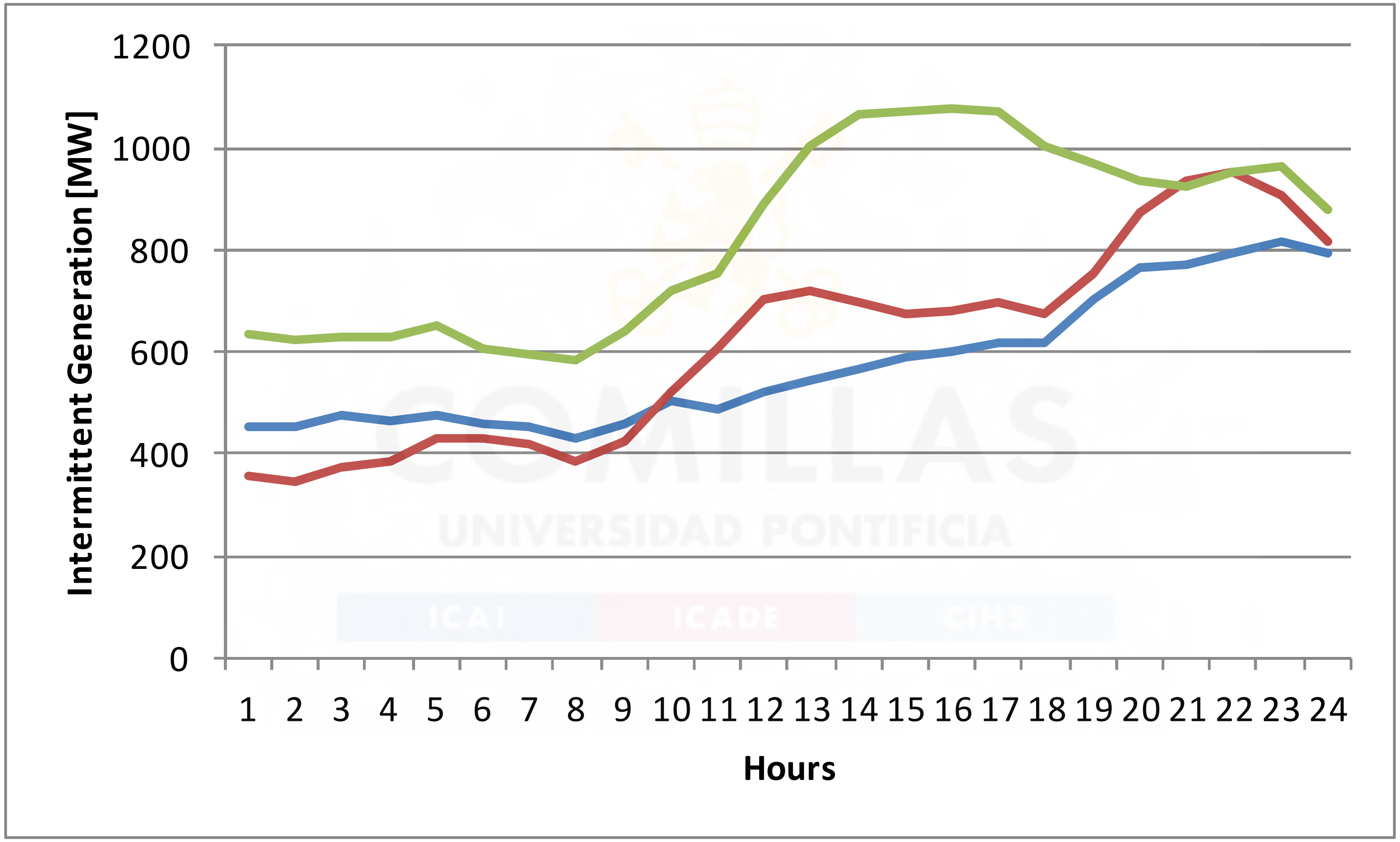
Demand (5 weekdays)

$$Demand\quad [MW]\quad D_n$$



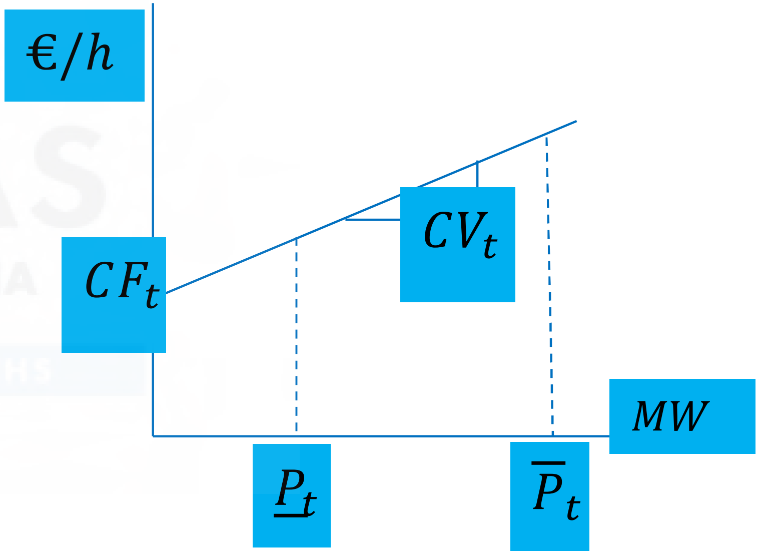
Intermittent generation (IG)

$$\text{Intermittent generation} \quad [MW] \quad IG_n^{\omega}$$



Technical characteristics of thermal units (t)

- Maximum and minimum output
- Fuel cost
- Slope and intercept of the heat rate straight line
- Operation and maintenance (O&M) variable cost
  - No load cost = fuel cost x heat rate intercept
  - Variable cost = fuel cost x heat rate slope + O&M cost
- Cold startup and shutdown cost
- Up and down ramps



Max and min output	[MW]	$\overline{P}_t, \underline{P}_t$
No load cost	[€/h]	CF_t
Variable cost	[€/MWh]	CV_t
Startup cost	[€]	CSU_t
Shutdown cost	[€]	CSD_t

Ramp up	[MW/h]	RU_t
Ramp down	[MW/h]	RD_t

Technical characteristics of hydro plants (h)

- Maximum and minimum output
- Production function (efficiency for conversion of water release in m^3/s to electric power MW)
- Round-trip efficiency of pumped storage hydro plants
  - Only this ratio of the energy consumed to pump the water is recovered by turbining this water

Max and min output	$[MW]$	$\overline{P}_h, \underline{P}_h$
Production function	$[kWh/m^3]$	C_h
Efficiency	$[p.u.]$	η_h

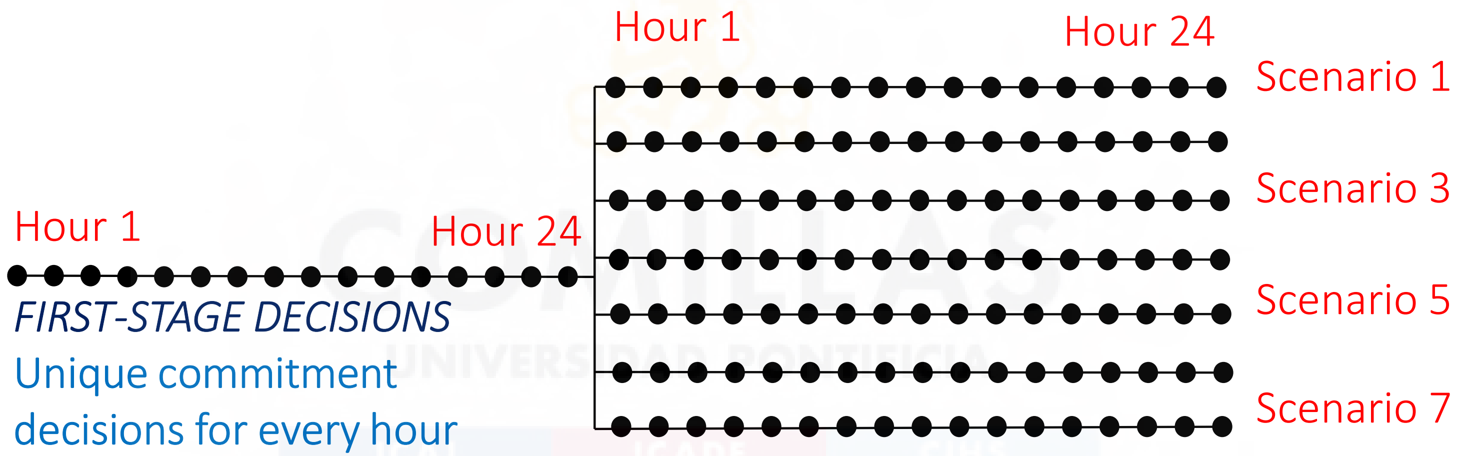
Technical characteristics of hydro reservoirs (h)

- Maximum and minimum reserve
- Initial reserve
  - Final reserve = initial reserve
- Inflows

Max and min reserve	$[hm^3]$	$\overline{R}_h, \underline{R}_h$
Initial and final reserve	$[hm^3]$	R'_h
Inflows	$[m^3/s]$	I_{nh}

Scenario tree for the stochastic unit commitment

- Commitment decisions of thermal units (the set of committed units) are unique under different stochastic scenarios (intermittent generation IG, demand, etc.)



FIRST-STAGE DECISIONS

Unique commitment decisions for every hour

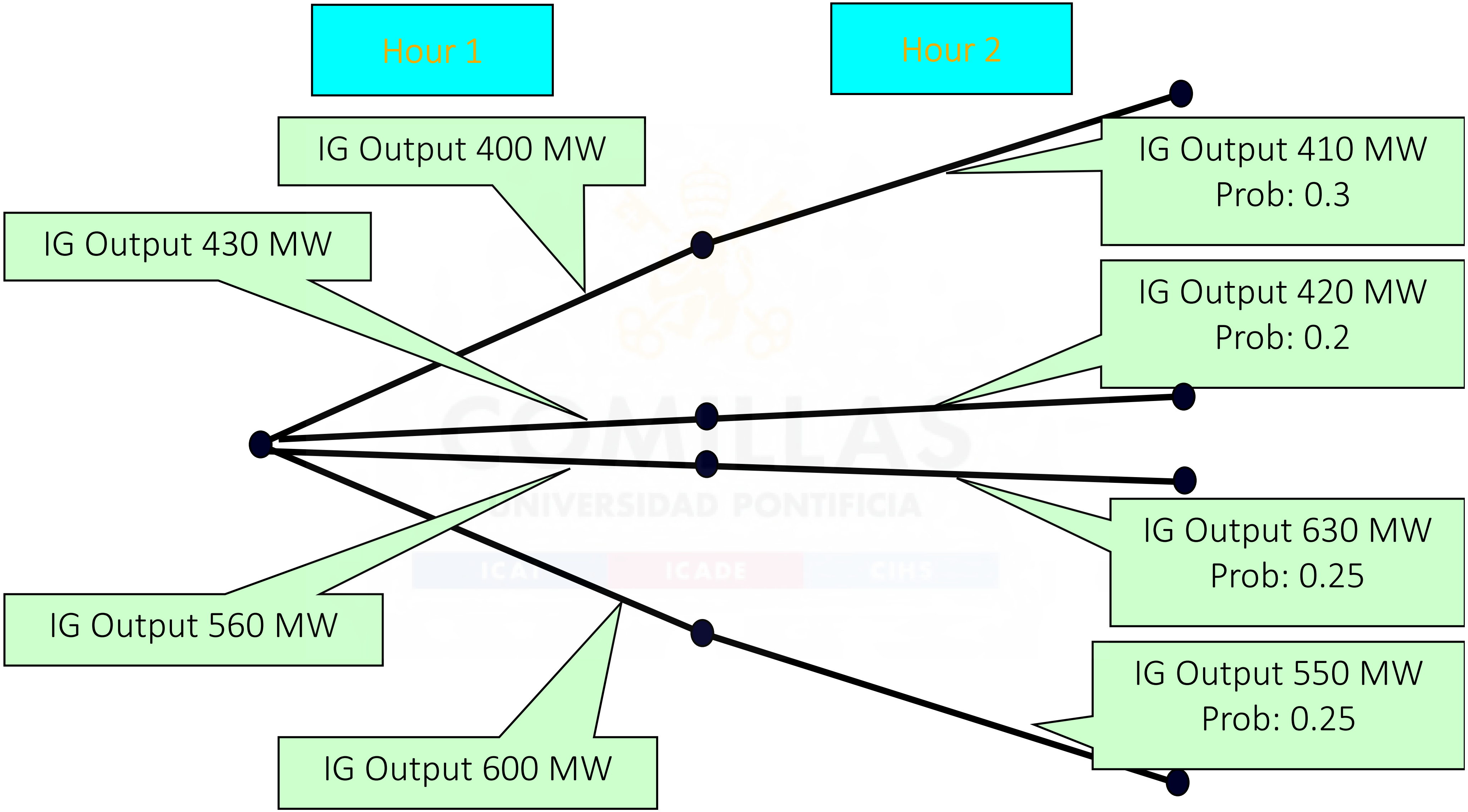
SECOND-STAGE DECISIONS

Generator output for every hour depend on the scenario

TWO-STAGE
DECISION PROBLEM

$$Probability\ of\ scenario \quad P^{\omega}$$

Scenario tree example with IG uncertainty



Hour 1

Hour 2

IG Output 400 MW

IG Output 430 MW

IG Output 560 MW

IG Output 600 MW

IG Output 410 MW
Prob: 0.3

IG Output 420 MW
Prob: 0.2

IG Output 630 MW
Prob: 0.25

IG Output 550 MW
Prob: 0.25

Variables

- Commitment, startup, and shutdown of thermal units (BINARY)

$$\textit{Commitment, startup and shutdown} \quad \{0,1\} \quad uc_{nt}, su_{nt}, sd_{nt}$$

- Production of hydro and thermal units

$$\textit{Production of a thermal and hydro unit} \quad [MW] \quad p_{nt}^{\omega}, p_{nh}^{\omega}$$

- Intermittent generation

$$\textit{Intermittent generation} \quad [MW] \quad ig_{n}^{\omega}$$

- Reservoir volume

$$\textit{Reservoir volumen} \quad [GWh] \quad r_{nh}^{\omega}$$

- Energy not served

$$\textit{Energy not served} \quad [MW] \quad ens_{n}^{\omega}$$

Constraints: Operating power reserve

Committed output of thermal units
+ *Maximum output of hydro plants*
≥ *Demand*
+ *Operating reserve* *for each load level and scenario* [*MW*]

$$\sum_t \overline{P}_t uc_{nt} + \sum_h \overline{P}_h \geq D_n + O_n \quad \forall n$$

Constraints: Generation and load balance

Generation of hydro and thermal units
+ Energy not served
= Demand for each load level and scenario [MW]

$$\sum_t p_{nt}^{\omega} + \sum_h p_{nh}^{\omega} + ig_n^{\omega} + ens_n^{\omega} = D_n \quad \forall \omega n$$

Constraints: Production in consecutive load levels

Unit output in any hour - Unit output in previous one ≤ ramp up [MW]

Unit output in any hour - Unit output in previous one ≥ – ramp down [MW]

$$p_{nt}^{\omega} - p_{n-1t}^{\omega} \leq RU_t \quad \forall \omega nt$$
$$p_{nt}^{\omega} - p_{n-1t}^{\omega} \geq -RD_t \quad \forall \omega nt$$

Constraints: Commitment, startup, and shutdown

Commitment of a thermal unit in an hour
– Commitment of a thermal unit in the previous hour
= Startup of a thermal unit in this hour
– Shutdown of a thermal unit in this hour [p.u.]

$$uc_{nt} - uc_{n-1t} = su_{nt} - sd_{nt} \quad \forall nt$$

Constraints: Commitment and production

Production of a thermal unit on every scenario
≤ Commitment of a thermal unit x *the maximum output* [*MW*]

Production of a thermal unit on every scenario
≥ Commitment of a thermal unit x *the minimum output* [*MW*]

$$uc_{nt}\underline{P}_t \le p_{nt}^{\omega} \le uc_{nt}\overline{P}_t \quad \forall \omega nt$$

- If the thermal unit is committed ($uc_{nt} = 1$) it can produce between its minimum and maximum output
- If the thermal unit is not committed ($uc_{nt} = 0$) it can't produce

Constraints: Energy balance for each reservoir

Reservoir energy in hour $n-1$
– *Reservoir energy in hour* n
+ *Natural inflows*
– *Spillage from this reservoir*
– *Turbined energy from this reservoir* = 0 *for each reservoir,*
hour and scenario [*GWh*]

$$r_{n-1h}^{\omega} - r_{nh}^{\omega} + I_{nh} - s_{nh}^{\omega} - p_{nh}^{\omega} = 0 \qquad \forall \omega nh$$

Constraints: Operation limits

Power output between limits for each unit [MW]

$0 \leq p_{nt}^{\omega} \leq \overline{P}_t \quad \forall \omega nt$

$0 \leq p_{nh}^{\omega} \leq \overline{P}_h \quad \forall \omega nh$

Commitment, startup, and shutdown for each unit [p.u.]

