
ROCKY MOUNTAIN
INSTITUTE

変動型電源と需要管理、電力貯蔵の調和を設計する

Amory B. Lovins　エイモリー B. ロビンス

Adjunct Professor of Civil & Environmental Engineering, Stanford University
Cofounder and Chairman Emeritus, RMI

スタンフォード大学非常勤教授　RMI共同創立者 兼 名誉会長

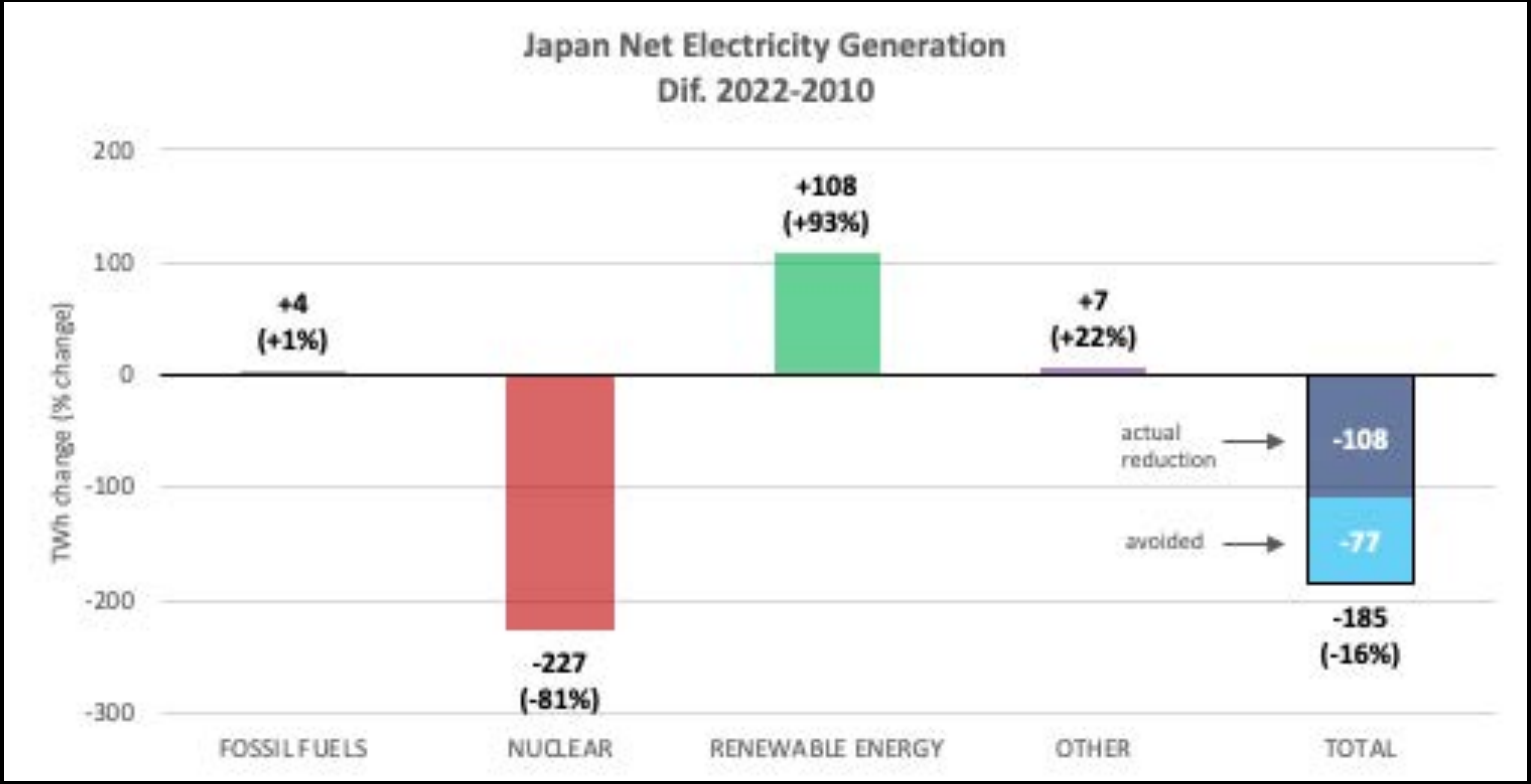
Renewable Energy Institute Special Seminar, Tōkyō, 18/19 June 2023

2023年8月31日　東京都

ENERGY. TRANSFORMED.

Japan since 3/11 has gained 29% more electricity from savings and renewables than it lost (through 2022, latest annual data available) from nuclear and fossil generation

