CiFE · Centre International de Formation Européenne

Deployment Architecture and Operation of Solar-Heavy Systems

A Comparative Analysis of California and Spain

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2 GW

installed per day in 2024

6%
of global electricity

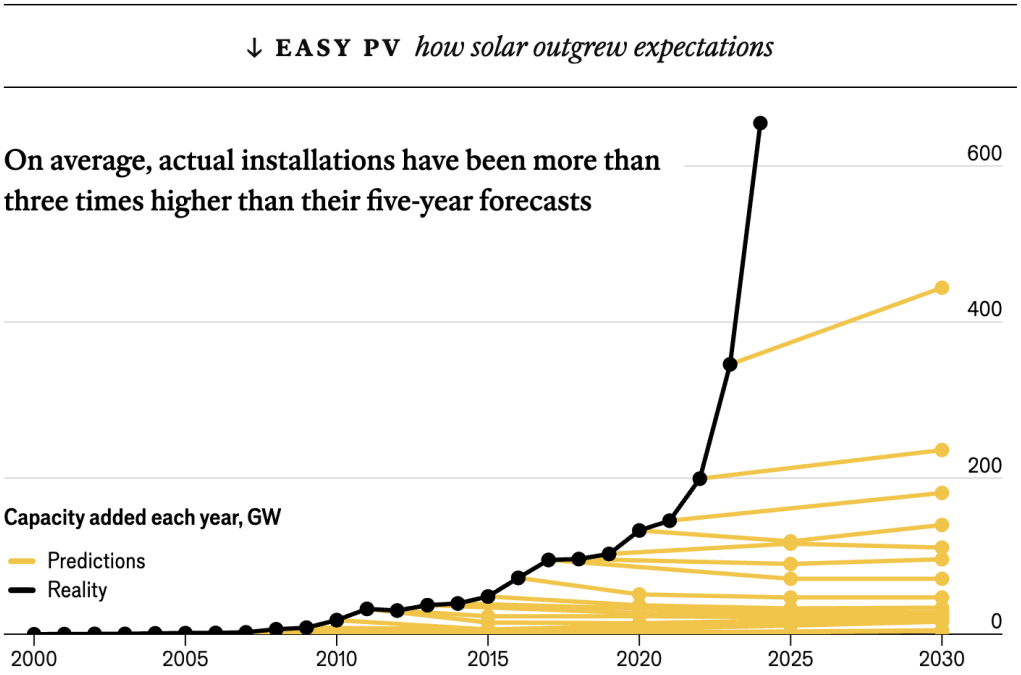
75%
of new renewable capacity

511 GW
added in 2025

SOLAR AT SCALE

Solar Growth

Source: *The Economist,* "Solar Power Is Going to Be Huge" (June 2024)

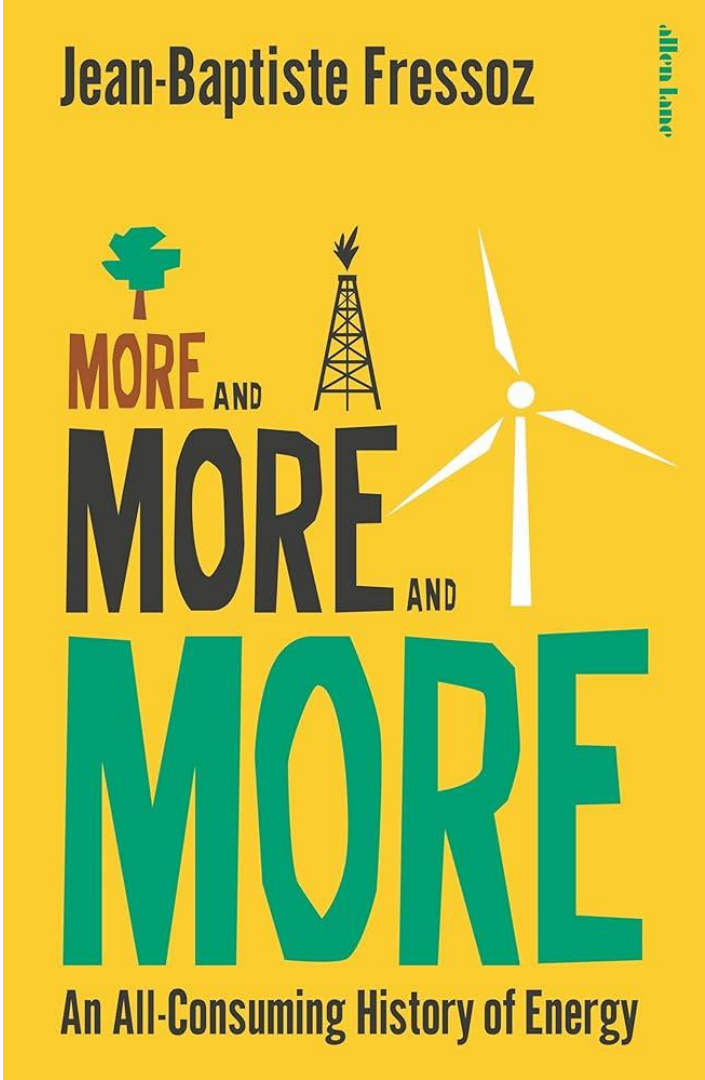


Study Thread

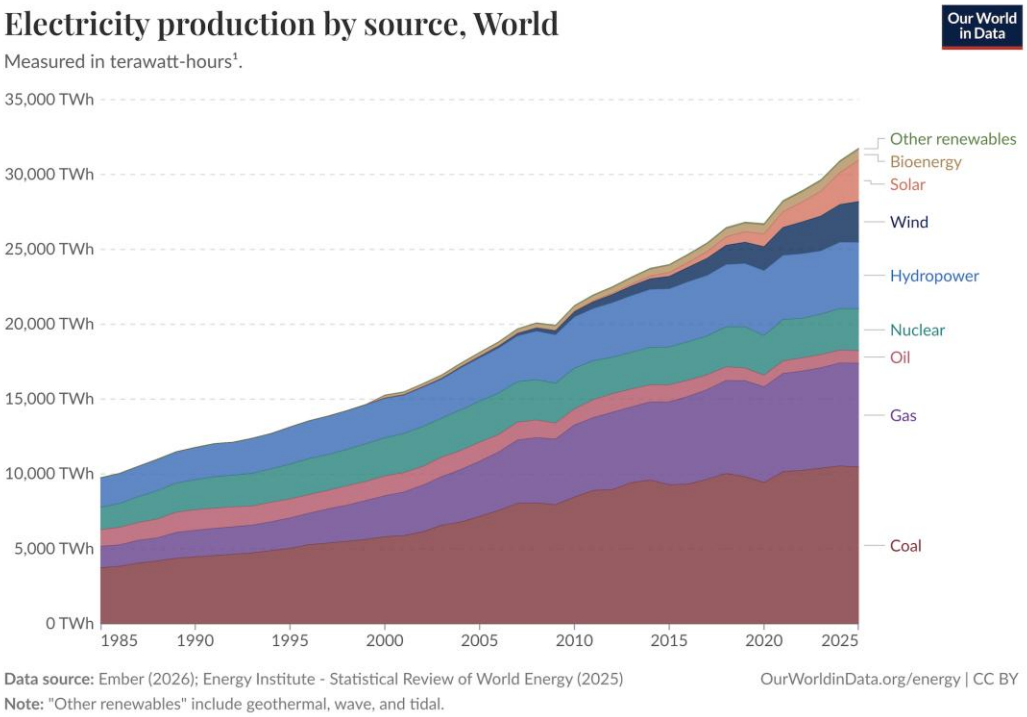
Fressoz 2024

Energy transitions are not replacements.