$uc_{nt}, su_{nt}, sd_{nt} \in \{0,1\} \quad \forall nt$

Intermittent generation limit [MW]

$0 \leq ig_n^{\omega} \leq IG_n^{\omega} \quad \forall \omega n$

Weighted-sum objective function

- Minimize
  - Thermal unit expected variable costs (first stage + second stage) [€]

$$\sum_{nt} CSU_t su_{nt} + \sum_{nt} CSD_t sd_{nt} + \sum_{nt} CF_t uc_{nt} +$$

$$\sum_{\omega nt} P^{\omega} CV_t p_{nt}^{\omega}$$

  - Expected penalty introduced in the objective function for energy not served [€]

$$\sum_{\omega n} P^{\omega} CV' ens_n^{\omega}$$

Short Run Marginal Cost (SRMC)

- Short Run Marginal Cost = Dual variable of generation and load balance when binary variables (commitment, startup, and shutdown) are fixed [€/MWh]
  - Change in the objective function due to a marginal increment in the demand

$$\sum_t p_{nt}^{\omega} + \sum_h p_{nh}^{\omega} + ig_n^{\omega} + ens_n^{\omega} = D_n \quad : \sigma_n^{\omega} \quad \forall \omega n$$

$$SRMC_n^{\omega} = \sigma_n^{\omega} / P^{\omega} \quad \forall \omega n$$

Dual variable = change in the objective function with respect to a marginal increase in the RHS of a constraint

7

Wind power

Impact of WP on medium and long-term planning

Impact of WP on short-term planning

Impact of WP on real-time operation

Stochastic UC

Prototype stochastic UC. Mathematical formulation

Prototype stochastic UC. Computer implementation

Prototype Stochastic UC. Computer implementation

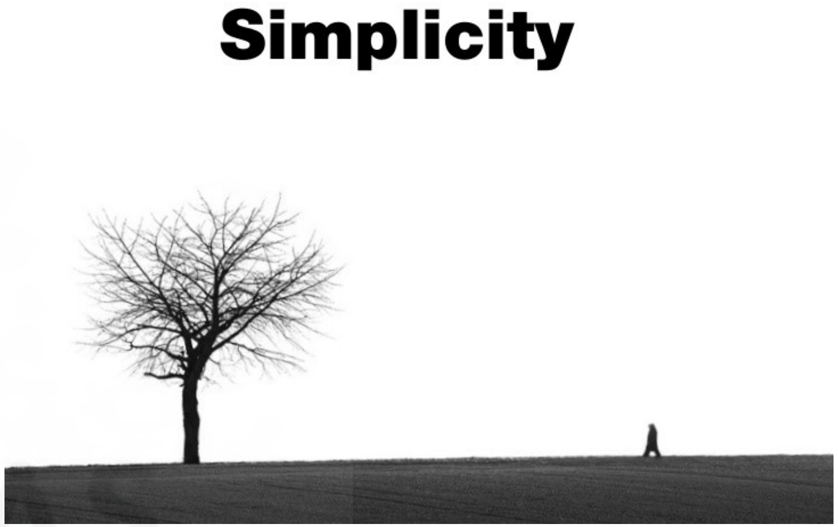
Stochastic Daily Unit Commitment

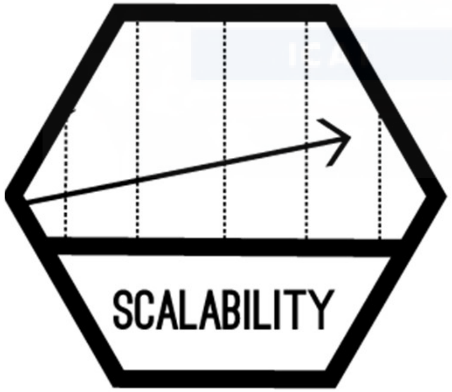
1. **openSDUC** Stochastic Daily Unit Commitment in Python/Pyomo (https://pascua.iit.comillas.edu/aramos/openSDUC/index.html)

2. **StarGenLite_SDUC** Stochastic Daily Unit Commitment Model (https://pascua.iit.comillas.edu/aramos/StarGenLite_SDUC.zip)

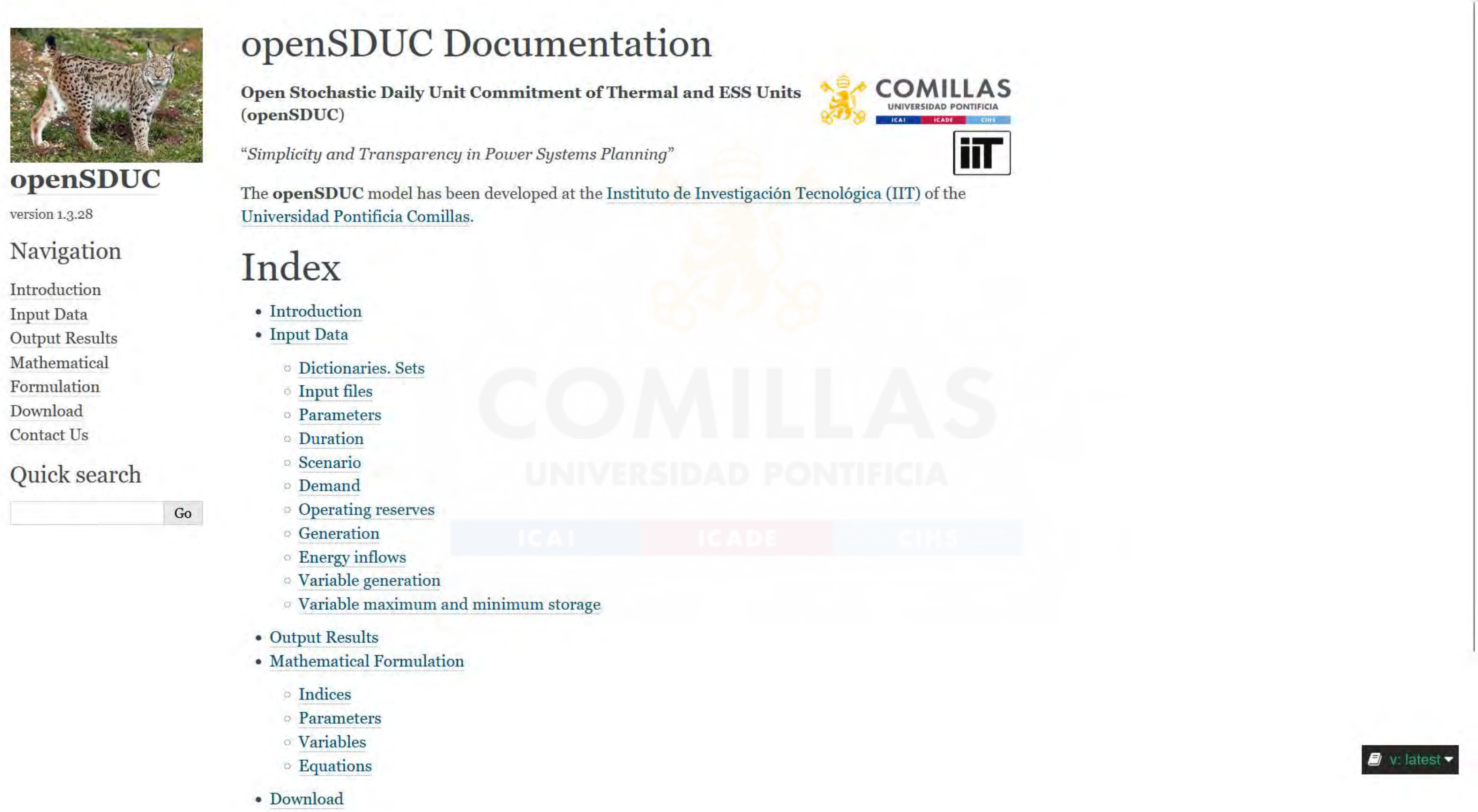
Main code features

- Simplicity and transparency
- Code is written to be read by humans
- Tight and compact formulation
- Careful implementation. Numerical stability
- Scalability: from small- to large-scale cases





openSDUC Stochastic Daily Unit Commitment in Python/Pyomo
(https://pascua.iit.comillas.edu/aramos/openSDUC/index.html)



openSDUC

version 1.3.28

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openSDUC Documentation

Open Stochastic Daily Unit Commitment of Thermal and ESS Units (openSDUC)

"Simplicity and Transparency in Power Systems Planning"

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

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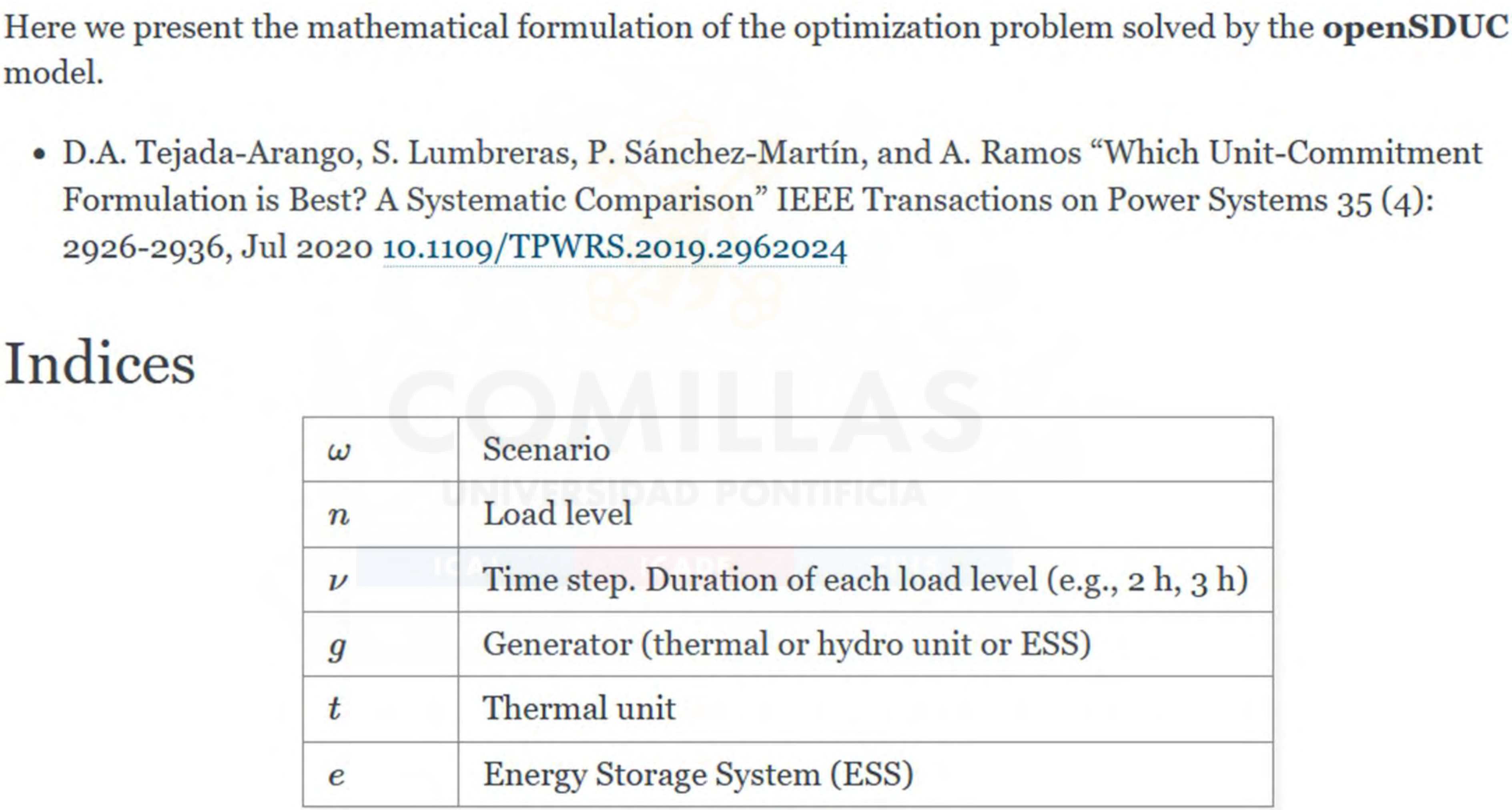
Sets/Indices



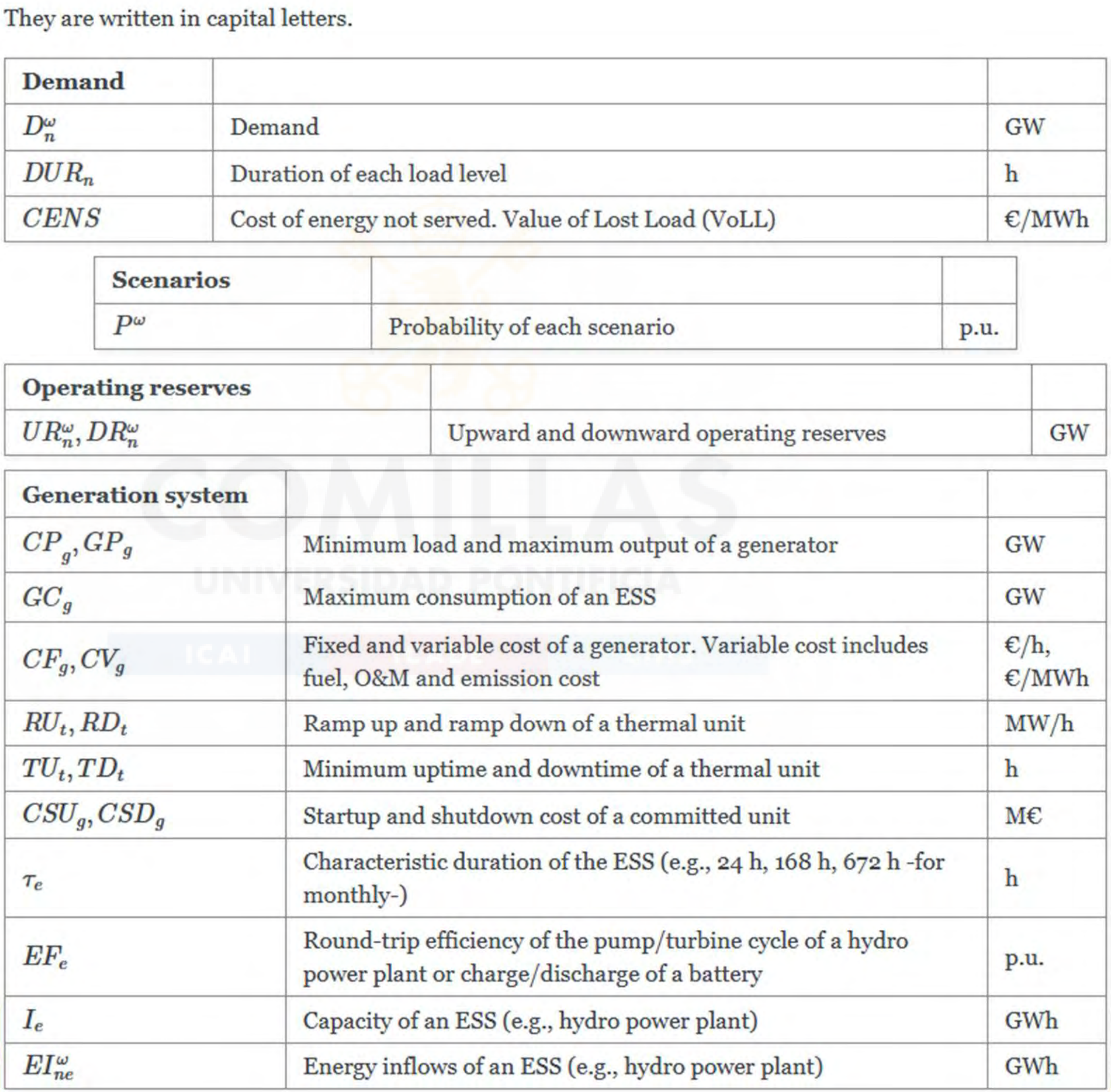
Here we present the mathematical formulation of the optimization problem solved by the **openSDUC** model.