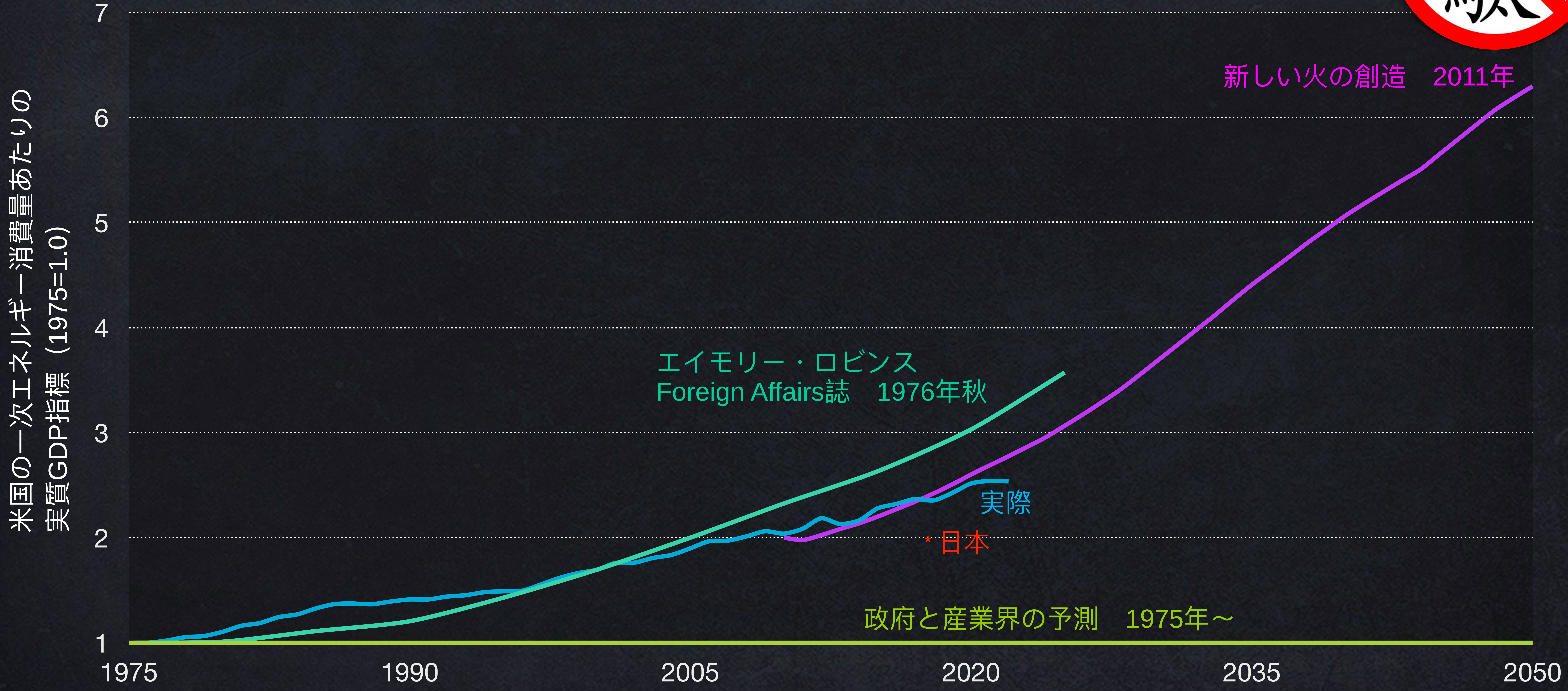
Yet some Japanese utilities still do the opposite of economic dispatch—curtailing renewables while dispatching their own nuclear capacity at higher cost—and they are allowed to curtail renewables at any time, for any reason or none, making renewables hard to finance



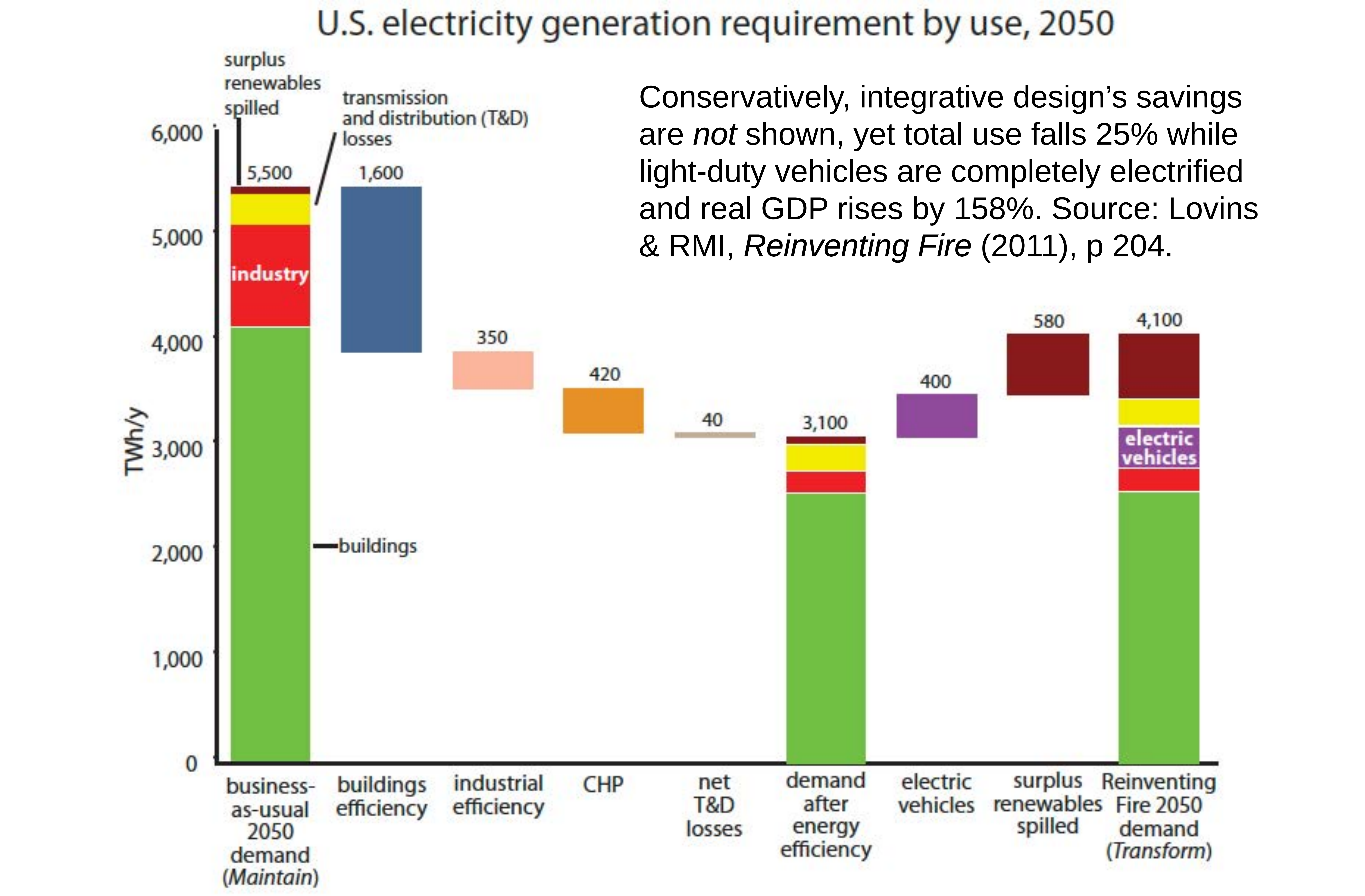
Source: Government of Japan and IEA data analyzed by R. Zissler, Renewable Energy Institute, Tōkyō, personal communication,13 June 2023.
Japanese renewable energy data are still maturing, and report biomass co-fired with coal (an unknown amount) as coal, not as renewable fuel. “Other” is obscure.
See also *World Nuclear Industry Status Report 2019*, pp. 228–256, Sep. 2019, worldnuclearreport.org, on nuclear operating cost and climate opportunity cost.