Layering process

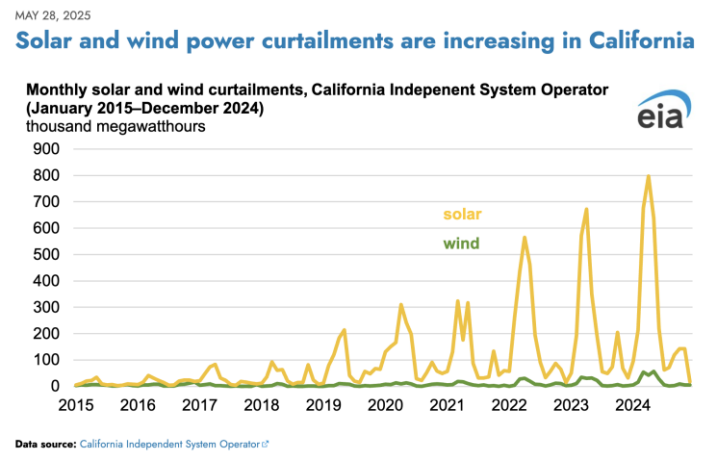


Transition? Addition?



THE PUZZLE

CALIFORNIA

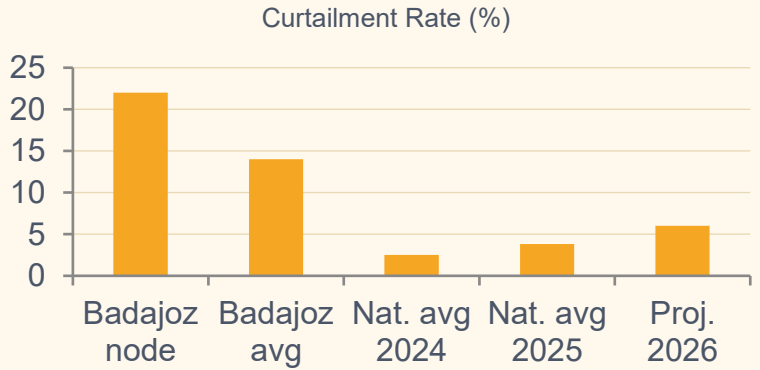


Temporal challenge: Duck Curve

11.5% curtailment (Jan–May 2025)

17 GW battery storage deployed

SPAIN



Spatial challenge: Congestion

2.5–3.8% national avg (up to 30% locally)

<100 MW utility battery storage

Source: Author's graph (AI-generated visualization), based on data from Aurora Energy (2026)

Both have: similar solar irradiation · liberalized markets · ~50–60% renewable share · comparable land area · decarbonization targets (2045 and 2050)

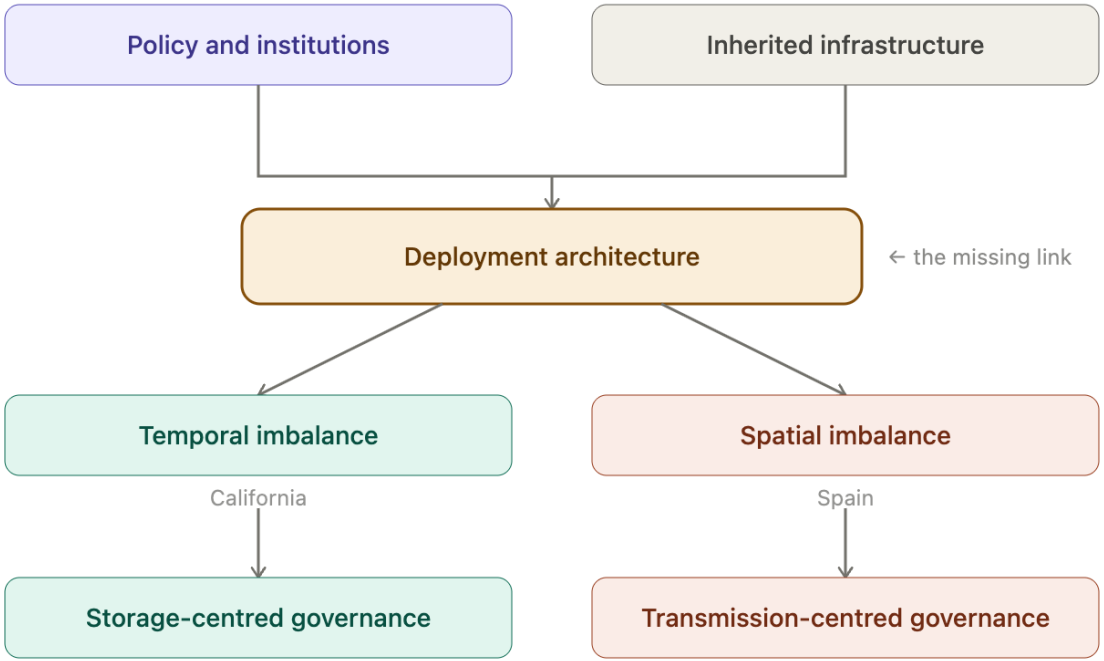
RESEARCH QUESTION

Why have California and Spain, despite similar commitments to solar-led decarbonization, experienced different system-level outcomes?

MAIN ARGUMENT

Integration outcomes are shaped not by how much solar is deployed, but by WHERE and at WHAT SCALE

Framework: Missing Link



THEORETICAL FRAMEWORK

Political Economy

Geels 2002; Unruh 2000; Arent et al. 2017; Goldthau 2014; Meckling 2019

Energy transitions shaped by policies and market designs

Explains renewable deployment but not differing integration stresses

Technical Integration

Bird et al. 2016 · Jenkins et al. 2018 · NREL · IEA

Focus on grid challenges: curtailment, congestion, flexibility needs

Assumes similar solar deployment translates to similar grid challenges

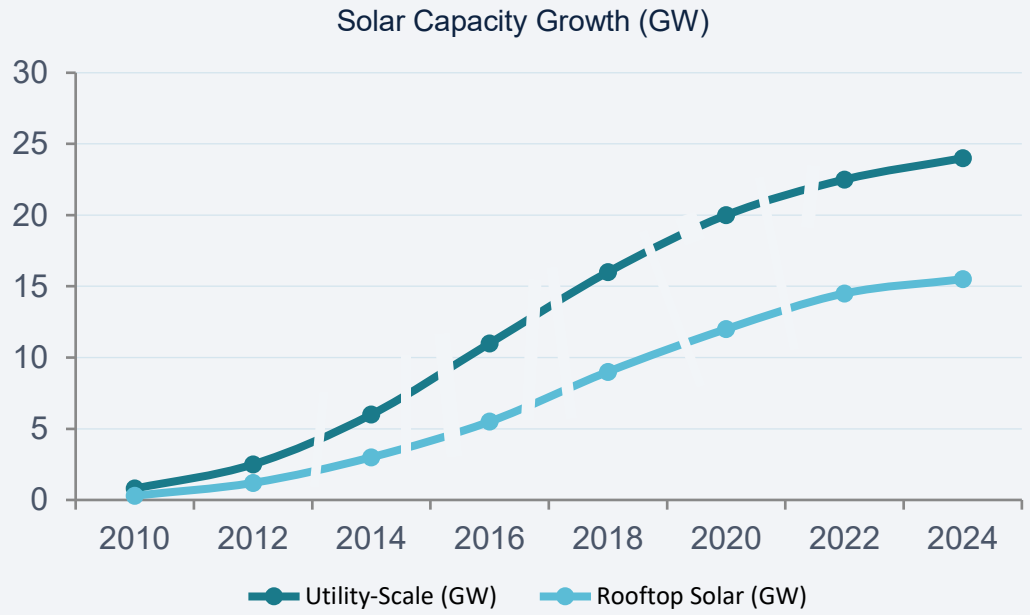
Socio-Technical Transition Theory

Pierson 2000; Smith et al. 2005; Kuzemko et al. 2016

Transition conceptualized as a path-dependent process that includes interaction with existing institutions and systems

→ ***Electricity systems are layered regimes. Solar interacts with inherited infrastructure, market design, and regulatory history.***

CALIFORNIA: Dual-Layer Deployment Architecture



Source: Author's graph (AI-generated visualization), based on data from California Energy Commission

Key Policy Drivers

RPS → SB 100

100% carbon-free by 2045

NEM Policies

Bill credits for rooftop export

Solar Mandate

Required on all new homes (2020)