- D.A. Tejada-Arango, S. Lumbreras, P. Sánchez-Martín, and A. Ramos "Which Unit-Commitment Formulation is Best? A Systematic Comparison" IEEE Transactions on Power Systems 35 (4): 2926-2936, Jul 2020 10.1109/TPWRS.2019.2962024

Indices

ω	Scenario
n	Load level
ν	Time step. Duration of each load level (e.g., 2 h, 3 h)
g	Generator (thermal or hydro unit or ESS)
t	Thermal unit
e	Energy Storage System (ESS)

Parameters



They are written in capital letters.

Demand		
D_n^ω	Demand	GW
DUR_n	Duration of each load level	h
$CENS$	Cost of energy not served. Value of Lost Load (VoLL)	€/MWh

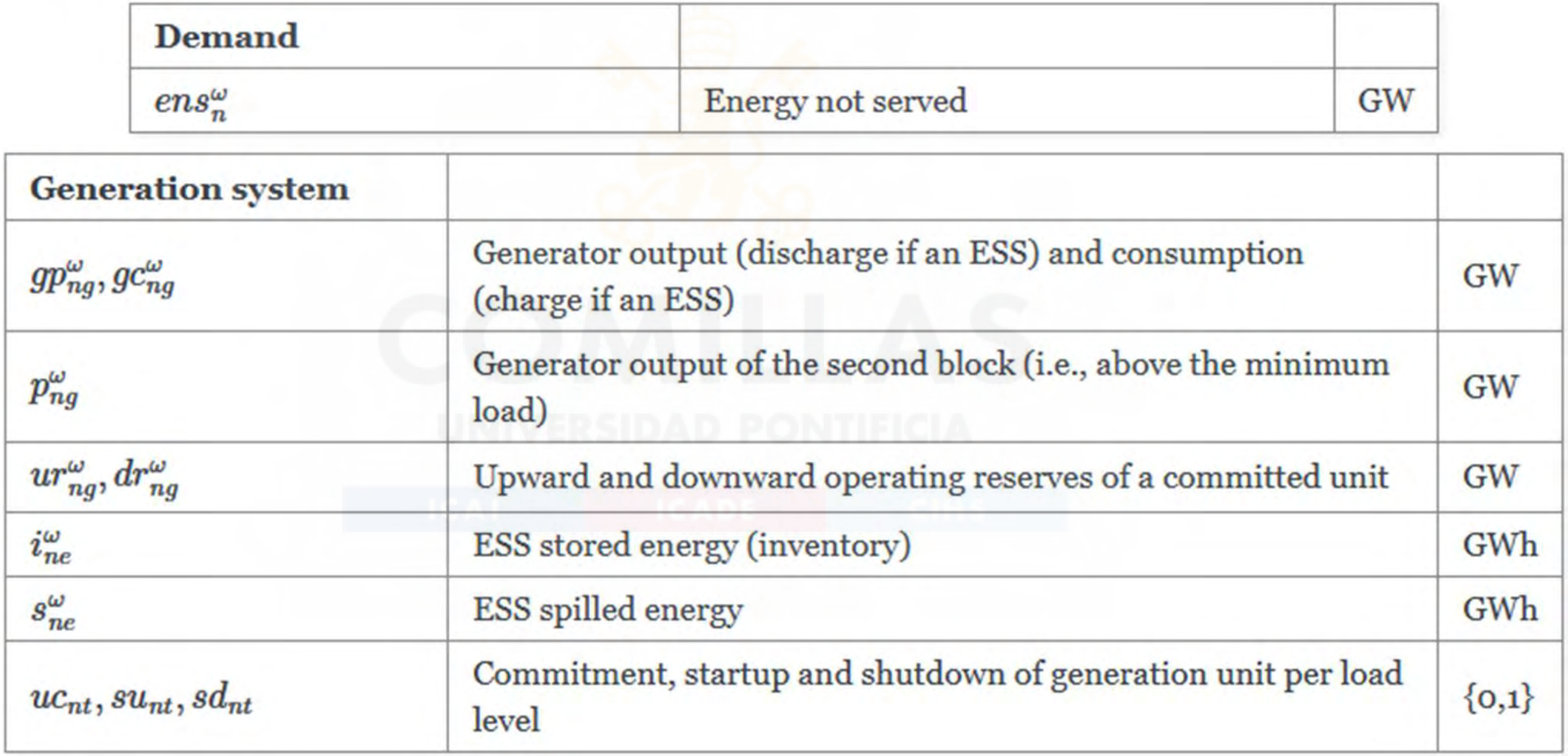
Scenarios		
P^ω	Probability of each scenario	p.u.

Operating reserves		
UR_n^ω, DR_n^ω	Upward and downward operating reserves	GW

Generation system		
CP_g, GP_g	Minimum load and maximum output of a generator	GW
GC_g	Maximum consumption of an ESS	GW
CF_g, CV_g	Fixed and variable cost of a generator. Variable cost includes fuel, O&M and emission cost	€/h, €/MWh
RU_t, RD_t	Ramp up and ramp down of a thermal unit	MW/h
TU_t, TD_t	Minimum uptime and downtime of a thermal unit	h
CSU_g, CSD_g	Startup and shutdown cost of a committed unit	M€
τ_e	Characteristic duration of the ESS (e.g., 24 h, 168 h, 672 h -for monthly-)	h
EF_e	Round-trip efficiency of the pump/turbine cycle of a hydro power plant or charge/discharge of a battery	p.u.
I_e	Capacity of an ESS (e.g., hydro power plant)	GWh
EI_{ne}^ω	Energy inflows of an ESS (e.g., hydro power plant)	GWh

Variables

They are written in lower letters.



Demand		
ens_n^ω	Energy not served	GW

Generation system		
$gp_{ng}^\omega, gc_{ng}^\omega$	Generator output (discharge if an ESS) and consumption (charge if an ESS)	GW
p_{ng}^ω	Generator output of the second block (i.e., above the minimum load)	GW
$ur_{ng}^\omega, dr_{ng}^\omega$	Upward and downward operating reserves of a committed unit	GW
i_{ne}^ω	ESS stored energy (inventory)	GWh
s_{ne}^ω	ESS spilled energy	GWh
$uc_{nt}, su_{nt}, sd_{nt}$	Commitment, startup and shutdown of generation unit per load level	{0,1}

Equations (i)

Objective function: minimization of operation cost for the scope of the model

Generation operation cost [M€] (`eTotalTCost`, `eTotalVCost`, `eTotalECost`)

$$\sum_{\omega n} P^{\omega} DUR_n (\sum_g CV_g gp^{\omega}_{ng} + CENS ens^{\omega}_n) + \sum_{ng} (DUR_n CF_g uc_{ng} + CSU_g su_{ng} + CSD_g sd_{ng})$$

Constraints

Balance of generation and demand [GW] (`eBalance`)

$$\sum_g gp^{\omega}_{ng} - \sum_g gc^{\omega}_{ng} + ens^{\omega}_n = D^{\omega}_n \quad \forall \omega n$$

Upward and downward operating reserves [GW] (`eOperReserveUp`, `eOperReserveDw`)

$$\sum_g ur^{\omega}_{ng} \geq UR^{\omega}_n \quad \forall \omega n$$

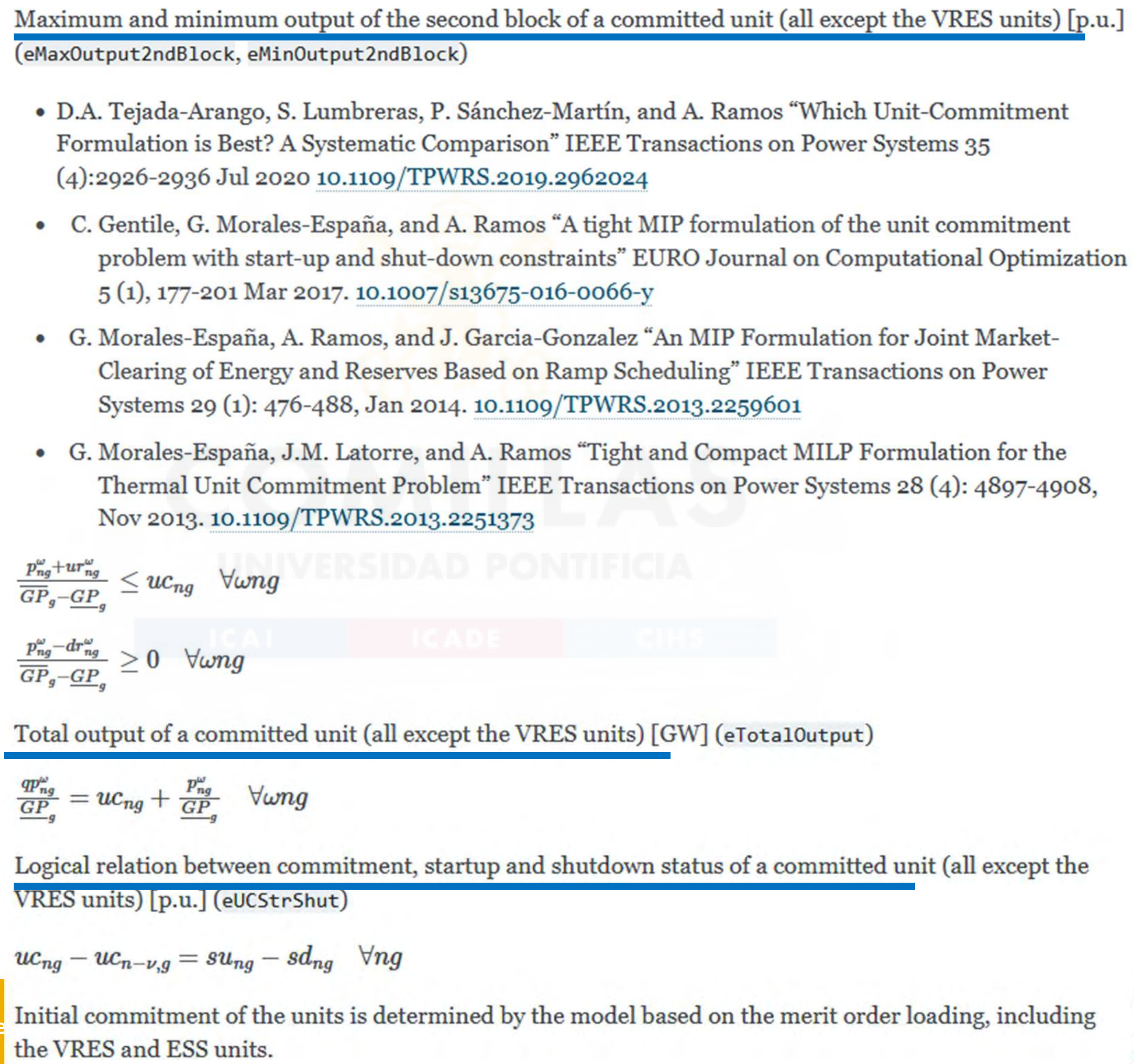
$$\sum_g dr^{\omega}_{ng} \geq DR^{\omega}_n \quad \forall \omega n$$

VRES units (i.e., those with linear variable cost equal to 0 and no storage capacity) do not contribute to the operating reserves.

ESS energy inventory (only for load levels multiple of 24, 168 or 672 h depending on the ESS type) [GWh] (`eESSInventory`)

$$i^{\omega}_{n-\tau_e,e} + \sum_{n'=n+\nu-\tau_e}^{n} DUR_n (EI^{\omega}_{ne} - gp^{\omega}_{ne} + EF_e gc^{\omega}_{ne}) = i^{\omega}_{ne} + s^{\omega}_{ne} \quad \forall \omega ne$$

Equations **(ii)**



Maximum and minimum output of the second block of a committed unit (all except the VRES units) [p.u.] (`eMaxOutput2ndBlock`, `eMinOutput2ndBlock`)

- D.A. Tejada-Arango, S. Lumbreras, P. Sánchez-Martín, and A. Ramos “Which Unit-Commitment Formulation is Best? A Systematic Comparison” IEEE Transactions on Power Systems 35 (4):2926-2936 Jul 2020 10.1109/TPWRS.2019.2962024
- C. Gentile, G. Morales-España, and A. Ramos “A tight MIP formulation of the unit commitment problem with start-up and shut-down constraints” EURO Journal on Computational Optimization 5 (1), 177-201 Mar 2017. 10.1007/s13675-016-0066-y
- G. Morales-España, A. Ramos, and J. Garcia-Gonzalez “An MIP Formulation for Joint Market-Clearing of Energy and Reserves Based on Ramp Scheduling” IEEE Transactions on Power Systems 29 (1): 476-488, Jan 2014. 10.1109/TPWRS.2013.2259601
- G. Morales-España, J.M. Latorre, and A. Ramos “Tight and Compact MILP Formulation for the Thermal Unit Commitment Problem” IEEE Transactions on Power Systems 28 (4): 4897-4908, Nov 2013. 10.1109/TPWRS.2013.2251373

$$\frac{p^{\omega}_{ng}+ur^{\omega}_{ng}}{\overline{GP}_g-\underline{GP}_g} \leq uc_{ng} \quad \forall \omega ng$$

$$\frac{p^{\omega}_{ng}-dr^{\omega}_{ng}}{\overline{GP}_g-\underline{GP}_g} \geq 0 \quad \forall \omega ng$$

Total output of a committed unit (all except the VRES units) [GW] (`eTotalOutput`)

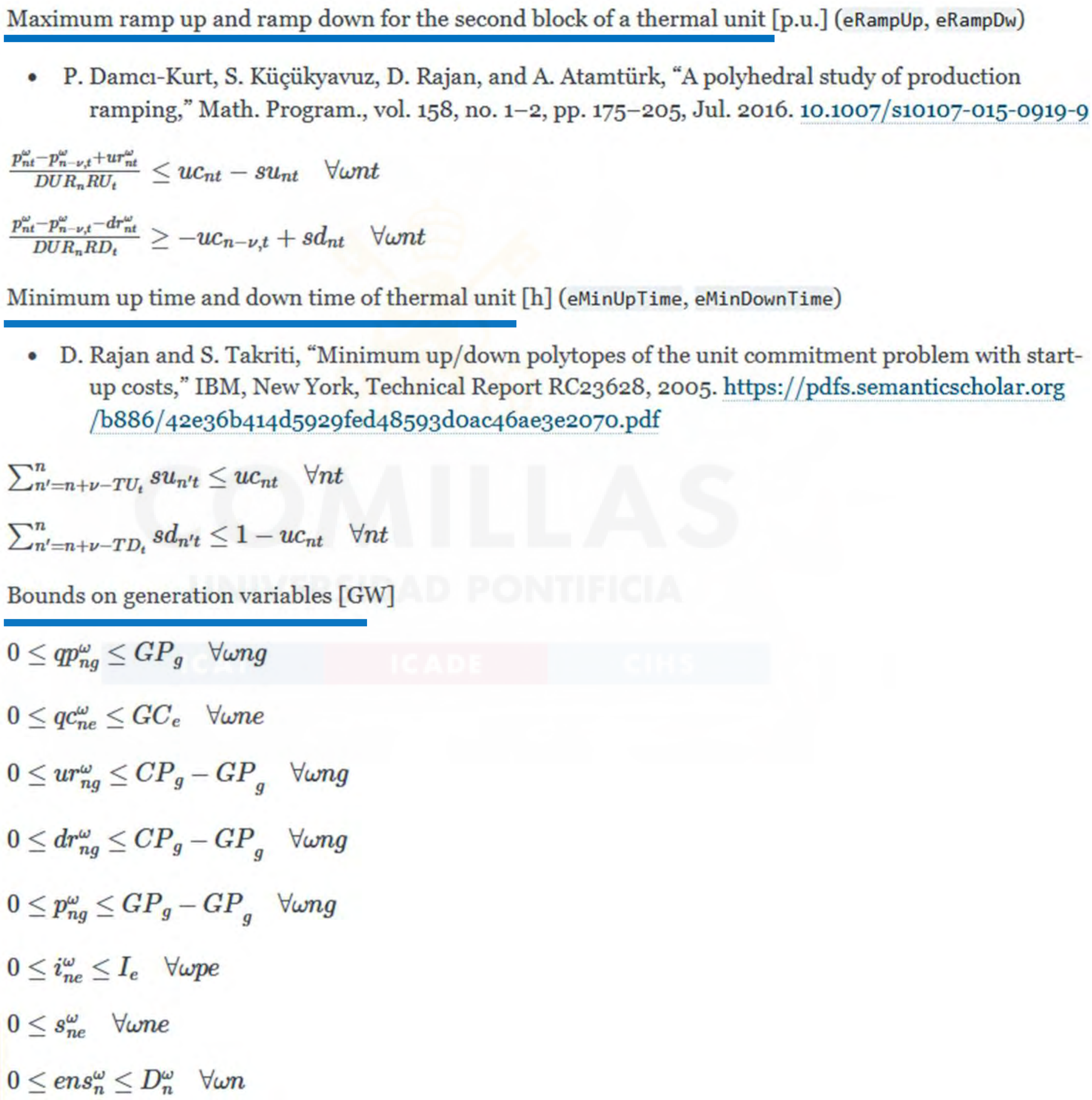
$$\frac{qp^{\omega}_{ng}}{\underline{GP}_g} = uc_{ng} + \frac{p^{\omega}_{ng}}{\underline{GP}_g} \quad \forall \omega ng$$

Logical relation between commitment, startup and shutdown status of a committed unit (all except the VRES units) [p.u.] (`eUCStrShut`)

$$uc_{ng} - uc_{n-\nu,g} = su_{ng} - sd_{ng} \quad \forall ng$$

Initial commitment of the units is determined by the model based on the merit order loading, including the VRES and ESS units.