常識とは異なる事態が起こっている

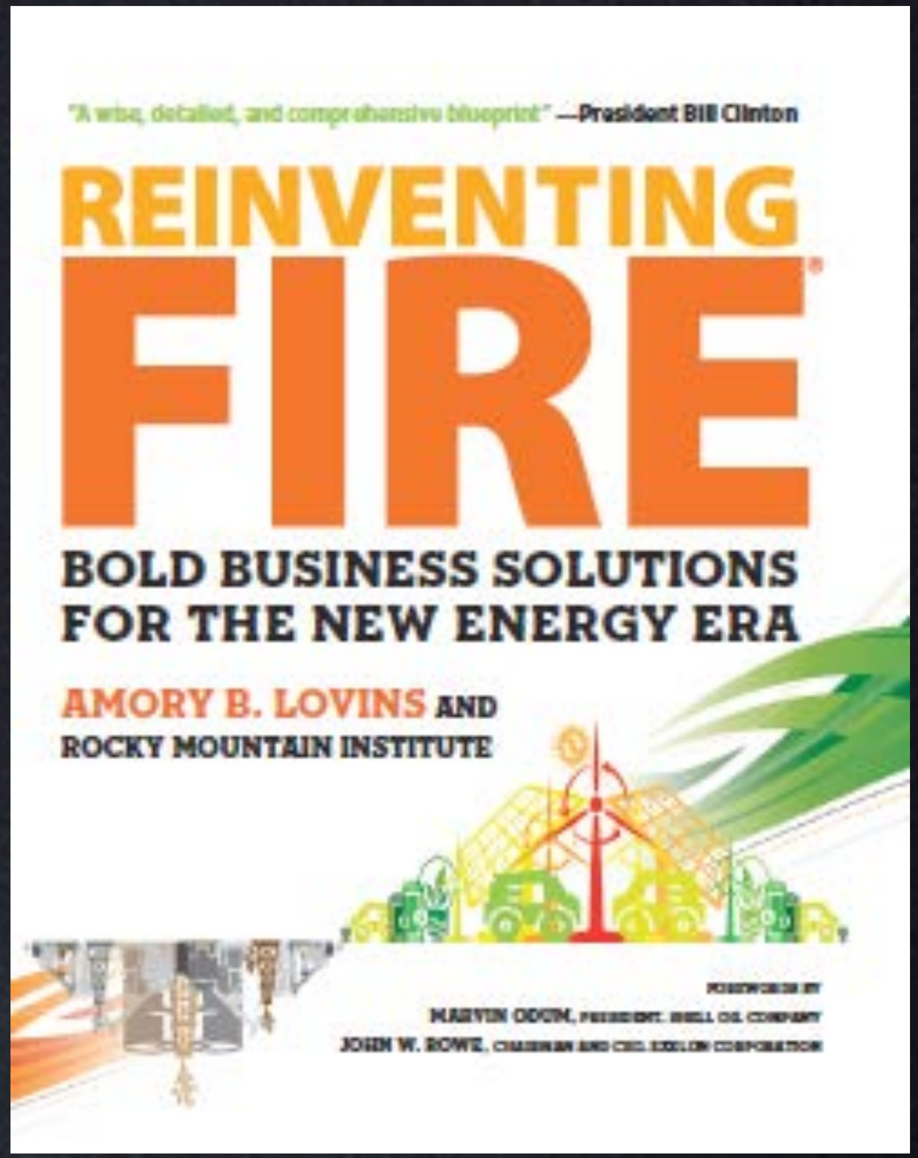
（米国の一次エネルギー生産性　1975-2021年）



U.S. Electric Productivity Can Quadruple in 2010–50



Conservatively, integrative design's savings are *not* shown, yet total use falls 25% while light-duty vehicles are completely electrified and real GDP rises by 158%. Source: Lovins & RMI, *Reinventing Fire* (2011), p 204.



Benchmarking a big new office

(~10,000+ m^2, semitropical climate, no PVs, USA; ~2012 Japan; 2015 1,451-m^2 RMI Innovation Center; ~2012 India

	Normal	Better	Best
delivered MJ/m^2-y	1,100/1,737	450–680/566	100–230/126/130/158–194
del. el. kWh/m^2-y (EPI)	270/203/~200–400	160/195	20–40/35/36/<75 (25 cooling)
lighting W/m^2 as-used	16–24/12	10	1–3/2/1/<1.6
plug W/m^2 as-used	50–90/12	10–20	2
glazing W/m^2K center-of-glass	2.9	1.4	0.3–0.5/0.43/1.1
glazing T_{vis}/SC	1.0	1.2	>2.0
perimeter heating	extensive	medium	none/none
roof α, ε	0.8, 0.2	0.4, 0.4	0.08, 0.97/0.1,0.9
m^2/kW_{th} cooling	7–9	13–16	26–32+/∞/20–26 (750–1000sf/TR)
cooling syst. COP	1.85	2.3/2.0–2.7	6.8–25+/–/>6.4 (<0.55 kW/TR)
relative cap. cost	1.0	1.03	0.95–0.97/1.11/0.85–0.90
relative space eff.	1.0	1.01	1.05–1.06/1.01

Japan standard: median of 40 buildings, Energy Conservation Center of Japan; better: average of six SHASEJ Junen Award-winning buildings; best: the most efficient of those six buildings (Nissei Yokkaichi Building, 293 MJ), now Takanaka Higashi Kantō 2015 retrofit, ~126 MJ); data courtesy of Urabe-san, CRIEPI, via Asano-sensei, Todai; 2 W/m^2 lighting is Shimizu Building 2012. India: empirical Infosys new-office performance data from Rohan Parikh; standard estimate from Indian designers—100 of the 200–400 (nom ~250) is cooling.