High retail prices

30–38¢/kWh vs 12.7¢ national avg

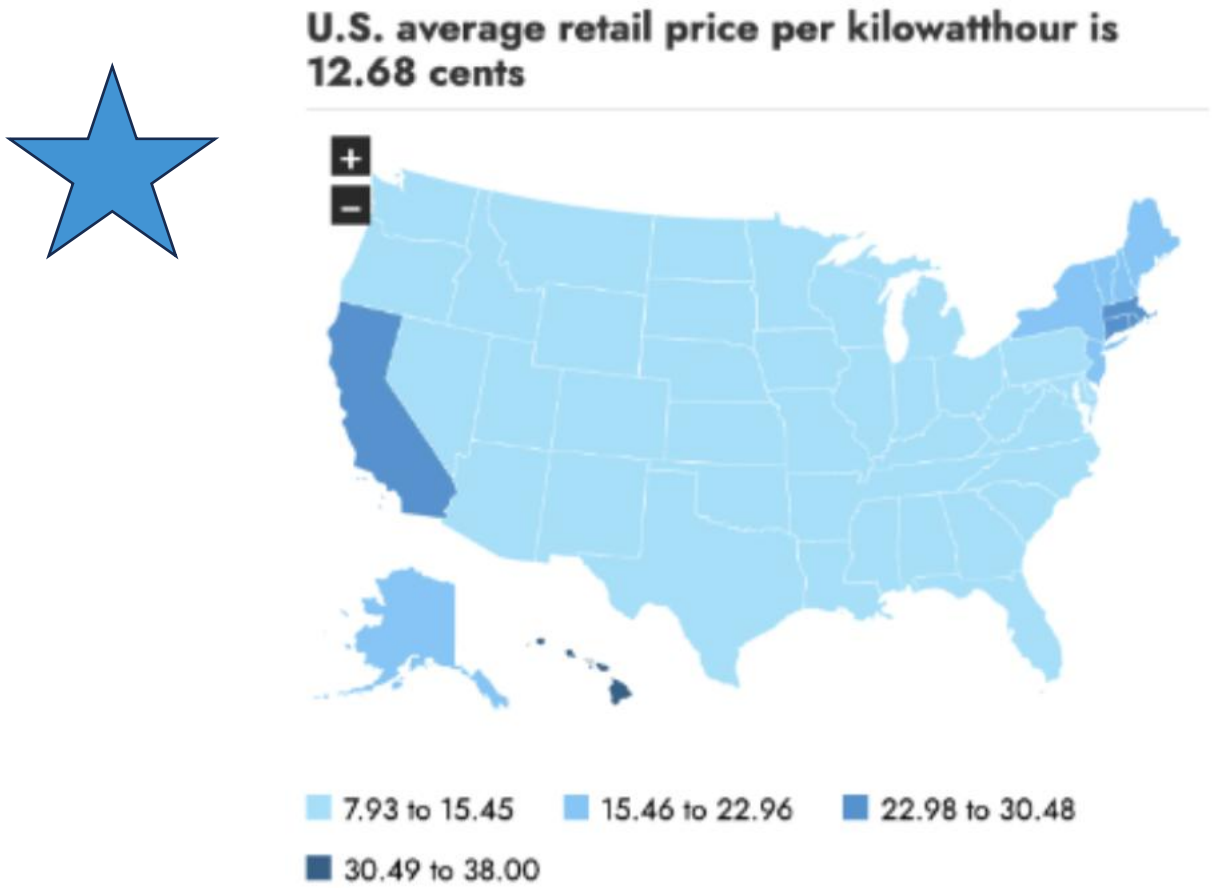
Result: Geographically concentrated inland (Central Valley, Mojave) + 25%+ of homes with rooftop PV

24 GW utility-scale

15 GW rooftop

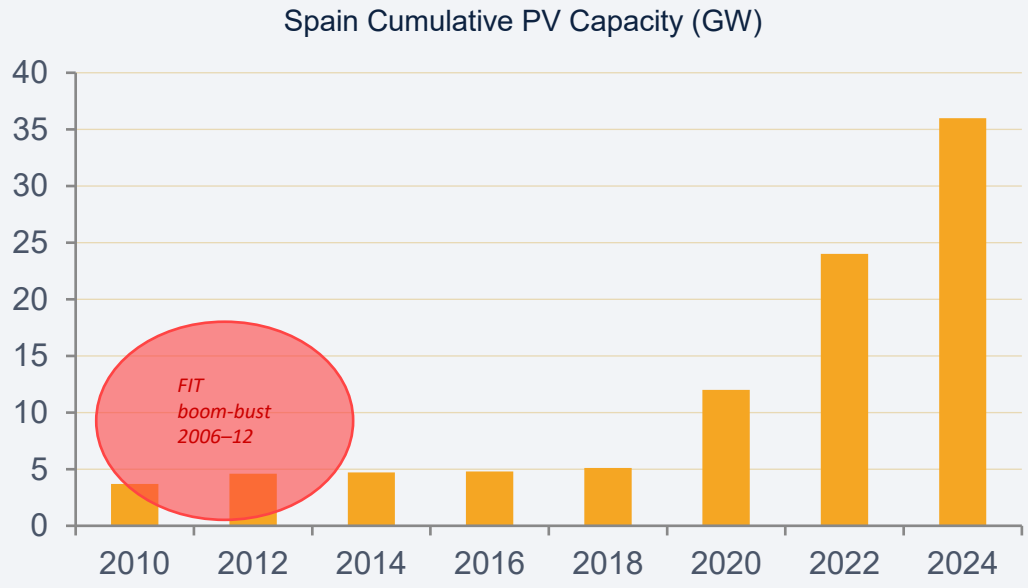
17 GW battery storage

>2000% BESS growth since 2019



Source: EIA 2025

SPAIN: Utility-Scale Concentration & Transmission Dependence



Source: Author's graph (AI-generated visualization), based on data from REE

Result: Solar concentrated far from demand hubs

Policy Trajectory

2004–07

Royal Decree 661/2007
Generous FIT → rapid boom

2008–12

FIT retroactively cut
>30 billion € tariff deficit

2013–17

"Sun tax" moratorium
Deployment collapses

2018+

New NECP targets
Utility-scale boom resumes

< 100 MW utility BESS

3.5 GW pumped hydro only

3 GW Spain–France link

70% hours congested (2024)

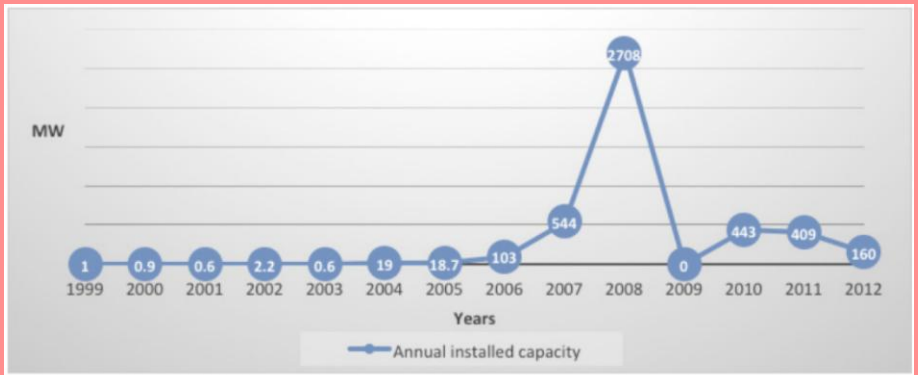
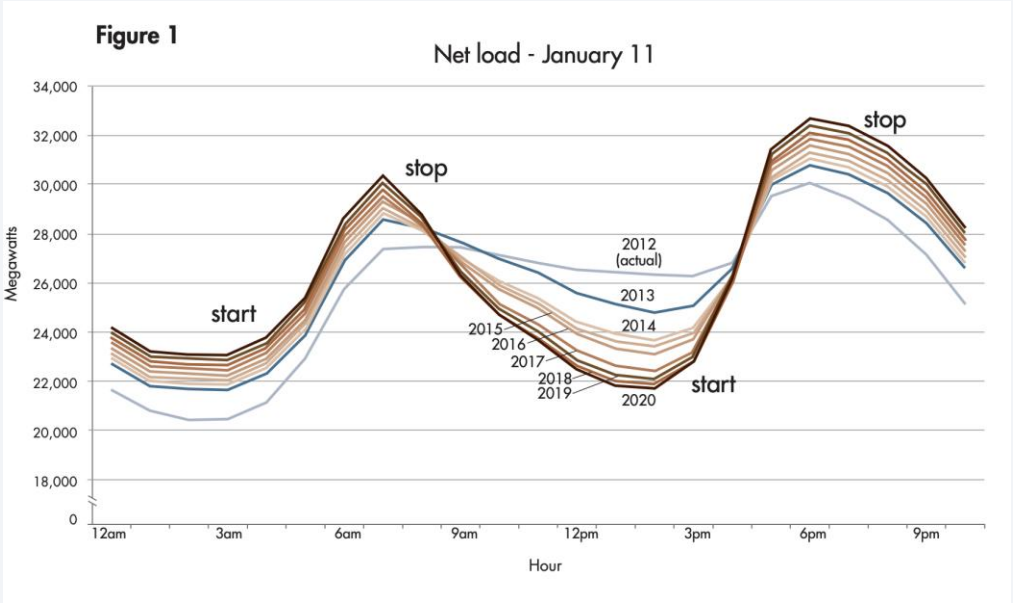