Equations **(iii)**



Maximum ramp up and ramp down for the second block of a thermal unit [p.u.] (`eRampUp`, `eRampDw`)

- P. Damcı-Kurt, S. Küçükyavuz, D. Rajan, and A. Atamtürk, "A polyhedral study of production ramping," Math. Program., vol. 158, no. 1–2, pp. 175–205, Jul. 2016. 10.1007/s10107-015-0919-9

$$\frac{p^{\omega}_{nt}-p^{\omega}_{n-\nu,t}+ur^{\omega}_{nt}}{DUR_n RU_t} \leq uc_{nt} - su_{nt} \quad \forall \omega nt$$

$$\frac{p^{\omega}_{nt}-p^{\omega}_{n-\nu,t}-dr^{\omega}_{nt}}{DUR_n RD_t} \geq -uc_{n-\nu,t} + sd_{nt} \quad \forall \omega nt$$

Minimum up time and down time of thermal unit [h] (`eMinUpTime`, `eMinDownTime`)

- D. Rajan and S. Takriti, "Minimum up/down polytopes of the unit commitment problem with start-up costs," IBM, New York, Technical Report RC23628, 2005. https://pdfs.semanticscholar.org/b886/42e36b414d5929fed48593d0ac46ae3e2070.pdf

$$\sum_{n'=n+\nu-TU_t}^{n} su_{n't} \leq uc_{nt} \quad \forall nt$$

$$\sum_{n'=n+\nu-TD_t}^{n} sd_{n't} \leq 1 - uc_{nt} \quad \forall nt$$

Bounds on generation variables [GW]

$$0 \leq qp^{\omega}_{ng} \leq GP_g \quad \forall \omega ng$$

$$0 \leq qc^{\omega}_{ne} \leq GC_e \quad \forall \omega ne$$

$$0 \leq ur^{\omega}_{ng} \leq CP_g - GP_g \quad \forall \omega ng$$

$$0 \leq dr^{\omega}_{ng} \leq CP_g - GP_g \quad \forall \omega ng$$

$$0 \leq p^{\omega}_{ng} \leq GP_g - GP_g \quad \forall \omega ng$$

$$0 \leq i^{\omega}_{ne} \leq I_e \quad \forall \omega pe$$

$$0 \leq s^{\omega}_{ne} \quad \forall \omega ne$$

$$0 \leq ens^{\omega}_{n} \leq D^{\omega}_{n} \quad \forall \omega n$$

StarGenLite_SDUC Stochastic Daily Unit Commitment Model (https://pascua.iit.comillas.edu/aramos/StarGenLite_SDUC.zip)

- Files
  - Microsoft Excel interface for input data and output results StarGenLite_SDUC.xlsm
  - GAMS file StarGenLite_SDUC.gms
- How to run it from Windows
  - Save the Excel workbook if data have changed
  - Run the model
  - The model creates
    - tmp_StarGenLite_SDUC.xlsx with the output results
    - tmp_StarGenLite_SDUC.gdx with the output results
    - StarGenLite_SDUC.lst as the listing file of the GAMS execution
  - Load the results into the Excel interface

Run

Load results

StarGenLite_SDUC Stochastic Daily Unit Commitment Model (https://pascua.iit.comillas.edu/aramos/StarGenLite_SDUC.zip)

- Files
  - Text files for input data
  - GAMS file StarGenLite_SDUC.gms

- How to run it from MacOS
  - Run the model from GAMS Studio with these parameters
    - u1=StarGenLite_SDUC u2=1 u3=1
  - The model creates
    - tmp_StarGenLite_SDUC.gdx with the output results
    - StarGenLite_SDUC.lst as the listing file of the GAMS execution

Interface StarGenLite_SDUC. Menu

StarGenLite_SDUC.xlsm - Excel

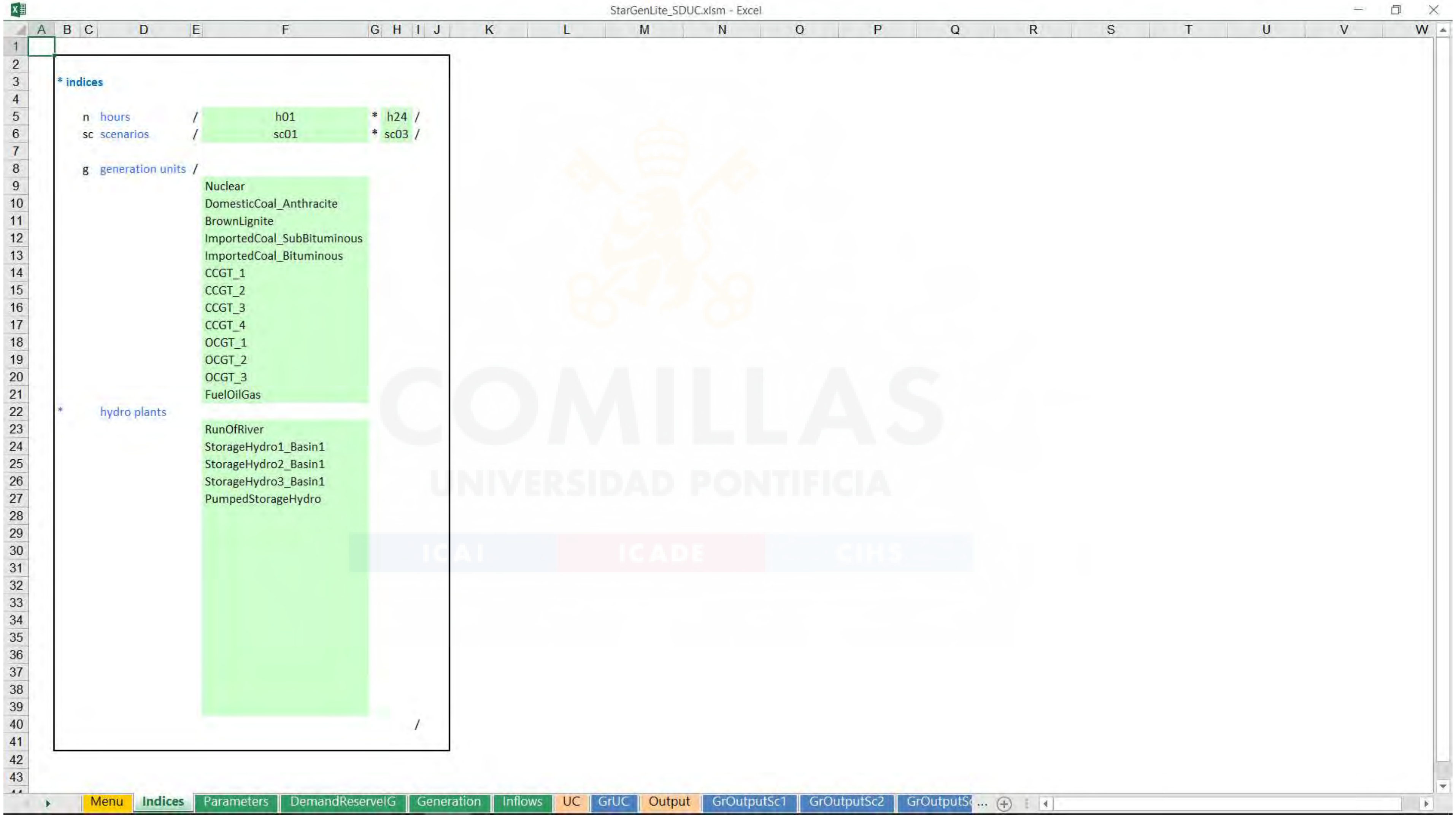
StarGen Lite Stochastic Daily Unit Commitment

Andrés Ramos

http://www.iit.comillas.edu/aramos/

andres.ramos@comillas.edu

Interface StarGenLite_SDUC. Indices



* indices

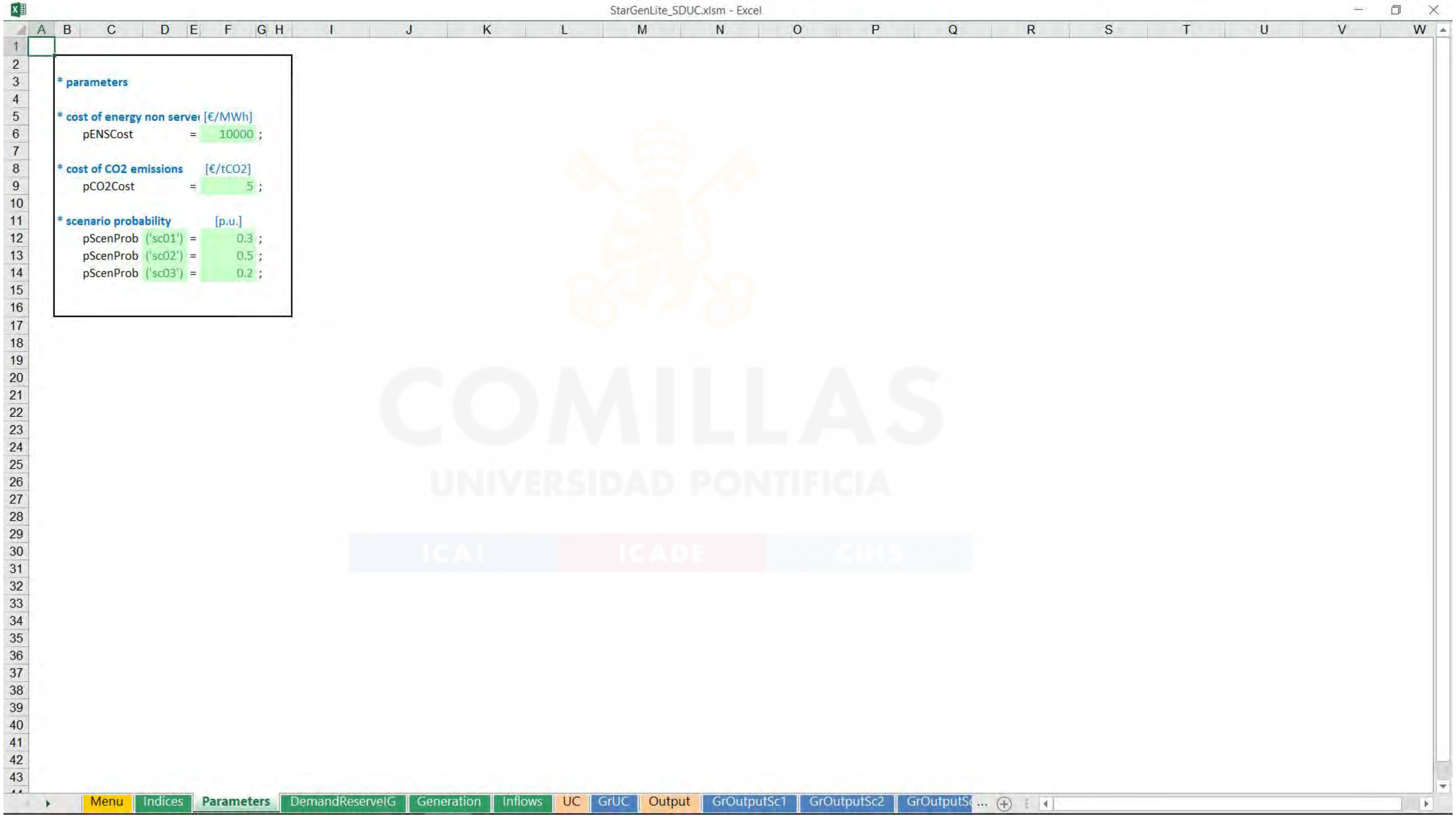
n hours / h01 * h24 /
sc scenarios / sc01 * sc03 /

g generation units /
Nuclear
DomesticCoal_Anthracite
BrownLignite
ImportedCoal_SubBituminous
ImportedCoal_Bituminous
CCGT_1
CCGT_2
CCGT_3
CCGT_4
OCGT_1
OCGT_2
OCGT_3
FuelOilGas

* hydro plants
RunOfRiver
StorageHydro1_Basin1
StorageHydro2_Basin1
StorageHydro3_Basin1
PumpedStorageHydro

/

Interface StarGenLite_SDUC. Parameters



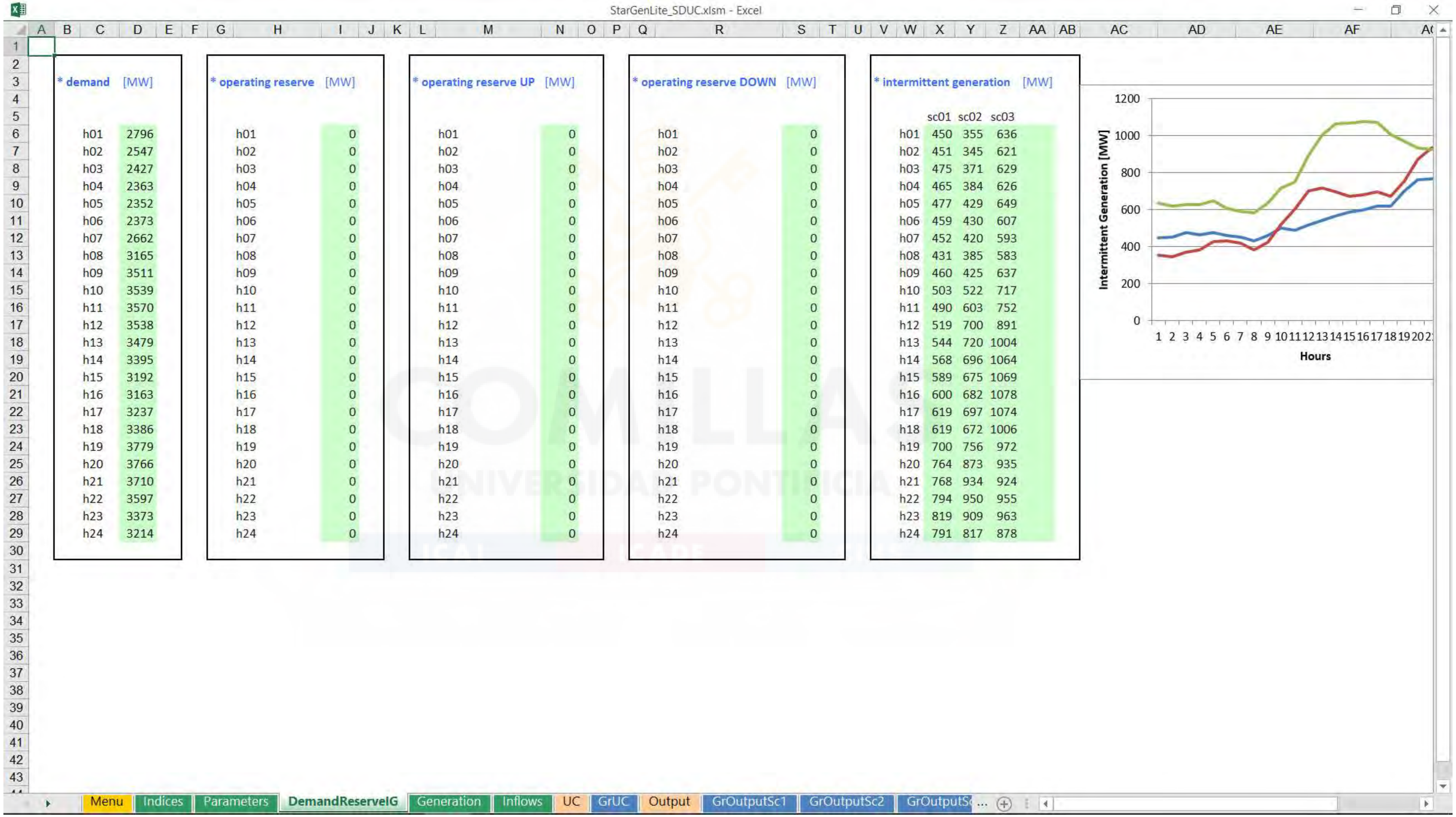
```
* parameters

* cost of energy non serve( [€/MWh]
     pENSCost              =      10000 ;

* cost of CO2 emissions     [€/tCO2]
     pCO2Cost              =          5 ;

* scenario probability        [p.u.]
     pScenProb  ('sc01')   =        0.3 ;
     pScenProb  ('sc02')   =        0.5 ;
     pScenProb  ('sc03')   =        0.2 ;
```