米国のオフィスビル：5年間で効率性は5–10倍に

（エネルギー源単位　kWh/㎡・年; 米国のオフィスの中央値　～293; 2015 日本 ~483）

~277➡173 (–38%, later 43%)
2010 改修

284➡85 (–70%)
2013 改修

...➡108 (–63%)
2010–11 新築

386➡107 (–72%)
2015 日本での改修

...36 (–88%)
2015 新築

...21 (–93%)
…そしてドイツの
2013年の新築
(オフィスと住居)

全ての技術は2005年よりずっと前から存在していた！

ピア・レビューを受けた統合的な設計に関する技術論文

ENVIRONMENTAL RESEARCH
LETTERS

EDITORIAL • OPEN ACCESS

How big is the energy efficiency resource?

Amory B Lovins[1]

Published 18 September 2018 •

Environmental Research Letters, Volume 13, Number 9

Citation Amory B Lovins 2018 *Environ. Res. Lett.* **13** 090401

https://doi.org/10.1088/1748-9326/aad965

What can integrative design do? (η ≡ end-use efficiency)

buildings: ~4–≥10η
automobiles: ~4–8η
trucks: ~3–4η
airplanes: ~3–8η
factories: ~2–3η old, ~2–10η new
use of steel, cement,….: >2η

so…world economy: ~5η, by ~2060
plus better conversion efficiency
from electrification and renewables

See "How big is the energy efficiency resource?", *Environ. Res. Ltrs.* **13** (2018) 090401, https://doi.org/10.1088/1748-9326/aad965