FIGURE 1. SPAIN'S ANNUAL INSTALLED SOLAR PV CAPACITY (MW), 1999-2012)

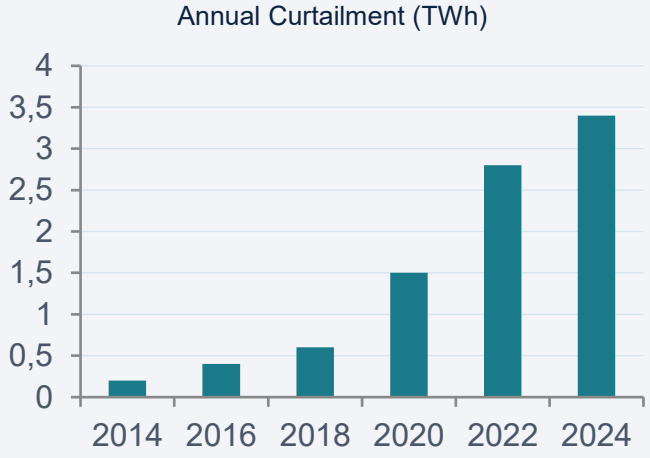
Source: IISD (Int. Institute for Sustainable Development 2014

CALIFORNIA: Temporal Imbalance — The Duck Curve



Source: CAISO (2012)

Transmission bottleneck: solar farms are inland; gas plants were coastal. New lines take 10–15 years to permit and build.



Core Problem

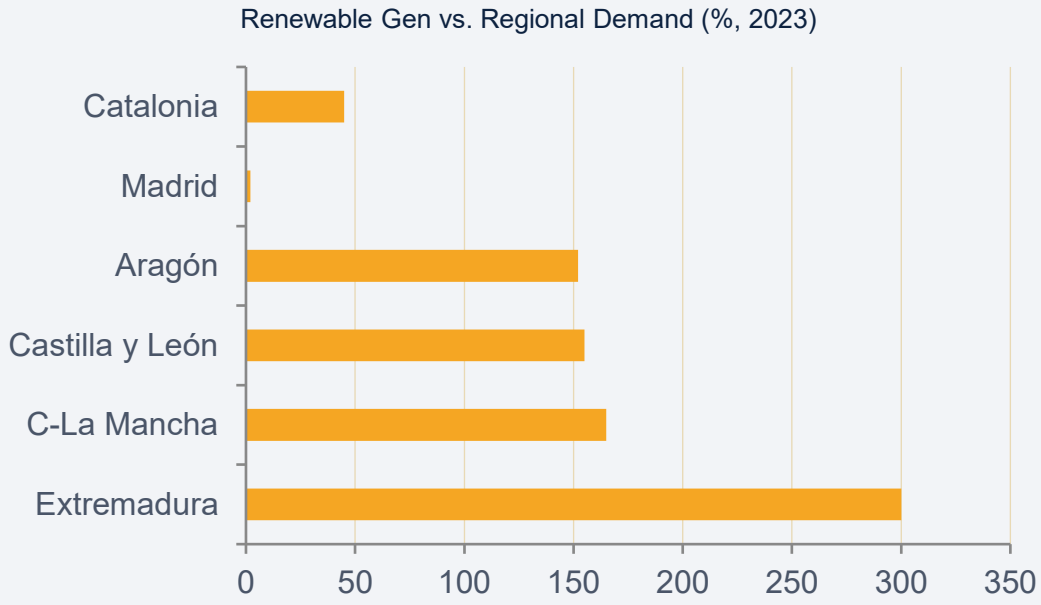
Generation peaks at midday.

Demand peaks at evening.

Batteries grow but curtailment continues to rise.

Despite 17 GW of BESS deployment (>2000% growth since 2019) — curtailment reached 3.4 million MWh in 2024

SPAIN: Spatial Imbalance — Congestion & Energy Island



"Energy Island" Problem: The Iberian Peninsula is one of Europe's least interconnected regions. Surplus cannot be easily exported to the broader EU market.

The Congestion Picture

>22%
curtailment at single Badajoz node

20%
of national curtailment from Badajoz province alone

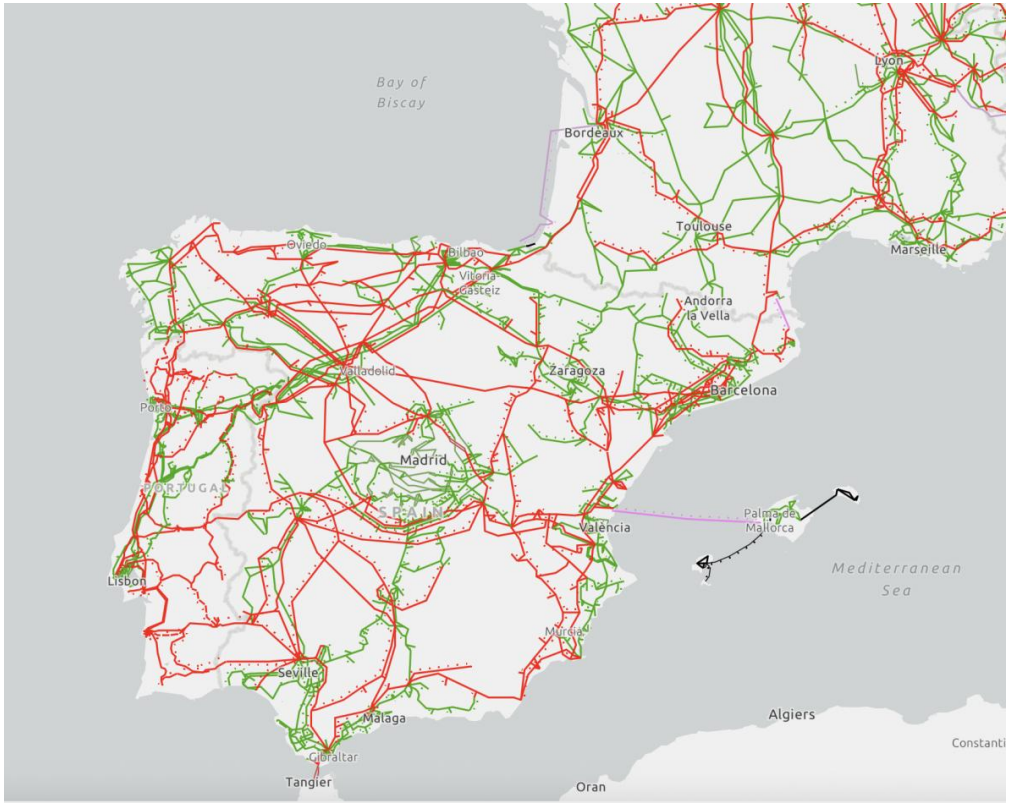
3 TWh
uncompensated curtailment projected by 2027