Interface StarGenLite_SDUC. DemandReserveIG



*** demand** [MW]

h01	2796
h02	2547
h03	2427
h04	2363
h05	2352
h06	2373
h07	2662
h08	3165
h09	3511
h10	3539
h11	3570
h12	3538
h13	3479
h14	3395
h15	3192
h16	3163
h17	3237
h18	3386
h19	3779
h20	3766
h21	3710
h22	3597
h23	3373
h24	3214

*** operating reserve** [MW]

h01	0
h02	0
h03	0
h04	0
h05	0
h06	0
h07	0
h08	0
h09	0
h10	0
h11	0
h12	0
h13	0
h14	0
h15	0
h16	0
h17	0
h18	0
h19	0
h20	0
h21	0
h22	0
h23	0
h24	0

*** operating reserve UP** [MW]

h01	0
h02	0
h03	0
h04	0
h05	0
h06	0
h07	0
h08	0
h09	0
h10	0
h11	0
h12	0
h13	0
h14	0
h15	0
h16	0
h17	0
h18	0
h19	0
h20	0
h21	0
h22	0
h23	0
h24	0

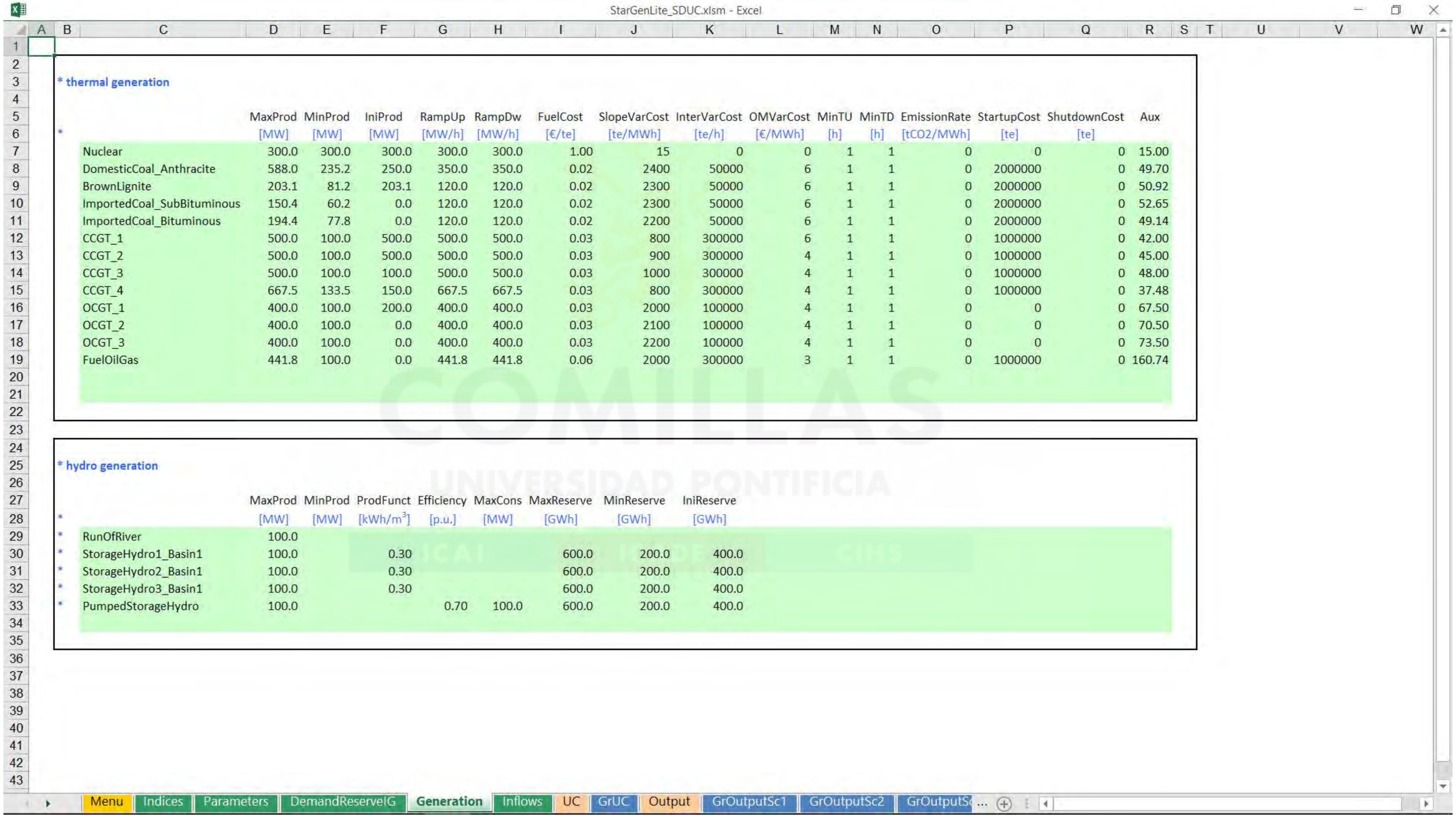
*** operating reserve DOWN** [MW]

h01	0
h02	0
h03	0
h04	0
h05	0
h06	0
h07	0
h08	0
h09	0
h10	0
h11	0
h12	0
h13	0
h14	0
h15	0
h16	0
h17	0
h18	0
h19	0
h20	0
h21	0
h22	0
h23	0
h24	0

*** intermittent generation** [MW]

	sc01	sc02	sc03
h01	450	355	636
h02	451	345	621
h03	475	371	629
h04	465	384	626
h05	477	429	649
h06	459	430	607
h07	452	420	593
h08	431	385	583
h09	460	425	637
h10	503	522	717
h11	490	603	752
h12	519	700	891
h13	544	720	1004
h14	568	696	1064
h15	589	675	1069
h16	600	682	1078
h17	619	697	1074
h18	619	672	1006
h19	700	756	972
h20	764	873	935
h21	768	934	924
h22	794	950	955
h23	819	909	963
h24	791	817	878

Interface StarGenLite_SDUC. Generation



*** thermal generation**

	MaxProd	MinProd	IniProd	RampUp	RampDw	FuelCost	SlopeVarCost	InterVarCost	OMVarCost	MinTU	MinTD	EmissionRate	StartupCost	ShutdownCost	Aux
*	[MW]	[MW]	[MW]	[MW/h]	[MW/h]	[€/te]	[te/MWh]	[te/h]	[€/MWh]	[h]	[h]	[tCO2/MWh]	[te]	[te]	
Nuclear	300.0	300.0	300.0	300.0	300.0	1.00	15	0	0	1	1	0	0	0	15.00
DomesticCoal_Anthracite	588.0	235.2	250.0	350.0	350.0	0.02	2400	50000	6	1	1	0	2000000	0	49.70
BrownLignite	203.1	81.2	203.1	120.0	120.0	0.02	2300	50000	6	1	1	0	2000000	0	50.92
ImportedCoal_SubBituminous	150.4	60.2	0.0	120.0	120.0	0.02	2300	50000	6	1	1	0	2000000	0	52.65
ImportedCoal_Bituminous	194.4	77.8	0.0	120.0	120.0	0.02	2200	50000	6	1	1	0	2000000	0	49.14
CCGT_1	500.0	100.0	500.0	500.0	500.0	0.03	800	300000	6	1	1	0	1000000	0	42.00
CCGT_2	500.0	100.0	500.0	500.0	500.0	0.03	900	300000	4	1	1	0	1000000	0	45.00
CCGT_3	500.0	100.0	100.0	500.0	500.0	0.03	1000	300000	4	1	1	0	1000000	0	48.00
CCGT_4	667.5	133.5	150.0	667.5	667.5	0.03	800	300000	4	1	1	0	1000000	0	37.48
OCGT_1	400.0	100.0	200.0	400.0	400.0	0.03	2000	100000	4	1	1	0	0	0	67.50
OCGT_2	400.0	100.0	0.0	400.0	400.0	0.03	2100	100000	4	1	1	0	0	0	70.50
OCGT_3	400.0	100.0	0.0	400.0	400.0	0.03	2200	100000	4	1	1	0	0	0	73.50
FuelOilGas	441.8	100.0	0.0	441.8	441.8	0.06	2000	300000	3	1	1	0	1000000	0	160.74

*** hydro generation**

		MaxProd	MinProd	ProdFunct	Efficiency	MaxCons	MaxReserve	MinReserve	IniReserve
*		[MW]	[MW]	[kWh/m^3]	[p.u.]	[MW]	[GWh]	[GWh]	[GWh]
*	RunOfRiver	100.0							
*	StorageHydro1_Basin1	100.0		0.30			600.0	200.0	400.0
*	StorageHydro2_Basin1	100.0		0.30			600.0	200.0	400.0
*	StorageHydro3_Basin1	100.0		0.30			600.0	200.0	400.0
*	PumpedStorageHydro	100.0			0.70	100.0	600.0	200.0	400.0

StarGenLite_SDUC in GAMS (i)

```
$Title StarGen Lite Stochastic Daily Unit Commitment of Thermal and Hydro Units (SDUC)

$OnText

Developed by

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   August 19, 2019

$OffText

$OnEmpty OnMulti OffListing

* options to skip or not the Excel input/output
* if you want to skip it put these values to 1
* in such a case input files must be already in the directory created by any other means
* output file will be the tmp.gdx that can be exported to Excel manually
$ifthen.OptSkipExcelInput       %gams.user2% == ""
$  setglobal OptSkipExcelInput  0
$else.OptSkipExcelInput
$  setglobal OptSkipExcelInput  %gams.user2%
$endif.OptSkipExcelInput

$ifthen.OptSkipExcelOutput      %gams.user3% == ""
$  setglobal OptSkipExcelOutput 0
$else.OptSkipExcelOutput
$  setglobal OptSkipExcelOutput %gams.user3%
$endif.OptSkipExcelOutput

* solve the optimization problems until optimality
option OptcR = 0
```

Model name

Authorship and version

Allow declaration of empty sets and multiple declaration. Suppress listing

Obtain the optimal solution

StarGenLite_SDUC in GAMS (ii)

```
* definitions

sets
   n      hour
   n1(n)  first hour of the day
   sc     scenario

   g      generating unit
   t (g)  thermal    unit
   h (g)  hydro      plant

alias (n,nn)

parameters
   pDemand        (n) hourly load                   [GW]
   pOperReserve   (n) hourly operating reserve      [GW]
   pOperReserveUp (n) hourly operating reserve up   [GW]
   pOperReserveDw (n) hourly operating reserve down [GW]
   pIntermGen  (n,sc) stochastic IG generation      [GW]
   pScenProb     (sc) probability of scenarios      [p.u.]
   pCommitt  (    g,n) commitment of the unit       [0-1]
   pProduct  (sc,g,n) output     of the unit        [GW]
   pIG       (sc,   n) output     of IG generation  [GW]
   pSRMC     (sc,   n) short run marginal cost      [ EUR per MWh]

   pMaxProd       (g) maximum output                [GW]
   pMinProd       (g) minimum output                [GW]
   pMaxCons       (g) maximum consumption           [GW]
   pIniOut        (g) initial output > min load     [GW]
   pIniUC         (g) initial commitment            [0-1]
   pRampUp        (g) ramp up                       [GW per    h]
   pRampDw        (g) ramp down                     [GW per    h]
   pMinTU         (g) minimum up   time             [h]
   pMinTD         (g) minimum down time             [h]
   pSlopeVarCost  (g) slope     variable cost       [MEUR per GWh]
   pInterVarCost  (g) intercept variable cost       [MEUR per   h]
   pEmissionCost  (g) emission           cost       [MEUR per GWh]
   pStartUpCost   (g) startup            cost       [MEUR]
   pShutDownCost  (g) shutdown           cost       [MEUR]
   pMaxReserve    (g) maximum reserve               [GWh]
   pMinReserve    (g) minimum reserve               [GWh]
   pIniReserve    (g) initial reserve               [GWh]
   pEffic         (g) pumping efficiency            [p.u.]
   pInflows     (g,n) inflows                       [GWh]
   pENSCost           energy not served  cost       [MEUR per GWh]
   pCO2Cost           CO2 emission       cost       [ EUR per tCO2]
```

Set definition

Parameter definition

StarGenLite_SDUC in GAMS (iii)

```
variables
   vTotalVCost         total system variable cost     [MEUR]

binary   variables
   vCommitment(  n,g) commitment of the unit         [0-1]
   vStartup   (  n,g) startup    of the unit         [0-1]
   vShutdown  (  n,g) shutdown   of the unit         [0-1]

positive variables
   vOutput   (sc,n,g) output of the unit             [GW]
   vOutput2nd(sc,n,g) output of the unit > min load  [GW]
   vConsump  (sc,n,g) consumption of the unit        [GW]
   vENS      (sc,n  ) energy not served              [GW]
   vIG       (sc,n  ) intermittent generation        [GW]
   vWtReserve(sc,n,g) water reserve at end of period [GWh]
   vSpillage (sc,n,g) spillage                       [GWh]

equations
   eTotalVCost         total system variable cost     [MEUR]
   eBalance  (sc,n  ) load generation balance        [GW]
   eOpReserve(   n  ) operating reserve              [GW]
   eReserveUp(sc,n  ) operating reserve upwards      [GW]
   eReserveDw(sc,n  ) operating reserve downwards    [GW]
   eMaxOutput(sc,n,g) max output of a committed unit [GW]
   eMinOutput(sc,n,g) min output of a committed unit [GW]
   eTotOutput(sc,n,g) tot output of a committed unit [GW]
   eRampUp   (sc,n,g) bound on ramp up               [GW]
   eRampDw   (sc,n,g) bound on ramp down             [GW]
   eUCStrShut(   n,g) relation among commitment startup and shutdown
   eMinTUp   (   n,g) minimum up   time (    committed)
   eMinTDw   (   n,g) minimum down time (not committed)
   eWtReserve(sc,n,g) water reserve                  [GWh] ;
```

Variables

Equation definition

StarGenLite_SDUC in GAMS (iv)

```
* mathematical formulation

eTotalVCost        .. vTotalVCost =e= sum[(sc,n  ), pENSCost        *vENS       (sc,n  )*pScenProb(sc)] +
                                      sum[(sc,n,t), pSlopeVarCost(t)*vOutput    (sc,n,t)*pScenProb(sc)] +
                                      sum[(sc,n,t), pEmissionCost(t)*vOutput    (sc,n,t)*pScenProb(sc)] +
                                      sum[(   n,t), pInterVarCost(t)*vCommitment(   n,t)] +
                                      sum[(   n,t), pStartUpCost (t)*vStartup   (   n,t)] +
                                      sum[(   n,t), pShutDownCost(t)*vShutdown  (   n,t)] ;

eBalance  (sc,n  ) $ pScenProb(sc) .. sum[t, vOutput(sc,n,t)] + sum[h, vOutput(sc,n,h)] - sum[h, vConsump(sc,n,h)] + vIG(sc,n) + vENS(sc,n) =e=
pDemand(n) ;

eOpReserve(   n  )                 .. sum[t, pMaxProd(t) * vCommitment(n,t)] + sum[h, pMaxProd(h)] =g=   pOperReserve  (n) + pDemand(n) ;
eReserveUp(sc,n  ) $ pScenProb(sc) .. sum[t, pMaxProd(t) * vCommitment(n,t)  - vOutput(sc,n,t)]    =g=   pOperReserveUp(n) ;
eReserveDw(sc,n  ) $ pScenProb(sc) .. sum[t, pMinProd(t) * vCommitment(n,t)  - vOutput(sc,n,t)]    =l= - pOperReserveDw(n) ;

eMaxOutput(sc,n,t) $[pScenProb(sc) and pMaxProd(t)] .. vOutput(sc,n,t) / pMaxProd(t) =l= vCommitment(n,t) ;
eMinOutput(sc,n,t) $[pScenProb(sc) and pMinProd(t)] .. vOutput(sc,n,t) / pMinProd(t) =g= vCommitment(n,t) ;

eTotOutput(sc,n,t) $ pScenProb(sc)                  .. vOutput(sc,n,t) =e= pMinProd(t)*vCommitment(n,t) + vOutput2nd(sc,n,t) ;

eRampUp   (sc,n,t) $ pScenProb(sc) .. vOutput2nd(sc,n,t) - vOutput2nd(sc,n-1,t) - max[pIniOut(t)-pMinProd(t),0] $n1(n) =l=   pRampUp(t) ;
eRampDw   (sc,n,t) $ pScenProb(sc) .. vOutput2nd(sc,n,t) - vOutput2nd(sc,n-1,t) - max[pIniOut(t)-pMinProd(t),0] $n1(n) =g= - pRampDw(t) ;

eUCStrShut(   n,t)                 .. vCommitment(n,t) - vCommitment(n-1,t) - pIniUC(t) $n1(n) =e= vStartup(n,t) - vShutdown(n,t) ;

eMinTUp   (   n,t) $[pMinTU(t) > 1 and ord(n) >= pMinTU(t)] .. sum[nn $(ord(nn) >= ord(n)+1-pMinTU(t) and ord(nn) <= ord(n)), vStartup (nn,t)]
=l=     vCommitment(n,t) ;
eMinTDw   (   n,t) $[pMinTD(t) > 1 and ord(n) >= pMinTD(t)] .. sum[nn $(ord(nn) >= ord(n)+1-pMinTD(t) and ord(nn) <= ord(n)), vShutdown(nn,t)]
=l= 1 - vCommitment(n,t) ;

eWtReserve(sc,n,h) $ pScenProb(sc) .. vWtReserve(sc,n-1,h) + pIniReserve(h) $n1(n) + pInflows(h,n) - vSpillage(sc,n,h) - vOutput(sc,n,h) +
vConsump(sc,n,h)*pEffic(h) =e= vWtReserve(sc,n,h) ;

model mSDUC / all / ;
mSDUC.solprint = 1 ; mSDUC.holdfixed = 1 ; mSDUC.optfile = 1 ;
```