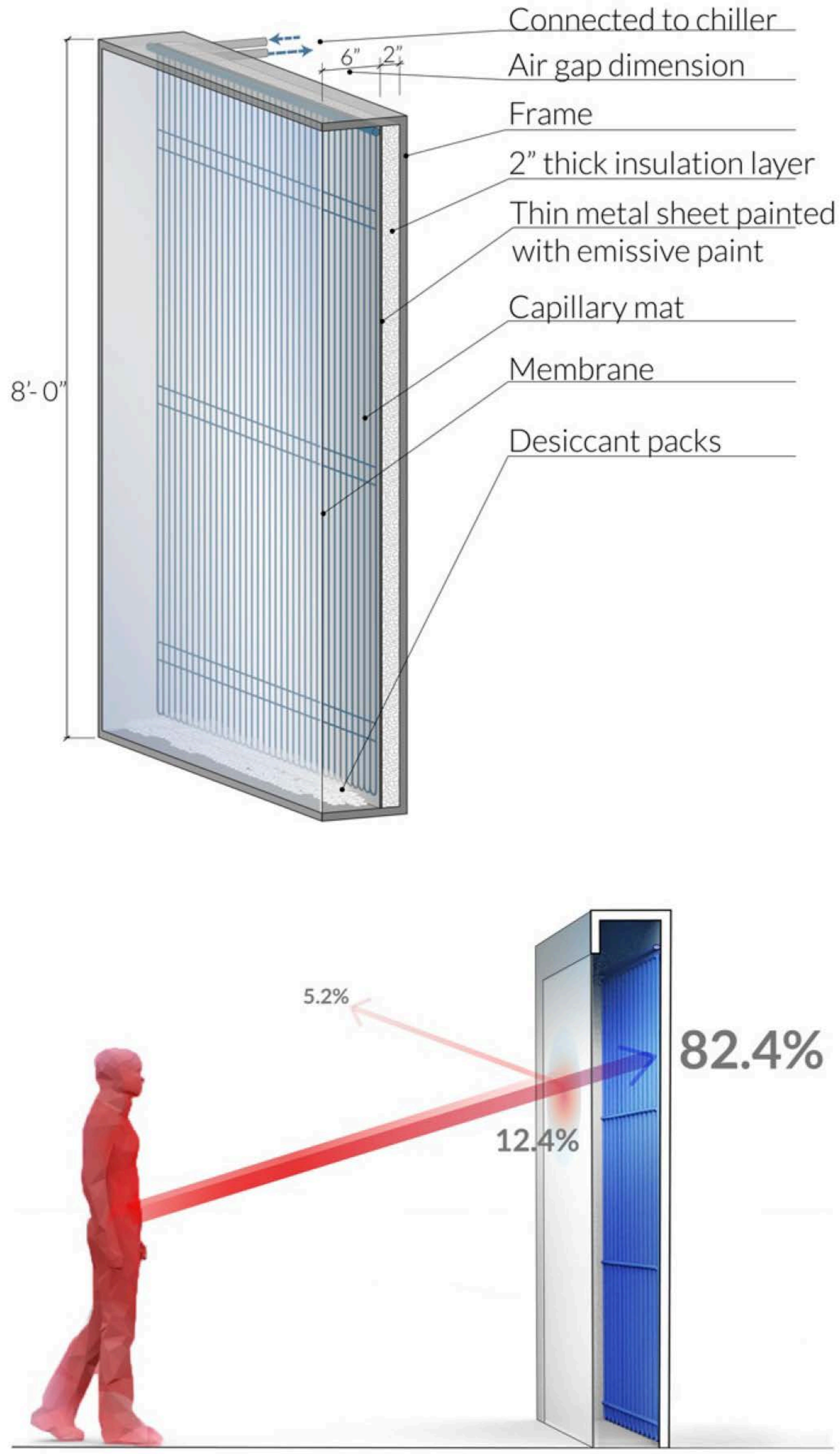
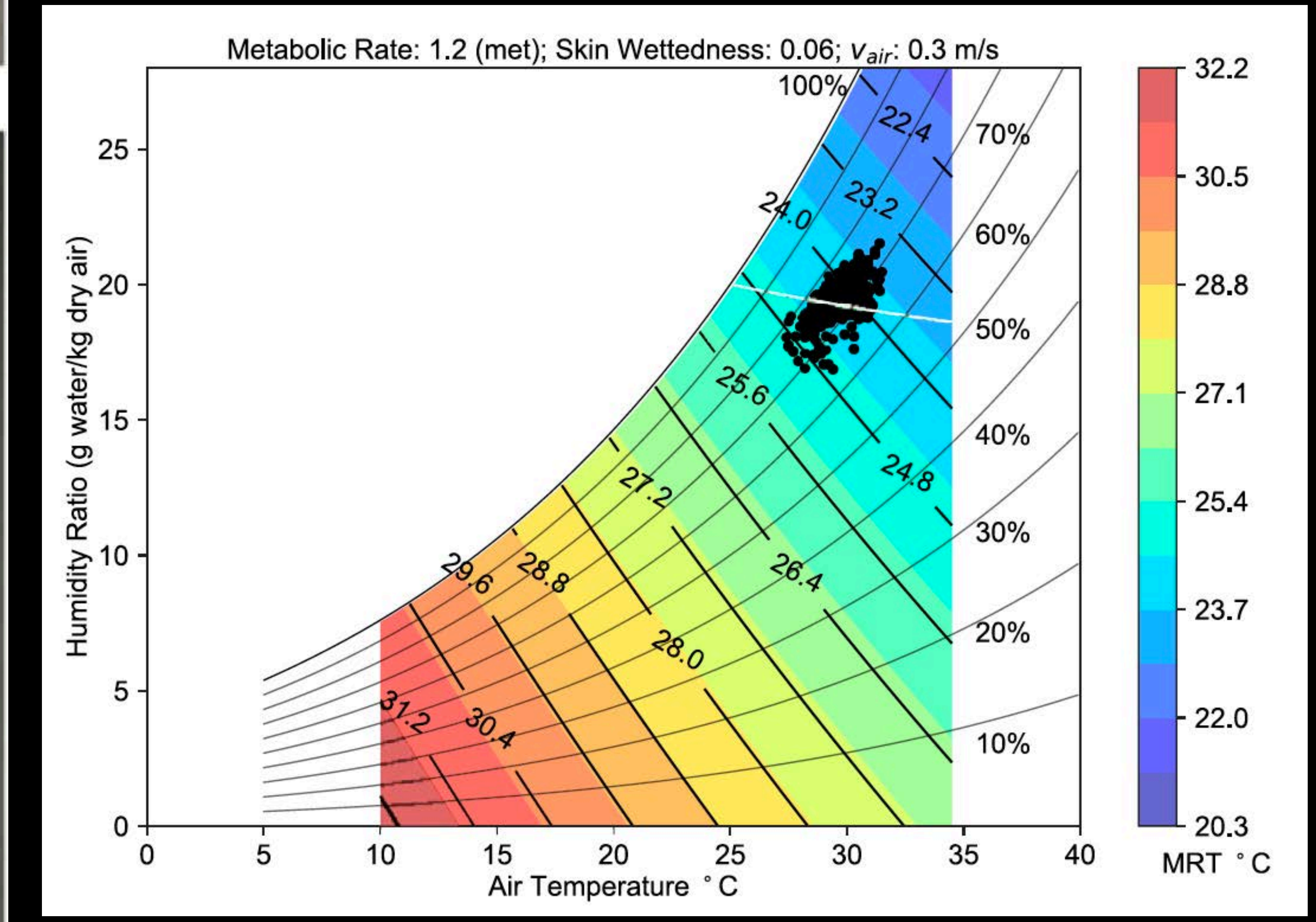


Fig. 1. Schematic of a Cold Tube radiant cooling panel (*Upper*) and radiant heat transfer through the IR-transparent membrane (*Lower*).

Fig. 2. The completed Cold Tube.