70%
of hours Spain–France interconnection is congested

2%
interconnection level vs 10% EU target

Spain's problem is not timing, it's geography: solar is produced in the wrong place, not the wrong hour

Energy Island



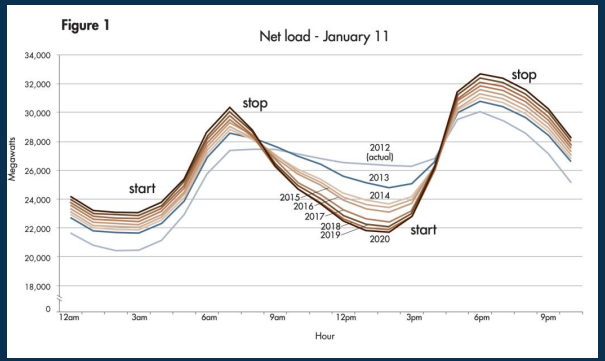
Source: ENTSO-e (2026)

TWO TYPES OF IMBALANCE

Similar solar penetration → different operational stress

TEMPORAL IMBALANCE

California

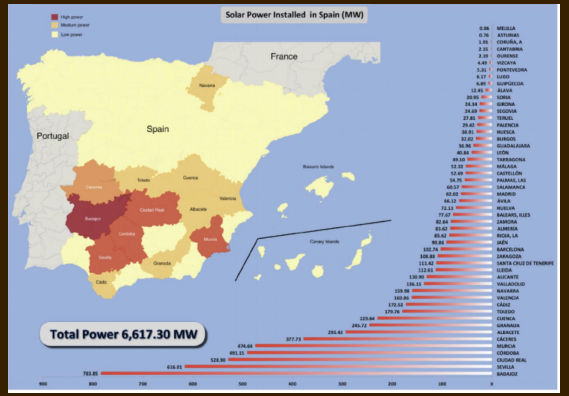


- Midday oversupply + steep evening ramp
- Duck curve deepens year on year
- Curtailment = temporal overflow

VS

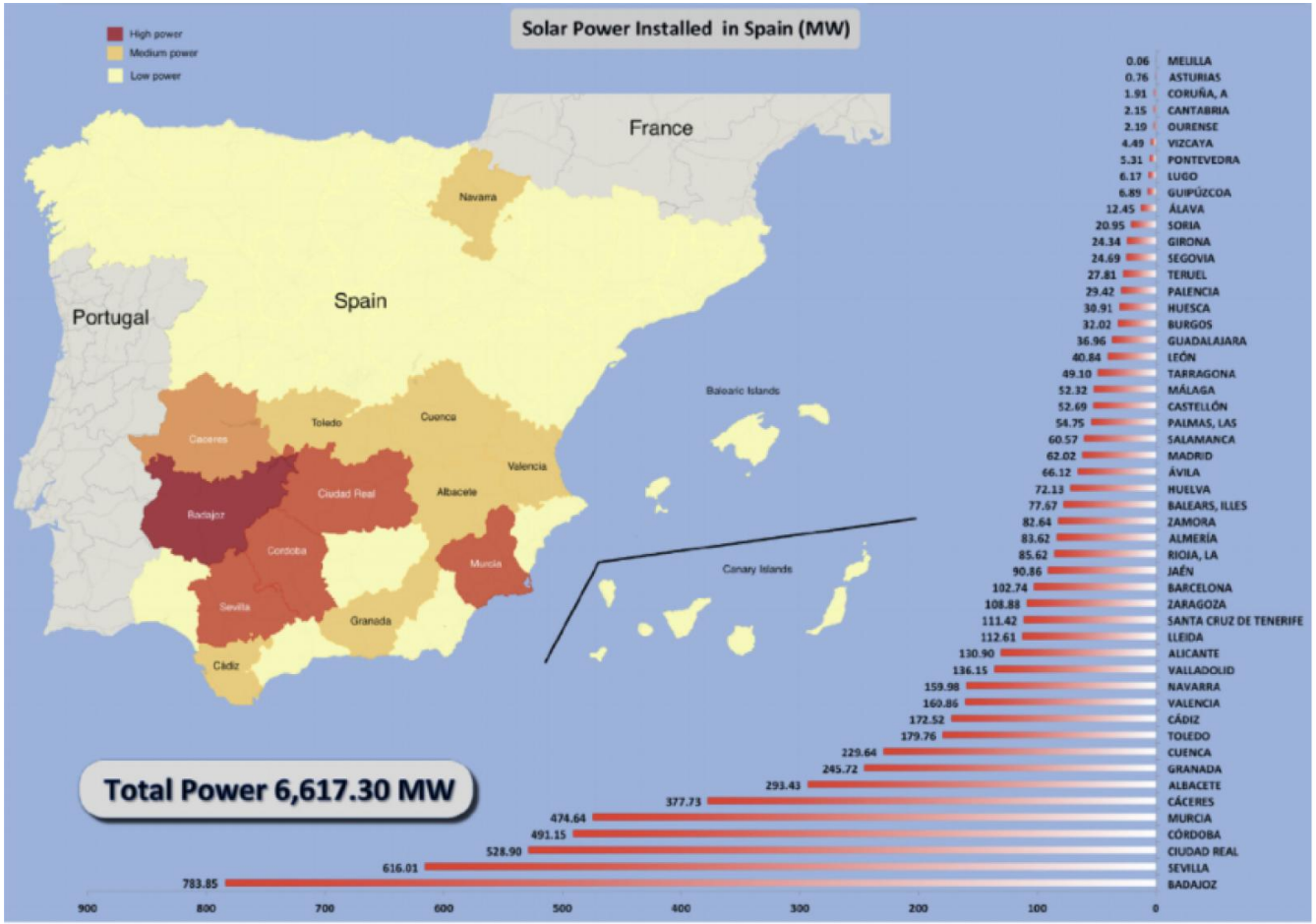
SPATIAL IMBALANCE

Spain



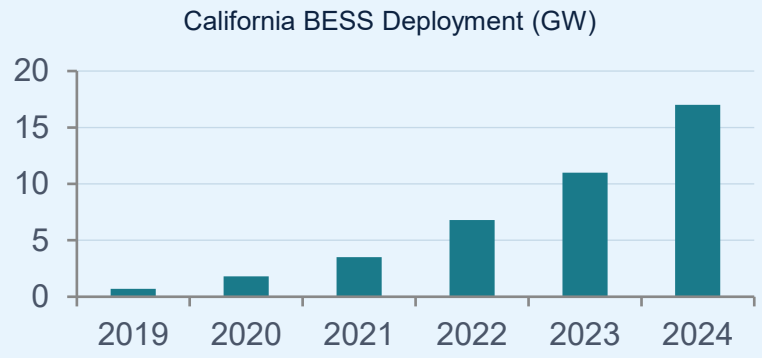
- Generation concentrated far from demand
- Transmission cannot carry the surplus
- Curtailment = spatial overflow

The difference is the deployment architecture — not the technology nor the amount of solar


Solar Power Installed in Spain (MW)
High power
Medium power
Low power
France
Navarra
Portugal
Spain
Balearic Islands
Canary Islands
Toledo
Cuenca
Caceres
Valencia
Ciudad Real
Albacete
Badajoz
Murcia
Cordoba
Sevilla
Granada
Cádiz
Total Power 6,617.30 MW
0.06 MELILLA
0.76 ASTURIAS
1.91 CORUÑA, A
2.15 CANTABRIA
2.19 OURENSE
4.49 VIZCAYA
5.31 PONTEVEDRA
6.17 LUGO
6.89 GUIPÚZCOA
12.45 ÁLAVA
20.95 SORIA
24.34 GIRONA
24.69 SEGOVIA
27.81 TERUEL
29.42 PALENCIA
30.91 HUESCA
32.02 BURGOS
36.96 GUADALAJARA
40.84 LEÓN
49.10 TARRAGONA
52.32 MÁLAGA
52.69 CASTELLÓN
54.75 PALMAS, LAS
60.57 SALAMANCA
62.02 MADRID
66.12 ÁVILA
72.13 HUELVA
77.67 BALEARS, ILLES
82.64 ZAMORA
83.62 ALMERÍA
85.62 RIOJA, LA
90.86 JAÉN
102.74 BARCELONA
108.88 ZARAGOZA
111.42 SANTA CRUZ DE TENERIFE
112.61 LLEIDA
130.90 ALICANTE
136.15 VALLADOLID
159.98 NAVARRA
160.86 VALENCIA
172.52 CÁDIZ
179.76 TOLEDO
229.64 CUENCA
245.72 GRANADA
293.43 ALBACETE
377.73 CÁCERES
474.64 MURCIA
491.15 CÓRDOBA
528.90 CIUDAD REAL
616.01 SEVILLA
783.85 BADAJOZ
900
800
700
600
500
400
300
200
100
0