Reduced solution output

Model includes all the equations

Eliminate fixed variables

Mathematical formulation of equations

StarGenLite_SDUC in GAMS (v)

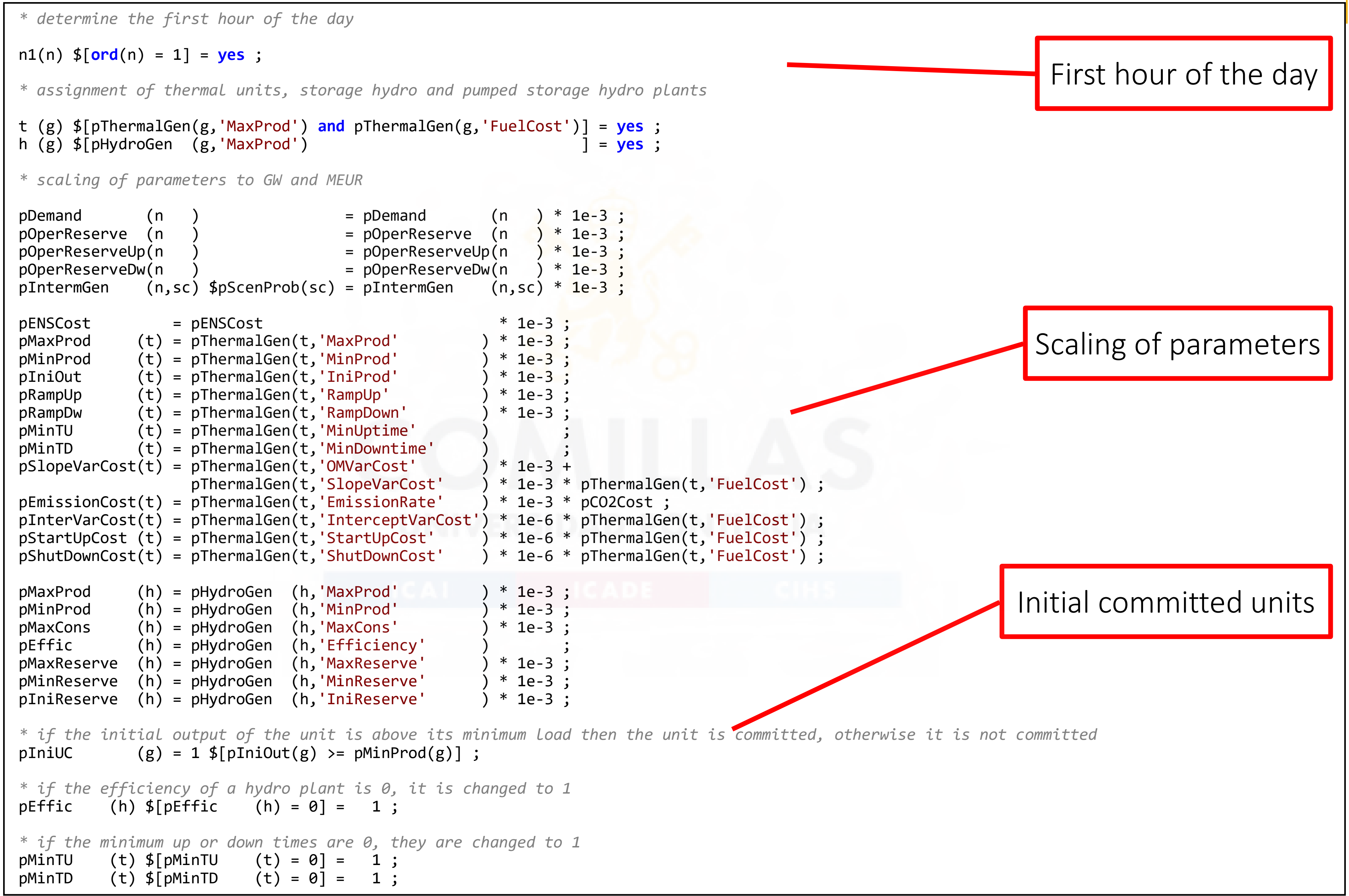
```
* read input data from Excel and include into the model

file TMP / tmp_%gams.user1%.txt /
$OnEcho  > tmp_%gams.user1%.txt
   r1=    indices
   o1=tmp_indices.txt
   r2=    param
   o2=tmp_param.txt
   r3=    demand
   o3=tmp_demand.txt
   r4=    oprres
   o4=tmp_oprres.txt
   r5=    oprresup
   o5=tmp_oprresup.txt
   r6=    oprresdw
   o6=tmp_oprresdw.txt
   r7=    IGgen
   o7=tmp_IGgen.txt
   r8=    thermalgen
   o8=tmp_thermalgen.txt
   r9=    hydrogen
   o9=tmp_hydrogen.txt
   r10=    inflows
   o10=tmp_inflows.txt
$OffEcho
* Mac OS X and Linux users must comment the following call and copy and paste the named ranges of the Excel interface into the txt files
$ifthen.OptSkipExcelInput '%OptSkipExcelInput%' == '0'
$call =xls2gms m i="%gams.user1%.xlsm" @"tmp_%gams.user1%.txt"
$else.OptSkipExcelInput
$  log Excel input skipped
$endif.OptSkipExcelInput

sets
$include  tmp_indices.txt
;
$include  tmp_param.txt
parameter pDemand(n)        hourly load                [MW] /
$include  tmp_demand.txt
                                                            /
parameter pOperReserve(n)   hourly operating reserve [MW] /
$include  tmp_oprres.txt
                                                            /
parameter pOperReserveUp(n) hourly operating reserve [MW] /
$include  tmp_oprresup.txt
                                                            /
parameter pOperReserveDw(n) hourly operating reserve [MW] /
$include  tmp_oprresdw.txt
                                                            /
table     pIntermGen(n,sc)  stochastic IG generation [MW]
$include  tmp_IGgen.txt
table     pThermalGen(g,*)
$include  tmp_thermalgen.txt
table     pHydroGen  (g,*)
$include  tmp_hydrogen.txt
table     pInflows   (g,n)
$include  tmp_inflows.txt
;

* Mac OS X and Linux users must comment the following execute
execute 'del tmp_"%gams.user1%".txt tmp_indices.txt tmp_param.txt tmp_demand.txt tmp_oprres.txt tmp_oprresup.txt tmp_oprresdw.txt tmp_IGgen.txt tmp_thermalgen.txt tmp_hydrogen.txt tmp_inflows.txt' ;
```

Read input from Excel named ranges and write into text files

Input from text files into GAMS

Delete read text files

StarGenLite_SDUC in GAMS (vi)



```
* determine the first hour of the day

n1(n) $[ord(n) = 1] = yes ;

* assignment of thermal units, storage hydro and pumped storage hydro plants

t (g) $[pThermalGen(g,'MaxProd') and pThermalGen(g,'FuelCost')] = yes ;
h (g) $[pHydroGen  (g,'MaxProd')                              ] = yes ;

* scaling of parameters to GW and MEUR

pDemand       (n   )                  = pDemand       (n   ) * 1e-3 ;
pOperReserve  (n   )                  = pOperReserve  (n   ) * 1e-3 ;
pOperReserveUp(n   )                  = pOperReserveUp(n   ) * 1e-3 ;
pOperReserveDw(n   )                  = pOperReserveDw(n   ) * 1e-3 ;
pIntermGen    (n,sc) $pScenProb(sc) = pIntermGen    (n,sc) * 1e-3 ;

pENSCost         = pENSCost                         * 1e-3 ;
pMaxProd     (t) = pThermalGen(t,'MaxProd'         ) * 1e-3 ;
pMinProd     (t) = pThermalGen(t,'MinProd'         ) * 1e-3 ;
pIniOut      (t) = pThermalGen(t,'IniProd'         ) * 1e-3 ;
pRampUp      (t) = pThermalGen(t,'RampUp'          ) * 1e-3 ;
pRampDw      (t) = pThermalGen(t,'RampDown'        ) * 1e-3 ;
pMinTU       (t) = pThermalGen(t,'MinUptime'       )        ;
pMinTD       (t) = pThermalGen(t,'MinDowntime'     )        ;
pSlopeVarCost(t) = pThermalGen(t,'OMVarCost'       ) * 1e-3 +
                   pThermalGen(t,'SlopeVarCost'    ) * 1e-3 * pThermalGen(t,'FuelCost') ;
pEmissionCost(t) = pThermalGen(t,'EmissionRate'    ) * 1e-3 * pCO2Cost ;
pInterVarCost(t) = pThermalGen(t,'InterceptVarCost') * 1e-6 * pThermalGen(t,'FuelCost') ;
pStartUpCost (t) = pThermalGen(t,'StartUpCost'     ) * 1e-6 * pThermalGen(t,'FuelCost') ;
pShutDownCost(t) = pThermalGen(t,'ShutDownCost'    ) * 1e-6 * pThermalGen(t,'FuelCost') ;

pMaxProd     (h) = pHydroGen  (h,'MaxProd'         ) * 1e-3 ;
pMinProd     (h) = pHydroGen  (h,'MinProd'         ) * 1e-3 ;
pMaxCons     (h) = pHydroGen  (h,'MaxCons'         ) * 1e-3 ;
pEffic       (h) = pHydroGen  (h,'Efficiency'      )        ;
pMaxReserve  (h) = pHydroGen  (h,'MaxReserve'      ) * 1e-3 ;
pMinReserve  (h) = pHydroGen  (h,'MinReserve'      ) * 1e-3 ;
pIniReserve  (h) = pHydroGen  (h,'IniReserve'      ) * 1e-3 ;

* if the initial output of the unit is above its minimum load then the unit is committed, otherwise it is not committed
pIniUC       (g) = 1 $[pIniOut(g) >= pMinProd(g)] ;

* if the efficiency of a hydro plant is 0, it is changed to 1
pEffic    (h) $[pEffic    (h) = 0] =   1 ;

* if the minimum up or down times are 0, they are changed to 1
pMinTU    (t) $[pMinTU    (t) = 0] =   1 ;
pMinTD    (t) $[pMinTD    (t) = 0] =   1 ;
```

First hour of the day

Scaling of parameters

Initial committed units

StarGenLite_SDUC in GAMS (vii)

```
* bounds on variables

vOutput.up   (sc,n,g) $pScenProb(sc) = pMaxProd   (g    ) ;
vConsump.up  (sc,n,g) $pScenProb(sc) = pMaxCons   (g    ) ;
vOutput2nd.up(sc,n,t) $pScenProb(sc) = pMaxProd   (t    ) - pMinProd(t) ;
vIG.up       (sc,n  ) $pScenProb(sc) = pIntermGen (n,sc) ;
vENS.up      (sc,n  ) $pScenProb(sc) = pDemand    (n    ) ;
vWtReserve.up(sc,n,g) $pScenProb(sc) = pMaxReserve(g    ) ;
vWtReserve.lo(sc,n,g) $pScenProb(sc) = pMinReserve(g    ) ;

vCommitment.up(n,g) = 1 ;
vStartup.up    (n,g) = 1 ;
vShutdown.up   (n,g) = 1 ;

* solve stochastic daily unit commitment model

solve mSDUC using MIP minimizing vTotalVCost ;

* scaling of the results

pCommitt(   t,n)                = vCommitment.l(   n,t)                 + eps ;
pProduct(sc,g,n) $pScenProb(sc) = vOutput.l    (sc,n,g)*1e3             + eps ;
pIG     (sc,  n) $pScenProb(sc) = vIG.l        (sc,n  )*1e3             + eps ;
pSRMC   (sc,  n) $pScenProb(sc) = eBalance.m   (sc,n  )*1e3/pScenProb(sc) + eps ;

* data output to xls file

put TMP putclose 'par=pCommitt rdim=1 rng=UC!a1' / 'par=pProduct rdim=2 rng=Output!a1' / 'par=pIG    rdim=1 rng=IG!a1' / 'par=pSRMC rdim=1
rng=SRMC!a1' /
                 'text="Unit"          rng=UC!a1' / 'text="Scen"          rng=Output!a1' / 'text="Scen"       rng=IG!a1' / 'text="Scen"
rng=SRMC!a1' /
                                                  'text="Unit"          rng=Output!b1'
execute_unload   'tmp_%gams.user1%.gdx' pProduct pCommitt pIG pSRMC
*$ifthen.OptSkipExcelOutput '%OptSkipExcelOutput%' == '0'
execute          'gdxxrw tmp_"%gams.user1%".gdx SQ=n EpsOut=0 O=tmp_"%gams.user1%".xlsx @tmp_"%gams.user1%".txt'
execute          'del    tmp_"%gams.user1%".gdx                                                                 '
*$else.OptSkipExcelOutput
*$  log Excel output skipped
*$endif.OptSkipExcelOutput
execute          'del                                                                    tmp_"%gams.user1%".txt'

$OnListing
```

Bounds on variables

Solve the optimization problem

Scaling the results

Write output to Excel

StarGenLite_SDUC in Julia/JuMP (i)

(https://pascua.iit.comillas.edu/aramos/StarGenLite_SDUC_J.zip)

```
# StarGen Lite Stochastic Daily Unit Commitment of Thermal and Hydro Units (SDUC)

# Developed by

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#    July 9, 2019

# Define the packages
using JuMP          # used for mathematical programming
using ExcelReaders  # used for data input from Excel
using DataFrames    # used for data frames
using Gurobi        # used as the solver
using CSV           # used for writing csv files
```

StarGenLite_SDUC in Julia/JuMP (ii)

```
N  = 24  # hours
SC =  3  # scenarios
G  = 13  # thermal and hydro generating units

# reading data from Excel
InputFile = openxl("StarGenLite_SDUC.xlsm")
dfDemand        = readxl(InputFile, "DemandReserveIG!D6:D29")
dfOperReserve   = readxl(InputFile, "DemandReserveIG!I6:I29")
dfOperReserveUp = readxl(InputFile, "DemandReserveIG!N6:N29")
dfOperReserveDw = readxl(InputFile, "DemandReserveIG!S6:S29")
dfIntermGen     = readxl(InputFile, "DemandReserveIG!X6:Z29")
dfThermalGen    = readxl(InputFile, "Generation!D7:R19"     )

#  parameters
pScenProb      = [0.3, 0.5, 0.2]            # probability of scenarios      [p.u.]
pENSCost       = 10                         # energy not served  cost       [MEUR per GWh]
pCO2Cost       =  5                         # CO2 emission       cost       [ EUR per tCO2]
# scaling of parameters to GW and MEUR
pDemand        =         dfDemand[1:N     ] * 1e-3  # hourly load                   [GW]
pOperReserve   =   dfOperReserve[1:N     ] * 1e-3  # hourly operating reserve      [GW]
pOperReserveUp = dfOperReserveUp[1:N     ] * 1e-3  # hourly operating reserve up   [GW]
pOperReserveDw = dfOperReserveDw[1:N     ] * 1e-3  # hourly operating reserve down [GW]
pIntermGen     =     dfIntermGen[1:N,1:SC] * 1e-3  # stochastic IG generation      [GW]

pMaxProd       = dfThermalGen[1:G, 1] * 1e-3                                                       # maximum output            [GW]
pMinProd       = dfThermalGen[1:G, 2] * 1e-3                                                       # minimum output            [GW]
pIniOut        = dfThermalGen[1:G, 3] * 1e-3                                                       # initial output > min load [GW]
pRampUp        = dfThermalGen[1:G, 4] * 1e-3                                                       # ramp up                   [GW per   h]
pRampDw        = dfThermalGen[1:G, 5] * 1e-3                                                       # ramp down                 [GW per   h]
pSlopeVarCost  = dfThermalGen[1:G, 7] * 1e-3 .* dfThermalGen[1:G,6] .+ dfThermalGen[1:G,9] * 1e-3  # slope     variable cost   [MEUR per GWh]
pInterVarCost  = dfThermalGen[1:G, 8] * 1e-6 .* dfThermalGen[1:G,6]                                # intercept variable cost   [MEUR per   h]
pMinTU0        = dfThermalGen[1:G,10]                                                              # minimum time up           [h]
pMinTD0        = dfThermalGen[1:G,11]                                                              # minimum time down         [h]
pEmissionCost  = dfThermalGen[1:G,12] * 1e-3  * pCO2Cost                                           # emission           cost   [MEUR per GWh]
pStartUpCost   = dfThermalGen[1:G,13] * 1e-6 .* dfThermalGen[1:G,6]                                # startup            cost   [MEUR]
pShutDownCost  = dfThermalGen[1:G,14] * 1e-6 .* dfThermalGen[1:G,6]                                # shutdown           cost   [MEUR]
```