2019年の放射冷却ブレークスルー：

シンガポールの夏の屋外の快適さを実現
日よけはあるが、
チラー、ファン、結露はない！

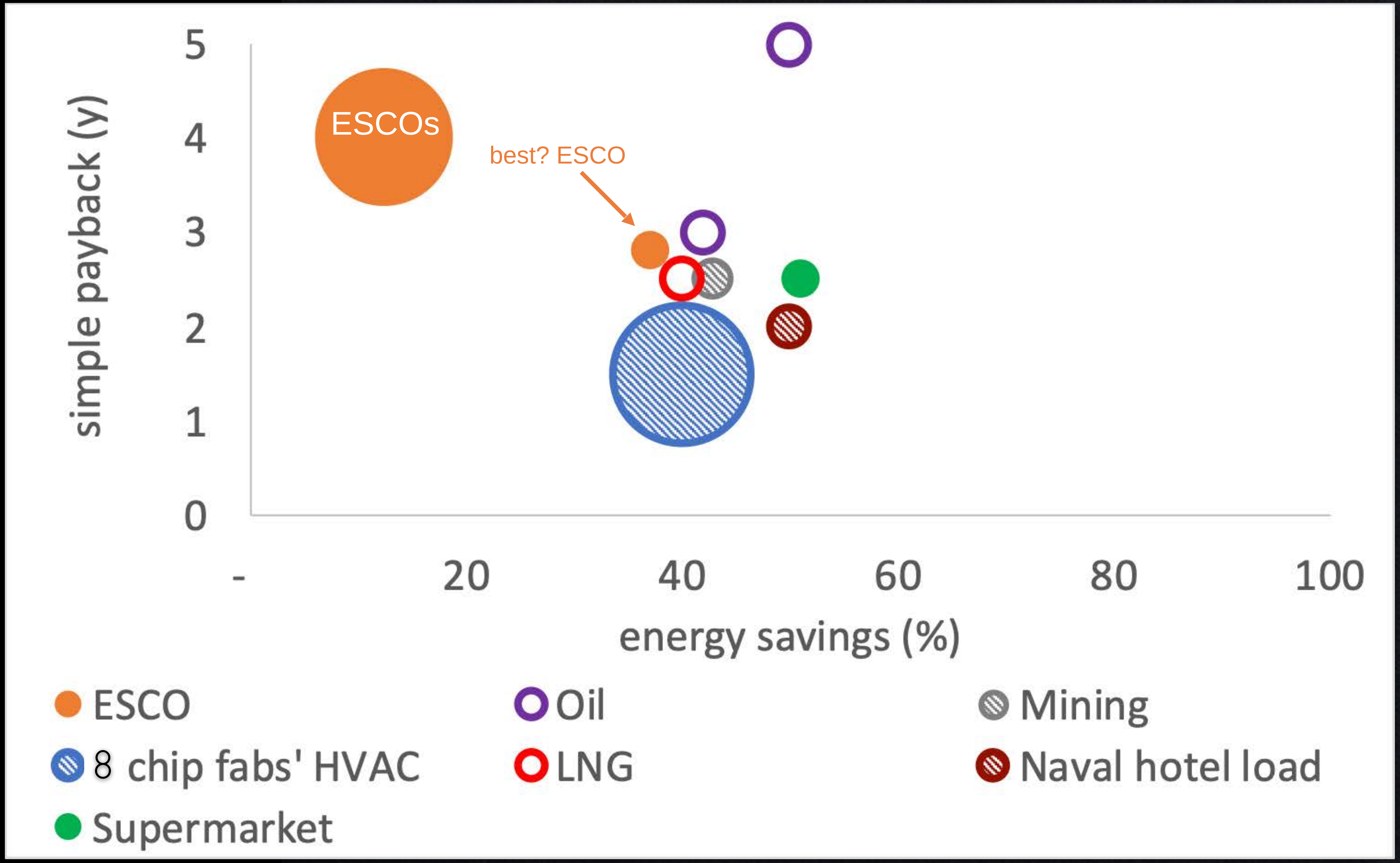


タイテルバルム他,米国科学アカデミー紀要,2019

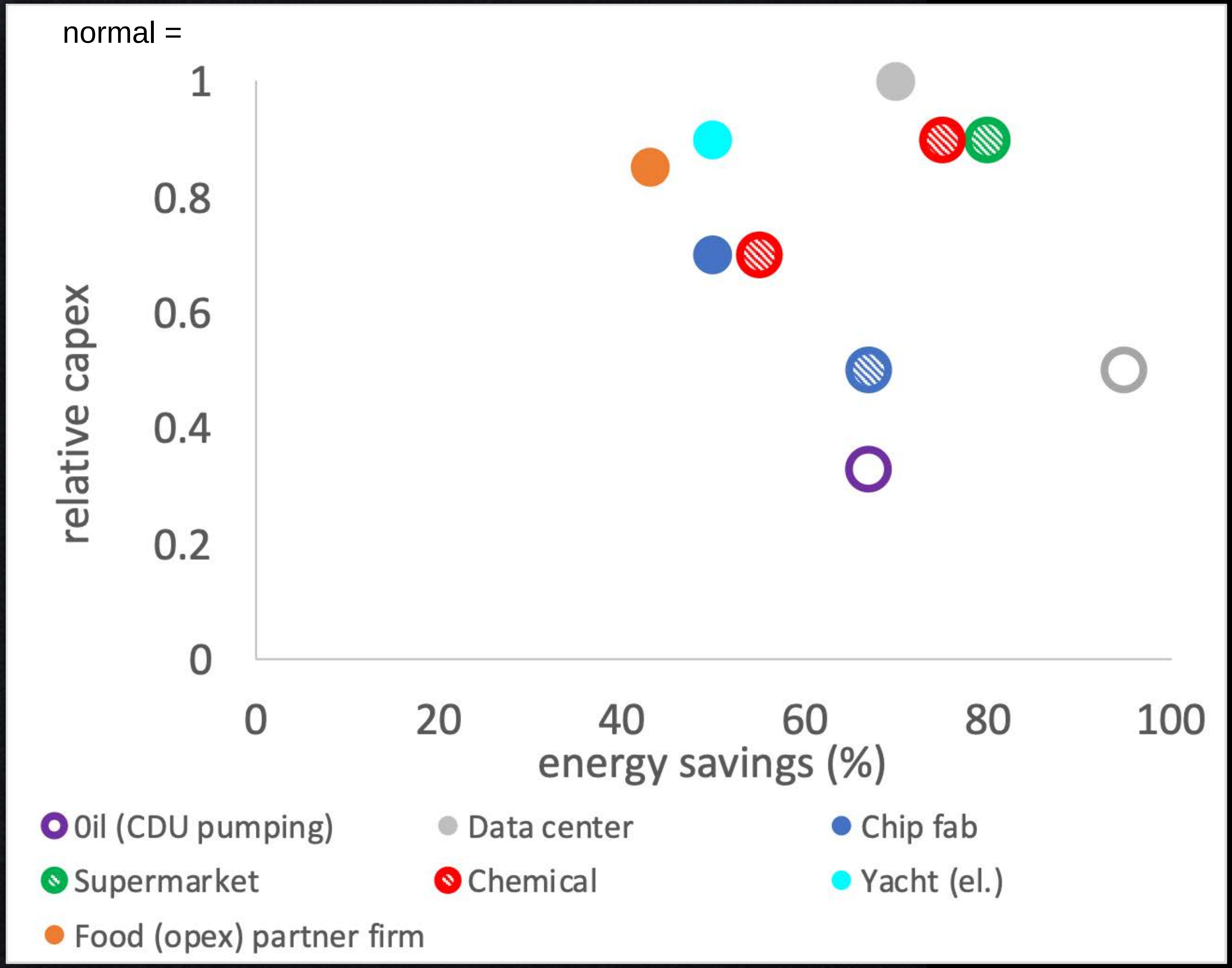
E. Teitelbaum *et al.*, *Proc. Natl. Acad. Scis. [USA]* **117**(35):21162–21169, 1 Sep 2020, www.pnas.org/cgi/doi/10.1073/pnas.2001678117