GOVERNANCE RESPONSES — Path-Dependent Flexibility Strategies

California — Storage Regime



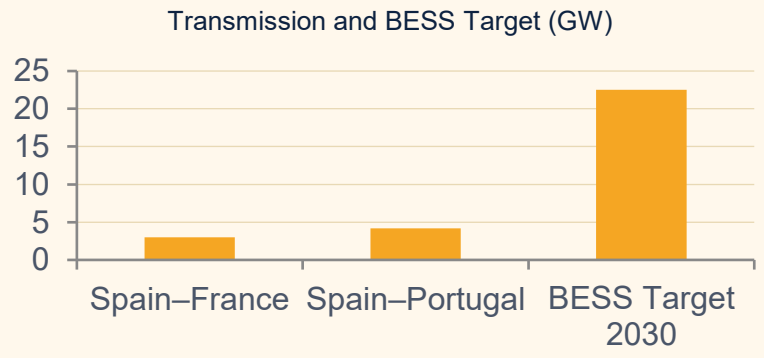
→ AB 2514: utilities mandated to procure storage

→ IRA investment tax credits (until 2025)

→ NEM 3.0: incentivizes solar+storage pairing

→ CPUC accelerated deployment post-2020 energy crisis

Spain — Transmission Regime



→ CECRE: centralized real-time curtailment control

→ Bay of Biscay interconnector (2.8 → 5 GW)

→ NECP: 22.5 GW BESS target by 2030

→ Regulatory barriers: storage taxed as consumer

CONCLUSIONS

01 Integration outcomes are shaped by deployment architecture — not just solar volume

02 California's dual-layer architecture created temporal stress → storage-centered governance

03 Spain's utility concentration created spatial stress → transmission-centered governance

04 Path dependence shapes both what stress emerges and what solutions become viable

05 There is no universal solar integration model — architecture determines the challenge

Future research: not "how much solar" — but "where, how, and into what system"

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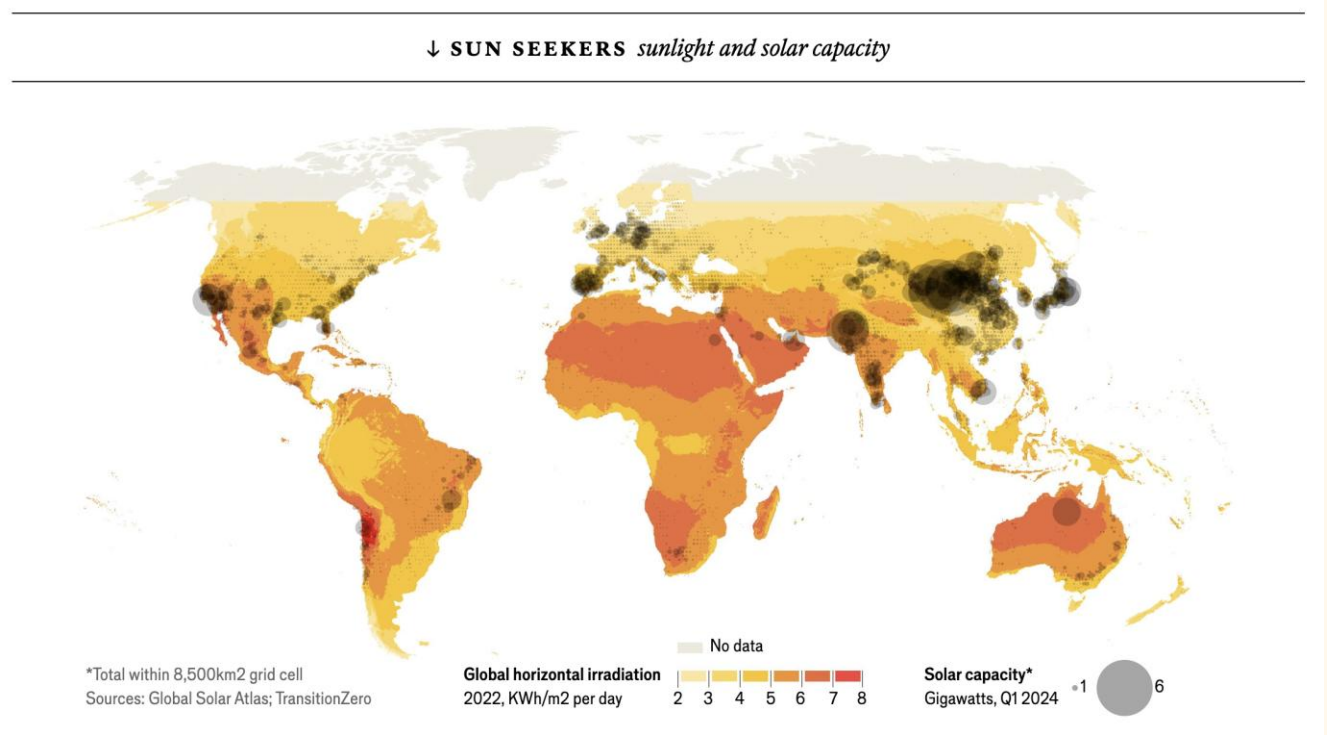
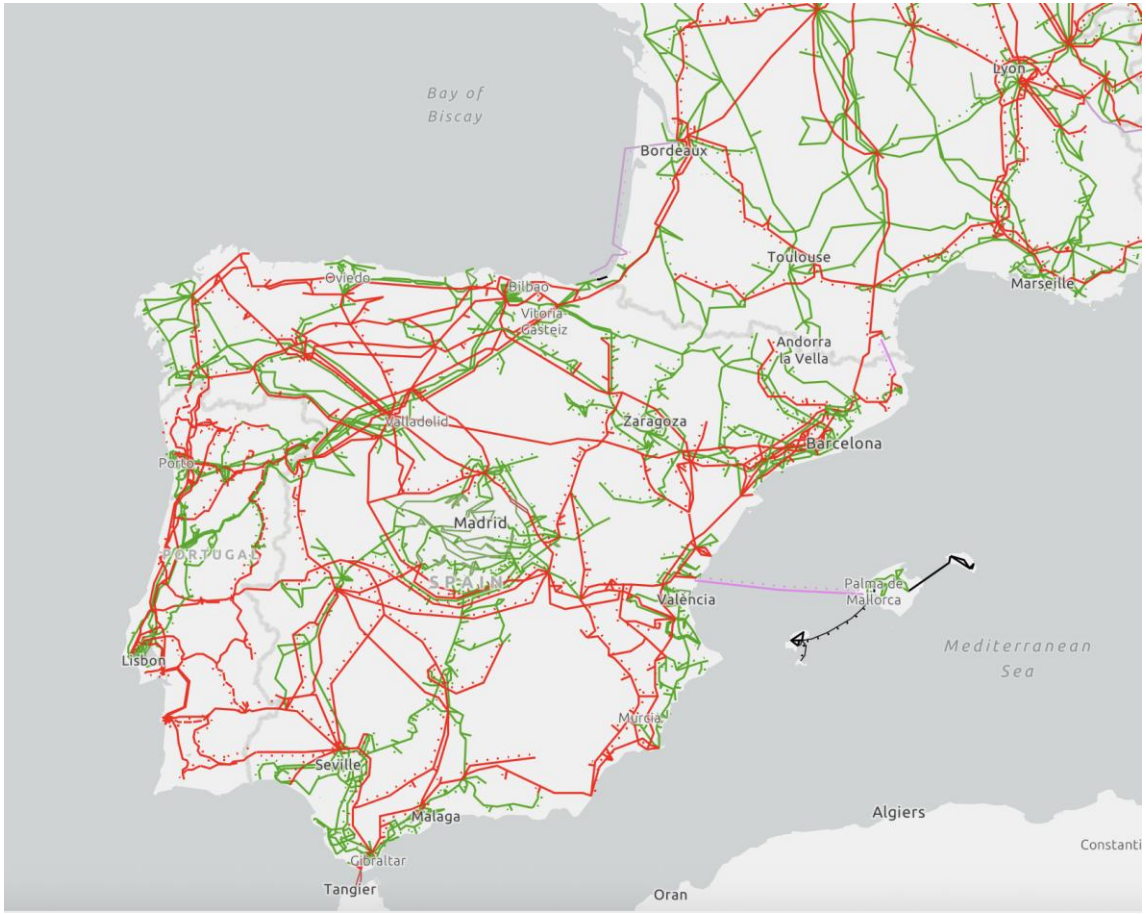
Solar Geography