StarGenLite_SDUC in Julia/JuMP (iii)

```
pIniUC = zeros(Int64,G)
pMinTU = zeros(Int64,G)
pMinTD = zeros(Int64,G)

for g in 1:G
  # if the initial output of the unit is above its minimum load then the unit is committed, otherwise it is
not committed
  if   pIniOut[g] >= pMinProd[g]
       pIniUC[g]   = 1
  else pIniOut[g] <  pMinProd[g]
       pIniUC[g]   = 0
  end
  # if the minimum up or down times are 0, they are changed to 1
  if pMinTU0[g] == 0
     pMinTU[g]  =  1
  end
  if pMinTD0[g] == 0
     pMinTD[g]  =  1
  end
  # round these integer parameters to integer numbers
  pMinTU[g] = round(Int,pMinTU0[g])
  pMinTD[g] = round(Int,pMinTD0[g])
end
```

StarGenLite_SDUC in Julia/JuMP (iv)

```
function solve_mSDUC(UC, N, SC, G, pMaxProd, pMinProd, pIntermGen, pDemand, pOperReserve, pOperReserveUp, pOperReserveDw, pSlopeVarCost, pEmissionCost, pInterVarCost, pStartUpCost, pShutDownCost, pIniUC, pIniOut, pMinTU, pMinTD, pCommitt_Lo, pCommitt_Up, pStartup_Lo,
pStartup_Up, pShutdown_Lo, pShutdown_Up)

  # stochastic daily unit commitment (UC) model
  mSDUC = Model(solver=GurobiSolver(MIPGap=0.0))

  # decision variables
  @variable(mSDUC, 0 <=    vOutput[sc=1:SC,n=1:N,g=1:G] <=    pMaxProd[g ]            )  # output of the unit             [GW]
  @variable(mSDUC, 0 <= vOutput2nd[sc=1:SC,n=1:N,g=1:G] <=    pMaxProd[g ]-pMinProd[g])  # output of the unit > min load  [GW]
  @variable(mSDUC, 0 <=        vIG[sc=1:SC,n=1:N      ] <= pIntermGen[n,sc]          )  # intermittent generation        [GW]
  @variable(mSDUC, 0 <=       vENS[sc=1:SC,n=1:N      ] <=     pDemand[n ]            )  # energy not served              [GW]

  @variable(mSDUC,    vCommitment[        n=1:N,g=1:G], Bin                          )  # binary commitment of the unit  {0,1}
  @variable(mSDUC,       vStartup[        n=1:N,g=1:G], Bin                          )  # binary startup    of the unit  {0,1}
  @variable(mSDUC,      vShutdown[        n=1:N,g=1:G], Bin                          )  # binary shutdown   of the unit  {0,1}

  # fix values of binary variables to get the dual variables of the relaxed problem
  setlowerbound.(vCommitment , pCommitt_Lo )
  setupperbound.(vCommitment , pCommitt_Up )
  setlowerbound.(vStartup , pStartup_Lo )
  setupperbound.(vStartup , pStartup_Up )
  setlowerbound.(vShutdown, pShutdown_Lo)
  setupperbound.(vShutdown, pShutdown_Up)

  # objective function total system variable cost     [MEUR]
  @objective(mSDUC, :Min, sum(     pENSCost    *      vENS[sc,n  ] * pScenProb[sc] for sc=1:SC,n=1:N      ) +
                        sum(pSlopeVarCost[g] *  vOutput[sc,n,g] * pScenProb[sc] for sc=1:SC,n=1:N,g=1:G) +
                        sum(pEmissionCost[g] *  vOutput[sc,n,g] * pScenProb[sc] for sc=1:SC,n=1:N,g=1:G) +
                        sum(pInterVarCost[g] *  vCommitment[   n,g]                 for         n=1:N,g=1:G) +
                        sum( pStartUpCost[g] *  vStartup[   n,g]                 for         n=1:N,g=1:G) +
                        sum(pShutDownCost[g] * vShutdown[   n,g]                 for         n=1:N,g=1:G) )

  # load generation balance        [GW]
  @constraint(mSDUC, eBalance[sc=1:SC,n=1:N], sum(vOutput[sc,n,g] for g=1:G) + vIG[sc,n] + vENS[sc,n] == pDemand[n])

  # operating reserve              [GW]
  @constraint(mSDUC, eOpReserve[n=1:N], sum(pMaxProd[g] * vCommitment[n,g] for g=1:G) >= pOperReserve[n] + pDemand[n])

  # operating reserve upwards and downwards    [GW]
  @constraint(mSDUC, eReserveUp[sc=1:SC,n=1:N], sum(pMaxProd[g] * vCommitment[n,g] - vOutput[sc,n,g] for g=1:G) >=   pOperReserveUp[n])
  @constraint(mSDUC, eReserveDw[sc=1:SC,n=1:N], sum(pMinProd[g] * vCommitment[n,g] - vOutput[sc,n,g] for g=1:G) <= - pOperReserveDw[n])

  # maximum and minimun output of a committed unit [GW]
  @constraint(mSDUC, eMaxOutput[sc=1:SC,n=1:N,g=1:G], vOutput[sc,n,g] / pMaxProd[g] <= vCommitment[n,g])
  @constraint(mSDUC, eMinOutput[sc=1:SC,n=1:N,g=1:G], vOutput[sc,n,g] / pMinProd[g] >= vCommitment[n,g])

  # total output of a committed unit [GW]
  @constraint(mSDUC, eTotOutput[sc=1:SC,n=1:N,g=1:G], vOutput[sc,n,g] == pMinProd[g]*vCommitment[n,g] + vOutput2nd[sc,n,g])

  # bounds on up and down ramps      [GW]
  @constraint(mSDUC, eRampUp[sc=1:SC,n=  1,g=1:G], vOutput2nd[sc,n,g] -      max(pIniOut[g] - pMinProd[g],0) <=   pRampUp[g])
  @constraint(mSDUC, eRampDw[sc=1:SC,n=  1,g=1:G], vOutput2nd[sc,n,g] -      max(pIniOut[g] - pMinProd[g],0) >= - pRampDw[g])
  @constraint(mSDUC, eRampUp[sc=1:SC,n=2:N,g=1:G], vOutput2nd[sc,n,g] - vOutput2nd[sc,n-1,g]                  <=   pRampUp[g])
  @constraint(mSDUC, eRampDw[sc=1:SC,n=2:N,g=1:G], vOutput2nd[sc,n,g] - vOutput2nd[sc,n-1,g]                  >= - pRampDw[g])

  # relation among commitment startup and shutdown
  @constraint(mSDUC, eUCStrShut[n=1  ,g=1:G], vCommitment[n,g] - pIniUC[      g] == vStartup[n,g] - vShutdown[n,g])
  @constraint(mSDUC, eUCStrShut[n=2:N,g=1:G], vCommitment[n,g] - vCommitment[n-1,g] == vStartup[n,g] - vShutdown[n,g])

  # minimum up (committed) and down (not committed) time       [GW]
  @constraint(mSDUC, eMinTUp[g=1:G,n=pMinTU[g]:N], sum( vStartup[nn,g] for nn=n+1-pMinTU[g]:n) <=     vCommitment[n,g])
  @constraint(mSDUC, eMinTDw[g=1:G,n=pMinTD[g]:N], sum(vShutdown[nn,g] for nn=n+1-pMinTD[g]:n) <= 1 - vCommitment[n,g])

  writeLP(mSDUC, "modelJuMP.lp", genericnames=false)

  # Solve statement
  if   UC == 1
    status = solve(mSDUC; relaxation=false)
    return status, getobjectivevalue(mSDUC), getvalue(vOutput), getvalue(vIG), getvalue(vCommitment), getvalue(vStartup), getvalue(vShutdown)
  else UC == 0
    status = solve(mSDUC; relaxation=true)
    return status, getobjectivevalue(mSDUC), getvalue(vOutput), getvalue(vIG), getvalue(vCommitment), getvalue(vStartup), getvalue(vShutdown), getdual(eBalance)
  end

end
```

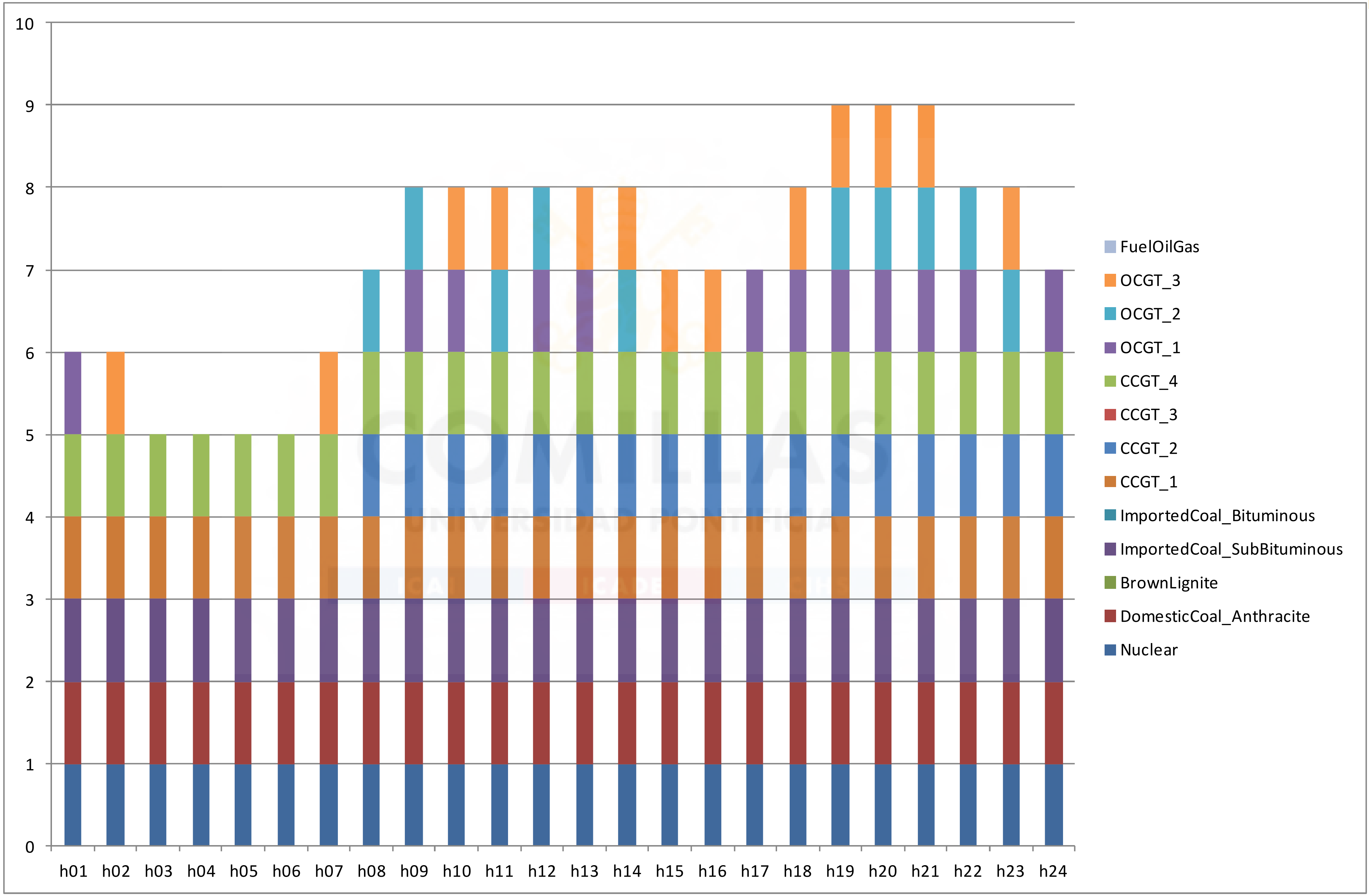
StarGenLite_SDUC in Julia/JuMP (v)

```
# solve the stochastic daily unit commitment problem
UC = 1
pCommitt_Lo  = zeros(Int64,N,G)
pCommitt_Up  =  ones(Int64,N,G)
pStartup_Lo  = zeros(Int64,N,G)
pStartup_Up  =  ones(Int64,N,G)
pShutdown_Lo = zeros(Int64,N,G)
pShutdown_Up =  ones(Int64,N,G)
(status_opt, obj, pProduct_opt, pIG_opt, pCommitt_opt, pStartup_opt, pShutdown_opt) =
solve_mSDUC(UC, N, SC, G, pMaxProd, pMinProd, pIntermGen, pDemand, pOperReserve, pOperReserveUp, pOperReserveDw, pSlopeVarCost, pEmissionCost, pInterVarCost, pStartUpCost,
pShutDownCost, pIniUC, pIniOut, pMinTU, pMinTD, pCommitt_Lo, pCommitt_Up, pStartup_Lo, pStartup_Up, pShutdown_Lo, pShutdown_Up)

# solve the economic dispatch problem with binary variables fixed to their binary values
UC = 0
pCommitt_Lo  =  pCommitt_opt
pCommitt_Up  =  pCommitt_opt
pStartup_Lo  =  pStartup_opt
pStartup_Up  =  pStartup_opt
pShutdown_Lo = pShutdown_opt
pShutdown_Up = pShutdown_opt
(status_opt, obj, pProduct_opt, pIG_opt, pCommitt_opt, pStartup_opt, pShutdown_opt, pSRMC_opt) =
solve_mSDUC(UC, N, SC, G, pMaxProd, pMinProd, pIntermGen, pDemand, pOperReserve, pOperReserveUp, pOperReserveDw, pSlopeVarCost, pEmissionCost, pInterVarCost, pStartUpCost,
pShutDownCost, pIniUC, pIniOut, pMinTU, pMinTD, pCommitt_Lo, pCommitt_Up, pStartup_Lo, pStartup_Up, pShutdown_Lo, pShutdown_Up)

# scaling of the results
pProduct_opt = pProduct_opt * 1e3
for sc in 1:SC
  for n in 1:N
      pSRMC_opt[sc,n]    = pSRMC_opt[sc,n]    * 1e3 / pScenProb[sc]
  end
end

# output of the results
dfProduct = DataFrame(vcat(hcat("Scenario", "Generator", reshape(1:N,1,N)), hcat(sort!(repeat(1:SC,G)), repeat(1:G,SC), reshape(pProduct_opt,SC*G,N))))
dfIG      = DataFrame(vcat(hcat("Scenario",              reshape(1:N,1,N)), hcat(             1:SC,                     reshape(pIG_opt     ,SC,  N))))
dfUC      = DataFrame(vcat(hcat(            "Generator", reshape(1:N,1,N)), hcat(                              1:G,     reshape(pCommitt_opt,   G,N))))
dfSRMC    = DataFrame(vcat(hcat("Scenario",              reshape(1:N,1,N)), hcat(             1:SC,                     reshape(pSRMC_opt   ,SC,  N))))
CSV.write("Output.csv", dfProduct, delim = ";")
CSV.write("IG.csv",     dfIG,      delim = ";")
CSV.write("UC.csv",     dfUC,      delim = ";")
CSV.write("SRMC.csv",   dfSRMC,    delim = ";")
```