RMI最新の600億ドルを超える価値のある、様々な産業プロジェクトにおける統合設計—改修と新築

（実線＝構築済み、影付き＝不完全なデータ、白抜き円＝未構築）



改修



新築

パイプとダクトにおける摩擦を約80〜90%節約するように設計
これは世界の石炭火力発電所の約半分に相当

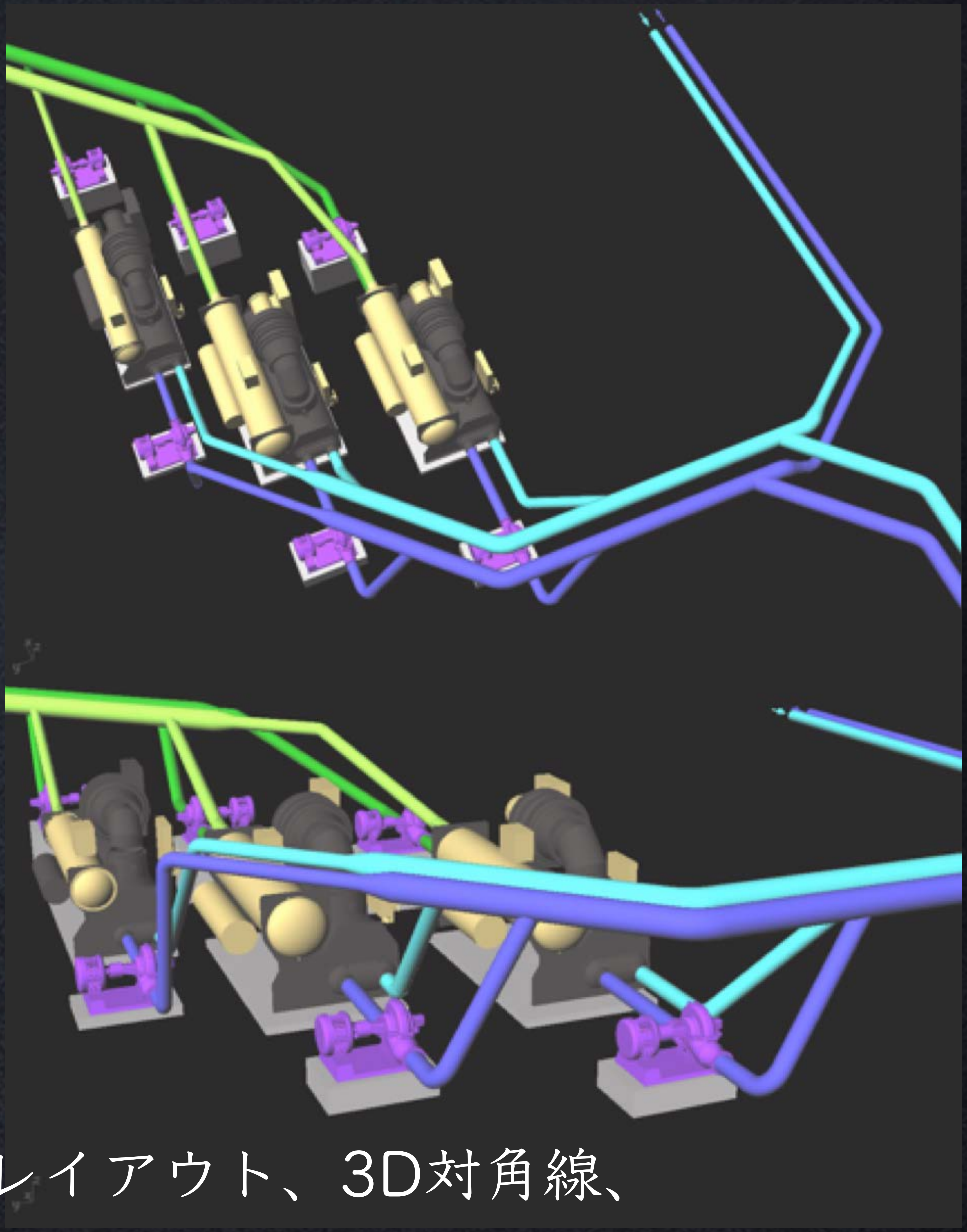
薄く、長く、曲がっている

太く、短く、まっすぐ

典型的な投資回収 改修で1年以内　新築で0年
しかし、教科書、公式調査、または業界予測にはまだ含まれていない

パイプとダクトにおける摩擦を最大80～90+%節約するように設計
―太く、短く、まっすぐ

大きいパイプ, 小さいポンプ



非直交レイアウト、3D対角線、
少しの緩やかな曲がり

上質で質素な構造設計により

工業プロセスの熱を間接的に脱炭素化

張力構造—材料が約80〜90%少ない

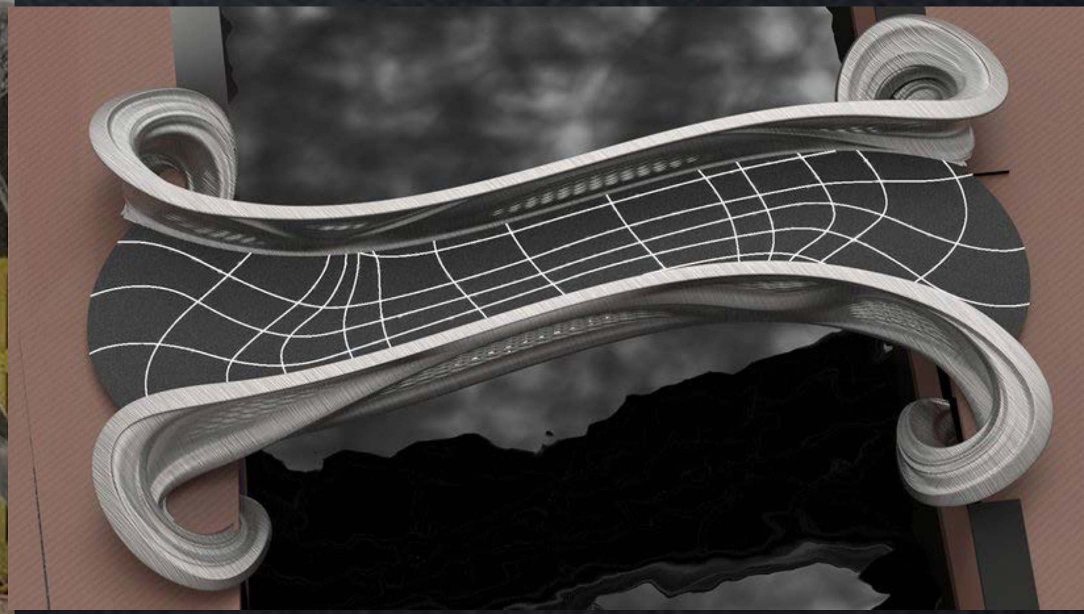