Source: *The Economist*, "Solar Power Is Going to Be Huge" (June 2024)





Source: ENTSO-e (2026)

California Power Mix

Fuel Type	In-state Gen. (GWh)	Share of in-state Gen. (%)	Total Imports (GWh)	Total Energy Mix (GWh)	Total Pwr Mix (%)
Coal	250	0%	6,000	6,000	2%
NG	86,000	40%	8,000	95,000	34%
Oil	~0	0%	0	~0	0
Other	~0	0%	0	~0	0
Unspecified	-		4,000	4,000	2%
Nuclear	18,000	9%	9,000	27,000	10%
Hydro	30,000	13%	6,000	36,000	13%
Biomass	5,000	2%	650	5,000	2%
Geothermal	10,000	5%	2,000	13,000	5%
Solar	50,000	24%	9,000	59,000	21%
Wind	15,000	8%	17,000	33,000	12%
Total	87,000	40%	18,000	105,000	38%
Total	130,000	60%	44,000	173,000	62%
Total	217,000	100%	62,000	278,000	100%

Source: Author's table based on data from the California Energy Commission, *2024 Total System Electric Generation* (2025).

Spain Power Mix

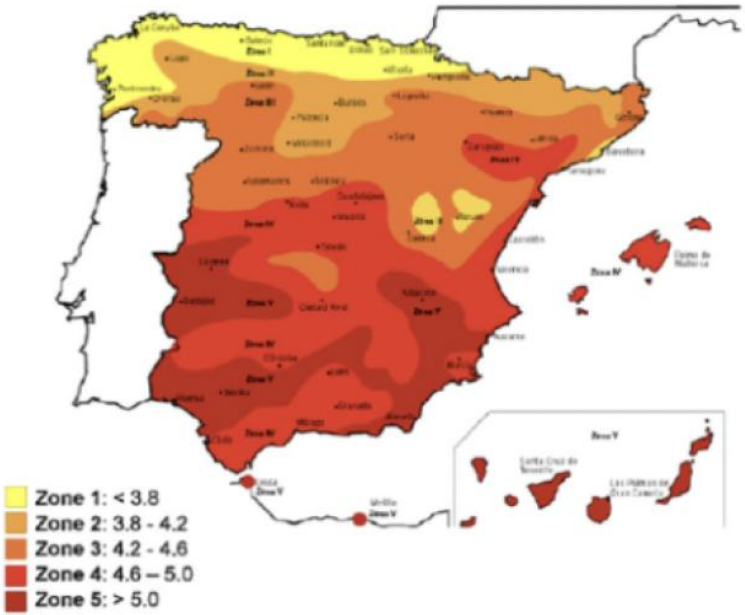
Fuel Type	Gen. (GWh)	Share of Gen. (%)
Coal	3,500	1%
NG	52,000	18%
Oil	9,000	3%
Nuclear	55,000	19%
Hydro	41,000	15%
Biomass	5,000	2%
Solar	58,000	20%
Wind	62,000	22%
Total	65,000	22%
Total	221,000	78%
Total	286,000	100%

Source: Author's table based on data from the International Energy Agency (IEA), *Spain: Electricity (2024)*

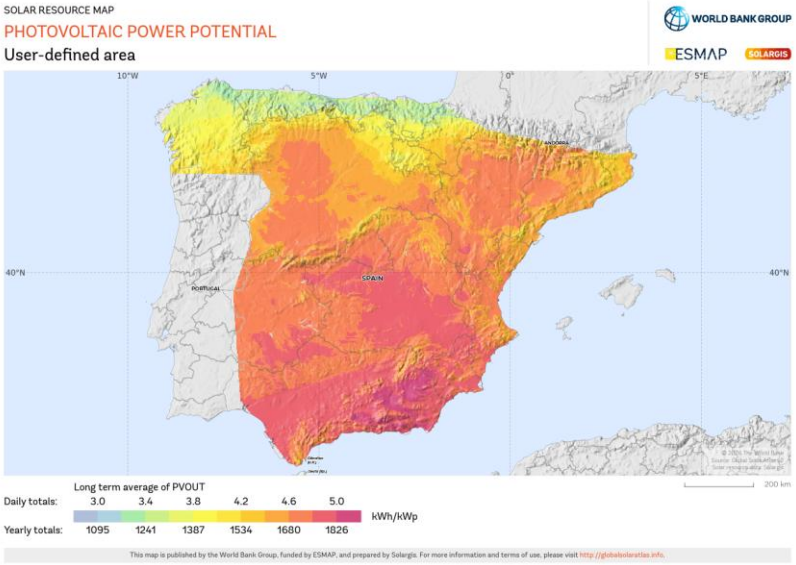
Spain NECP

Gross Installed Electrical Power (GW)				
	2020	2025	2030	Variation
Wind	26	36	62	Double
Solar PV	11	46	76	x7
Solar Thermal	2	2	5	Double
Hydro	14	14	14	Same
Coal	10	0	0	Complete Phase out
Combined Cycle	26	26	26	Same
Nuclear	7	7	3	Begin Phase Out
Storage	6	9	19	x3
Total	115	150	215	x2

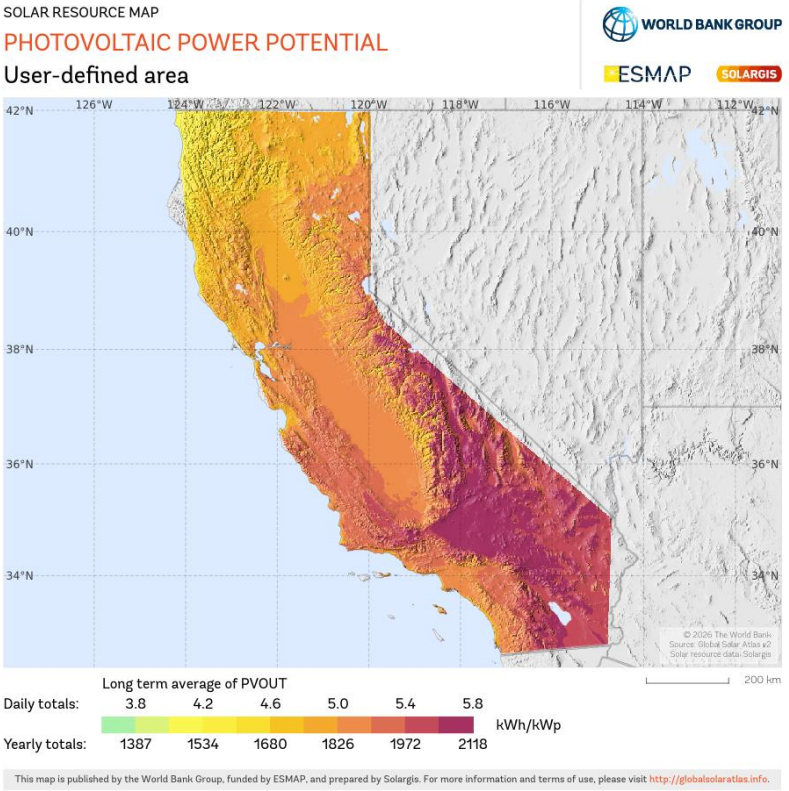
Source: Author's table based on data from European Commission (2024), *Spain – Final Updated National Energy and Climate Plan (NECP) 2021–2030*



Source: Spanish National Meteorological Institute. Note: Average daily irradiation in kWh/m² generated from annual global solar radiation isolines on horizontal surface.