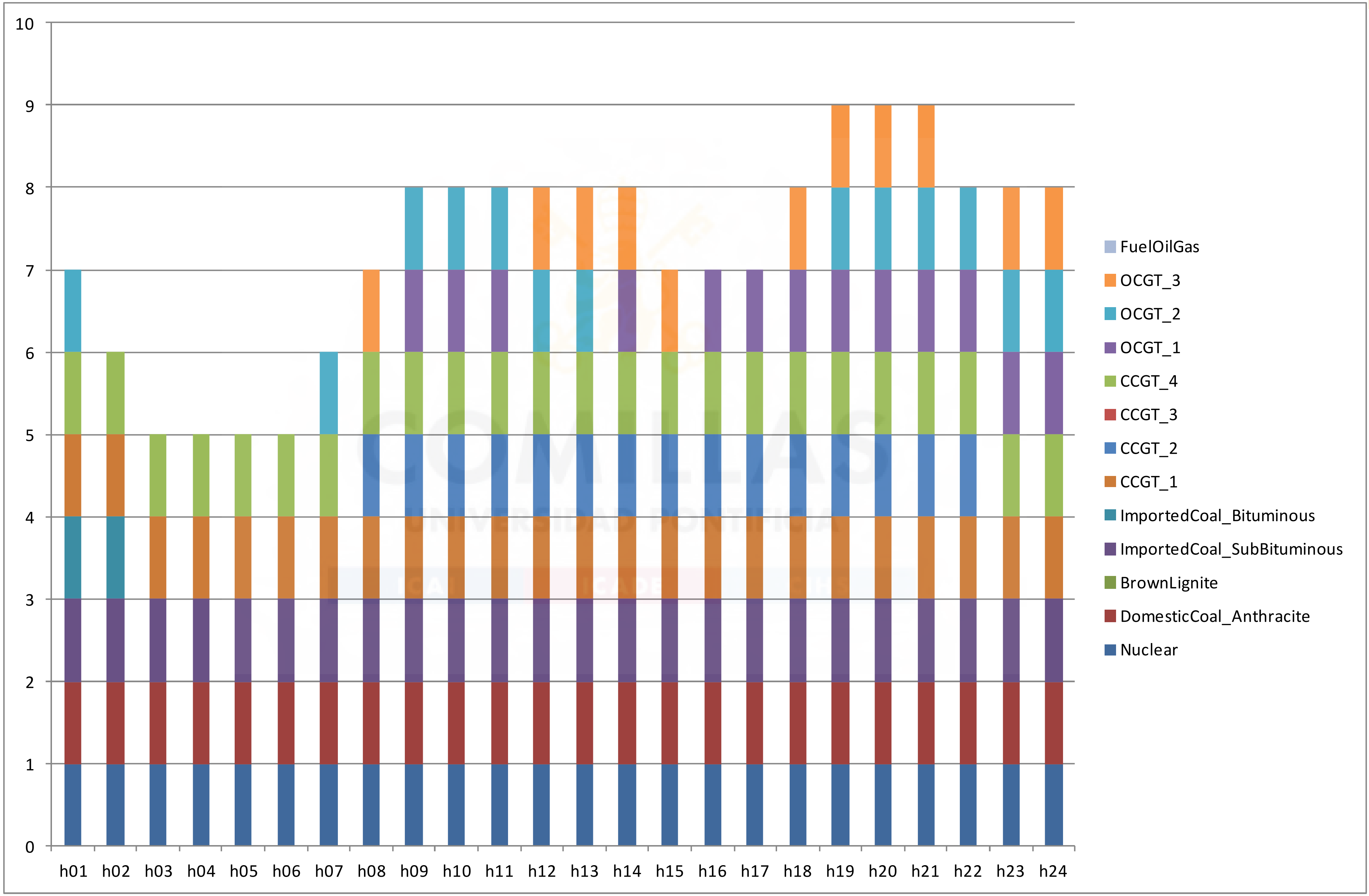
Task assignment

- Run a deterministic model version for every scenario (three cases). Run a deterministic model version for the mean value scenario (fourth case). Run the stochastic daily unit commitment model (fifth case)
  - Determine the committed units and the output of each unit and explain the differences
- Compare the results of the five cases
  - Total expected variable costs
  - Committed thermal units
  - Thermal unit and wind power output
- Introduce in the stochastic case two additional extreme intermittent generation scenarios with very low probability (1 %, for example) and analyze the results
  - Do the main results (UC and operation decisions) depend on the scenarios defined?
- Formulate using the previous symbols and introduce a constraint in the UC with a maximum emission allowance per unit and system for every scenario or all scenarios
- What are the specific changes in the mathematical formulation and the code to modify the time step of the model to 15 minutes?
- Formulate the introduction of Demand Side Management (load shifting, load shedding, etc.) strategies in the model mathematically

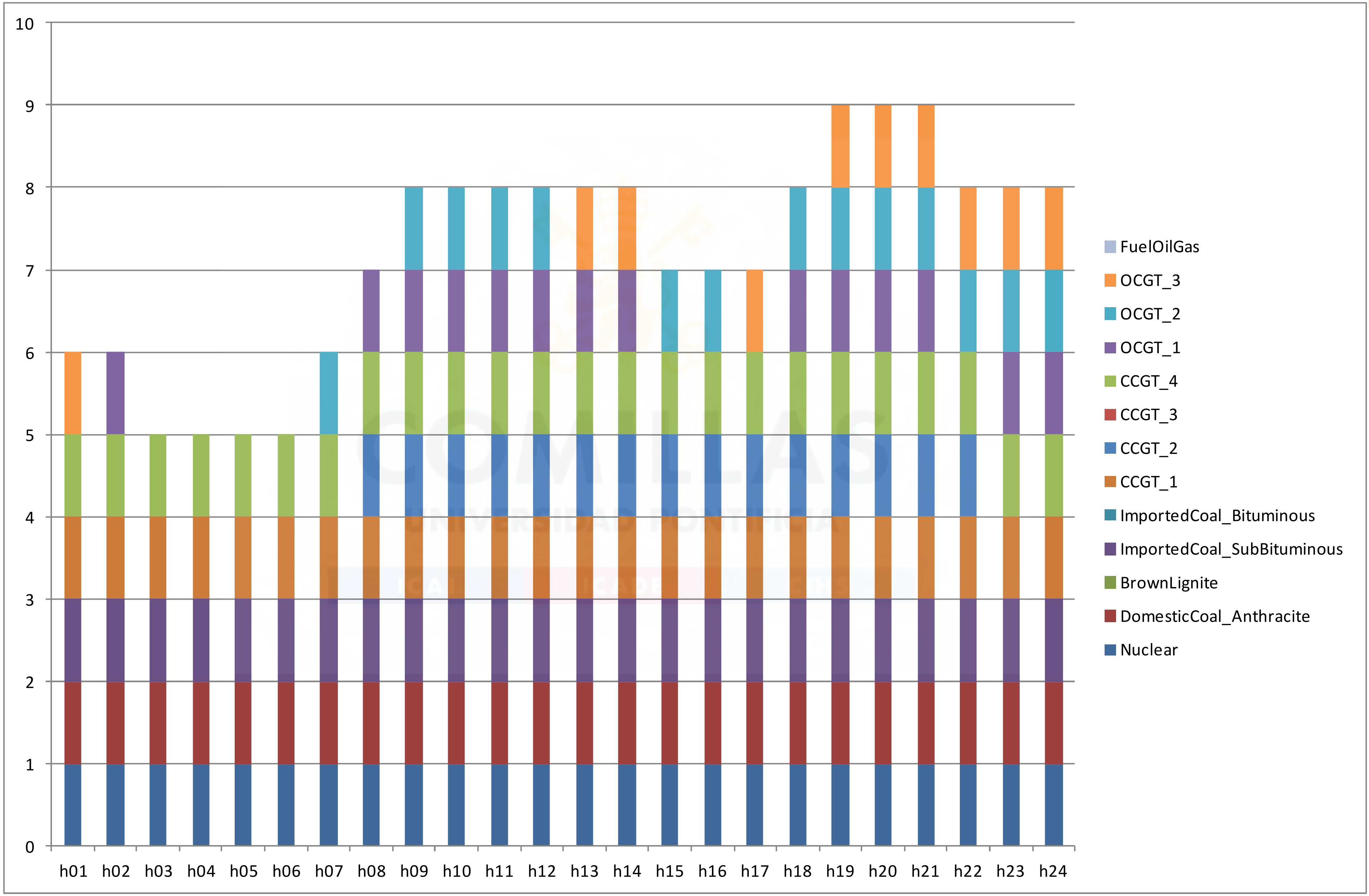
Deterministic solution for scenario 1



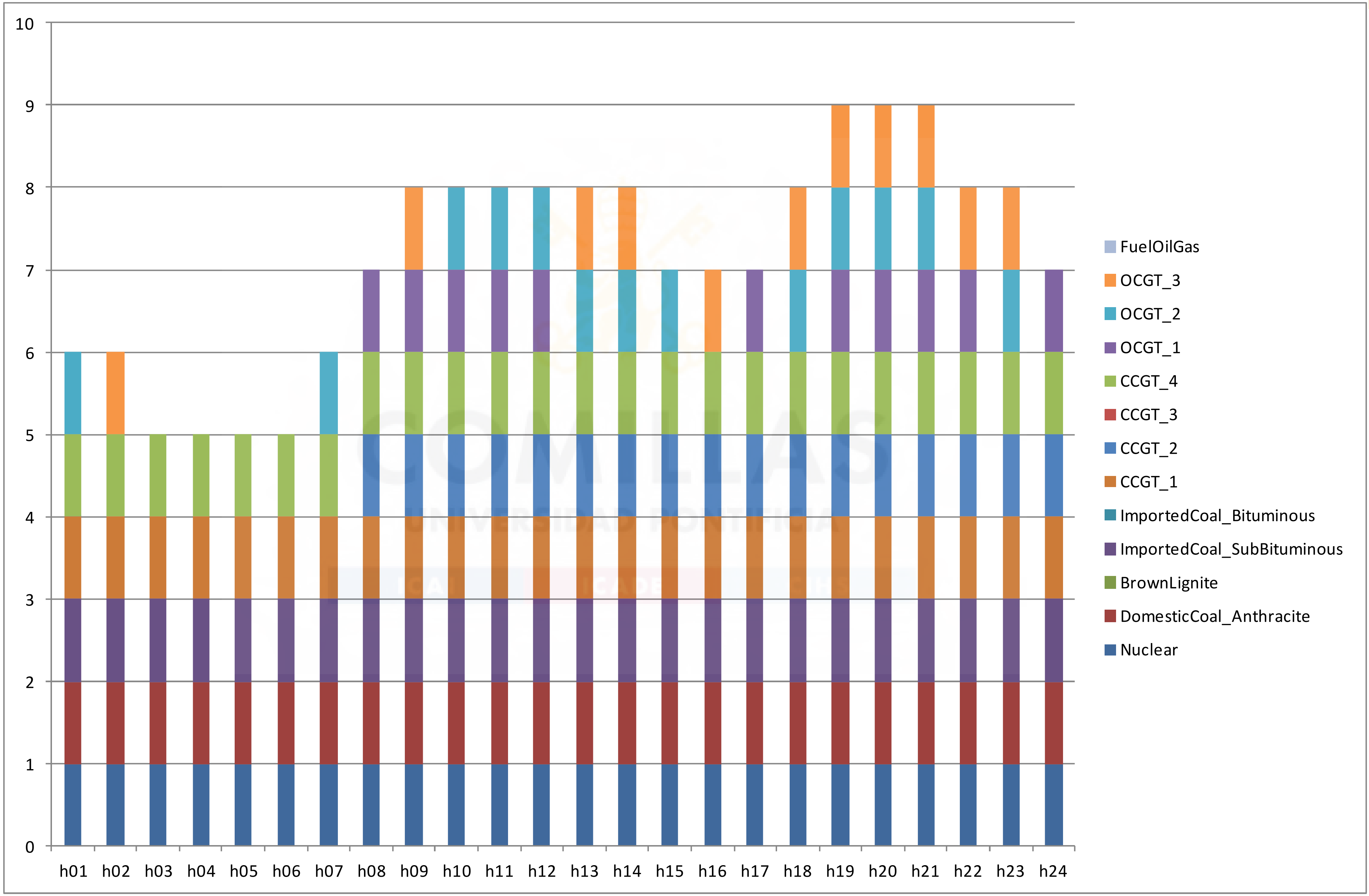
Deterministic solution for scenario 2



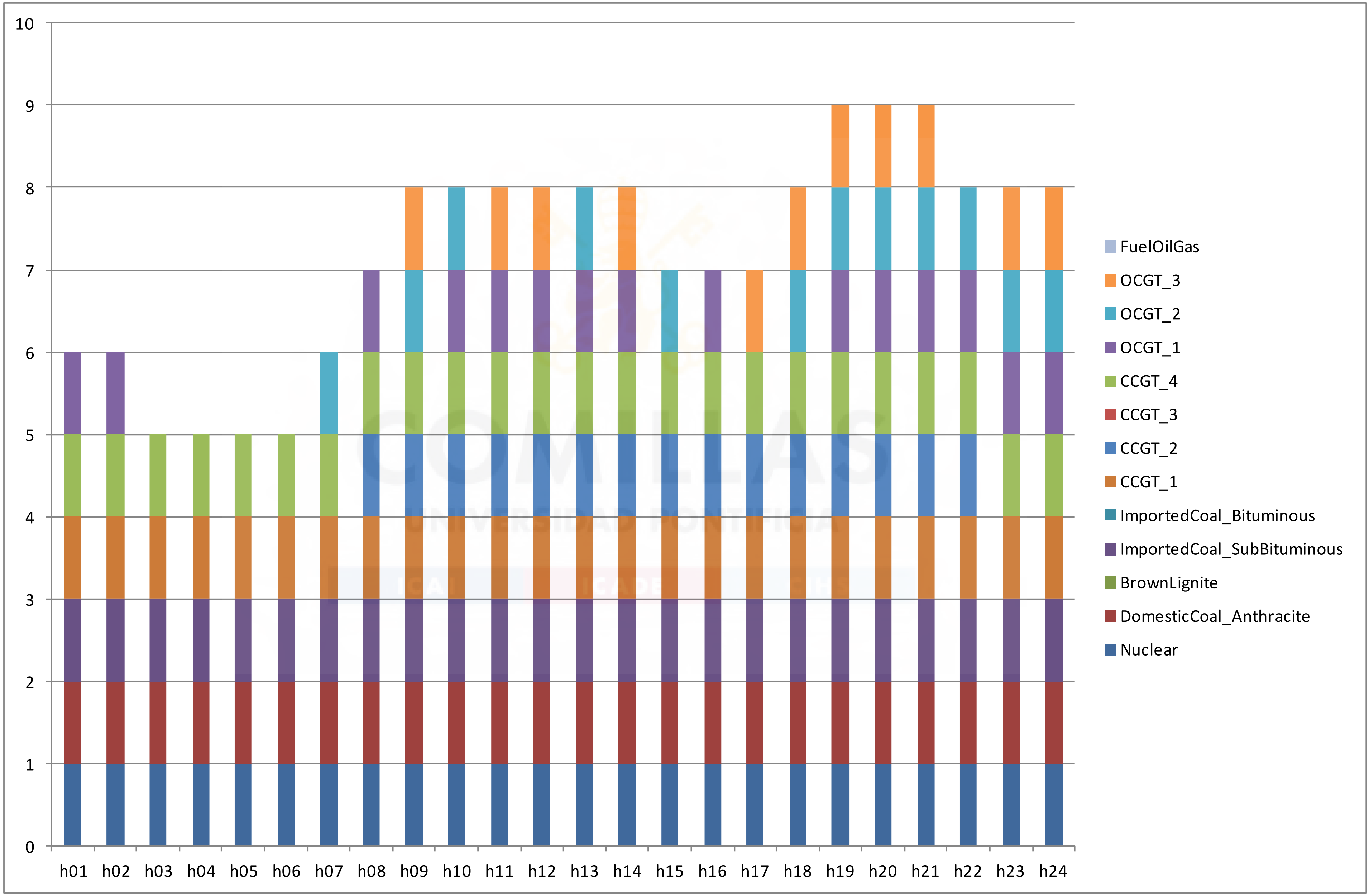
Deterministic solution for scenario 3



Deterministic solution for mean scenario



Stochastic solution for the scenario tree



Summary of results

	Scenario 1 *p*=0.3	Scenario 2 *p*=0.5	Scenario 3 *p*=0.2	Mean scenario	Stochastic Solution
Objective function [M€]	2.563975	2.514956	2.328417	2.488835	2.493131
Objective function [%]	3.0	1.0	-6.4		0.2
Thermal generation [MWh]	62329	61386	56270	60646	60646
Thermal generation [%]	2.8	1.2	-7.2		0.0
Wind power [MWh]	13805	14748	19863	15488	15488
Wind power [%]	-10.9	-4.8	28.2		0.0

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