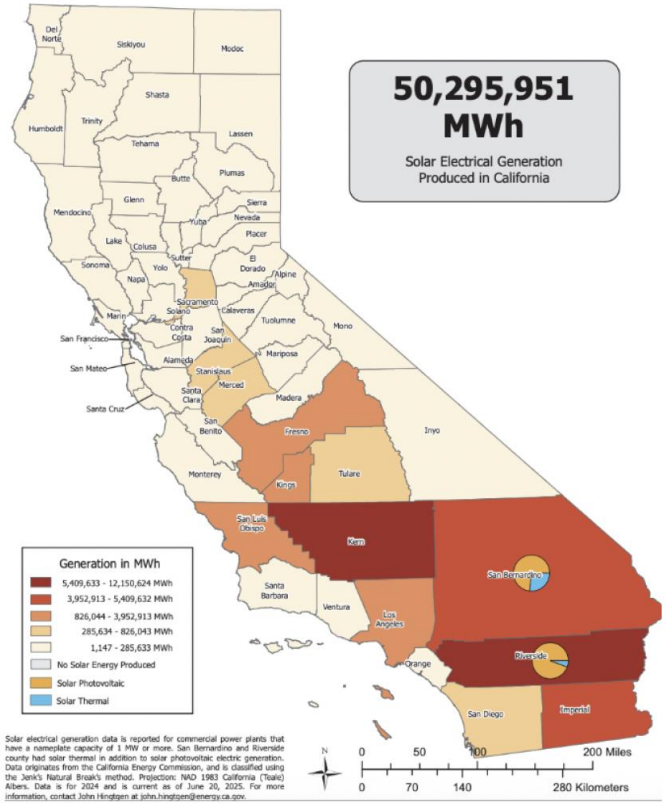


Source: Global Solar Atlas (Spain Data)



Source: Global Solar Atlas (California Data)

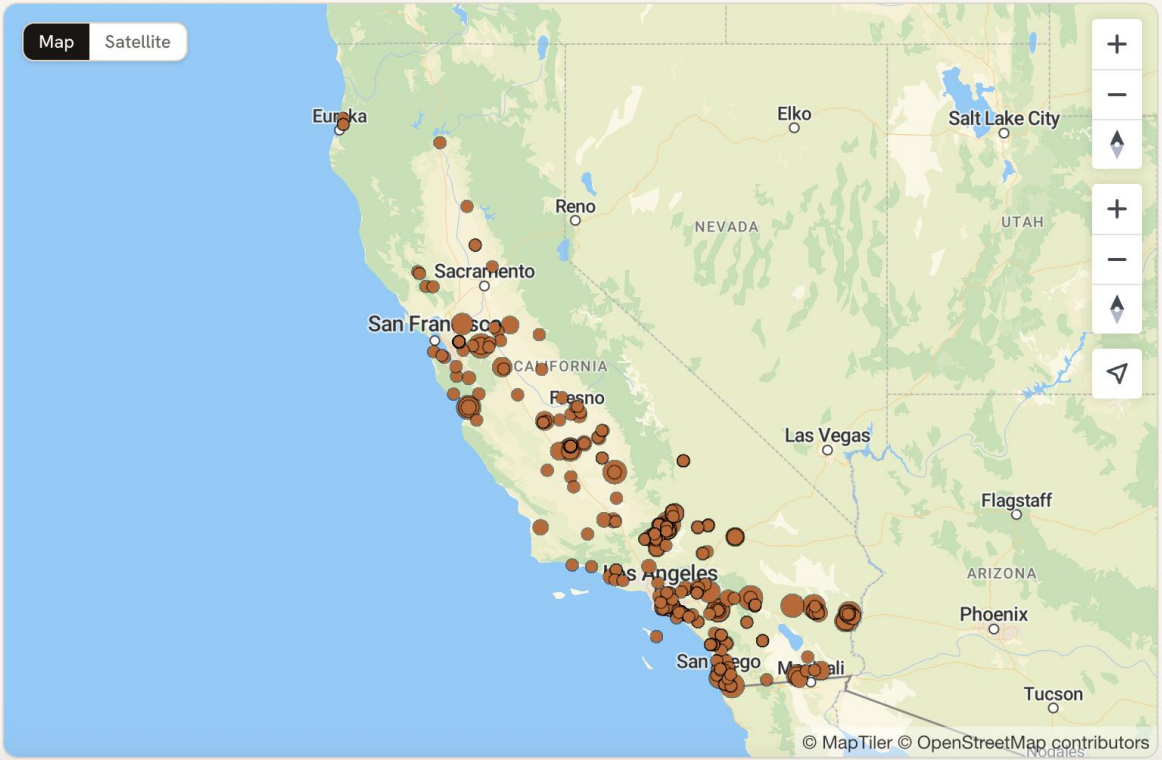
Utility Solar Generation by Type and County: 2024



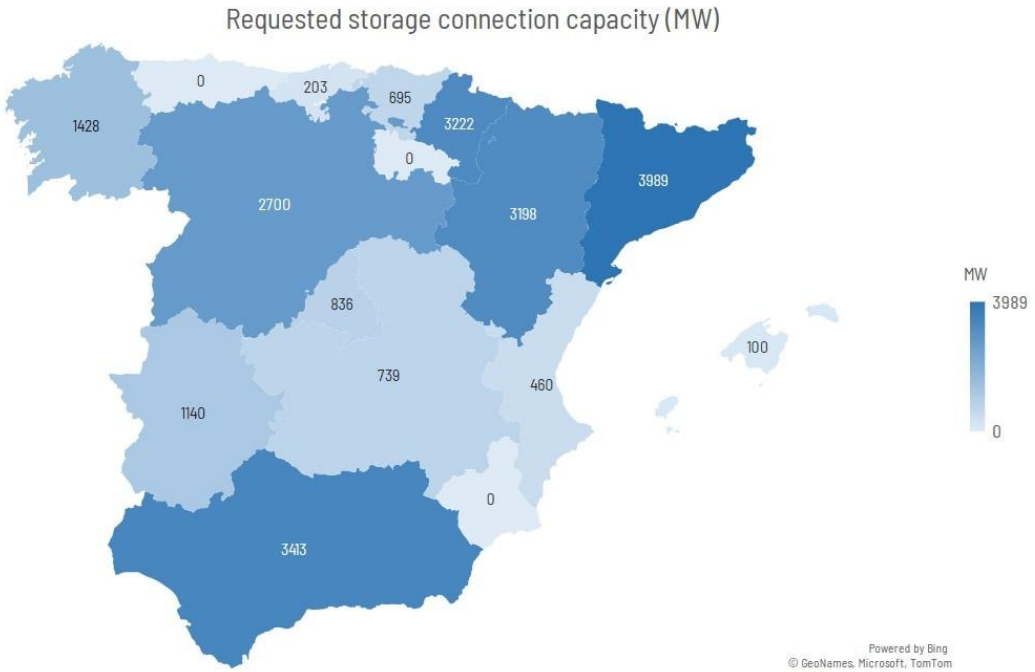
Solar electrical generation data is reported for commercial power plants that have a nameplate capacity of 1 MW or more. San Bernardino and Riverside county had solar thermal in addition to solar photovoltaic electric generation. Data originates from the California Energy Commission, and is classified using the Jenk's Natural Break's method. Projection: NAD 1983 California (Teale) Albers. Data is for 2024 and is current as of June 20, 2025. For more information, contact John Hingtgen at john.hingtgen@energy.ca.gov.

California Battery Storage Map

Map of battery storage projects in California. Marker size reflects capacity — only facilities with reported capacity data are shown.



Source: Cleanview. (n.d.). *Battery storage projects in California*



Source: Hutters & Ruiz 2025)