織物構造—材料が50%以上少ない

Mark West, ***The Fabric Formwork Book***, Routledge, 2016; CAST (Centre for Architectural Structures and Technology), University of Manitoba, Winnipeg. See Hawkins ***et al***'s 172-reference 2016 review, doi:10.1002/suco.201600117

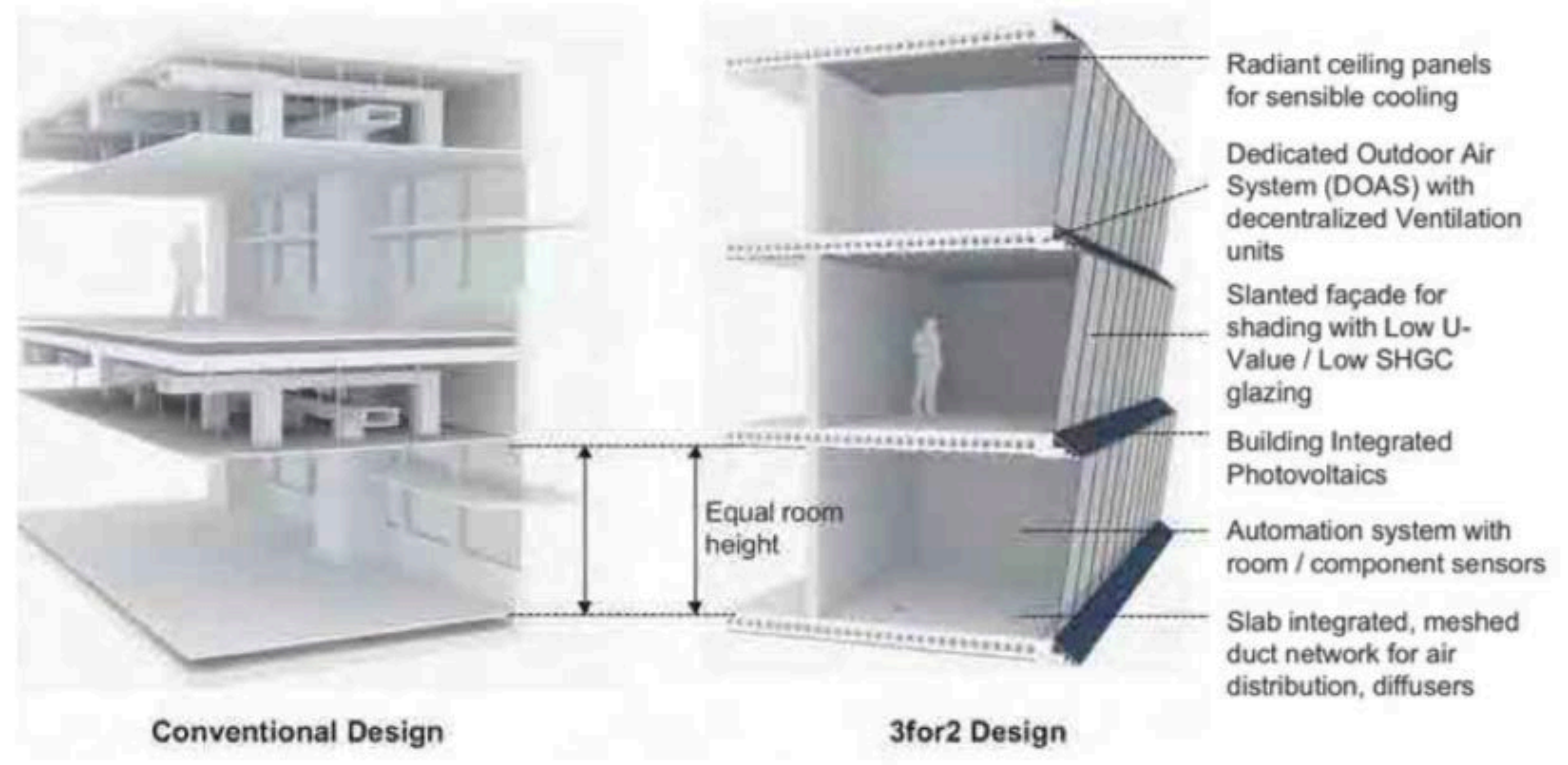
Schlaich Bergermann—see the remarkable book ***Leicht Weit***

https://www.shapeways.com/blog/archives/35854-3d-printed-bridges-now.html (Joris Laarman Lab, MX3D)

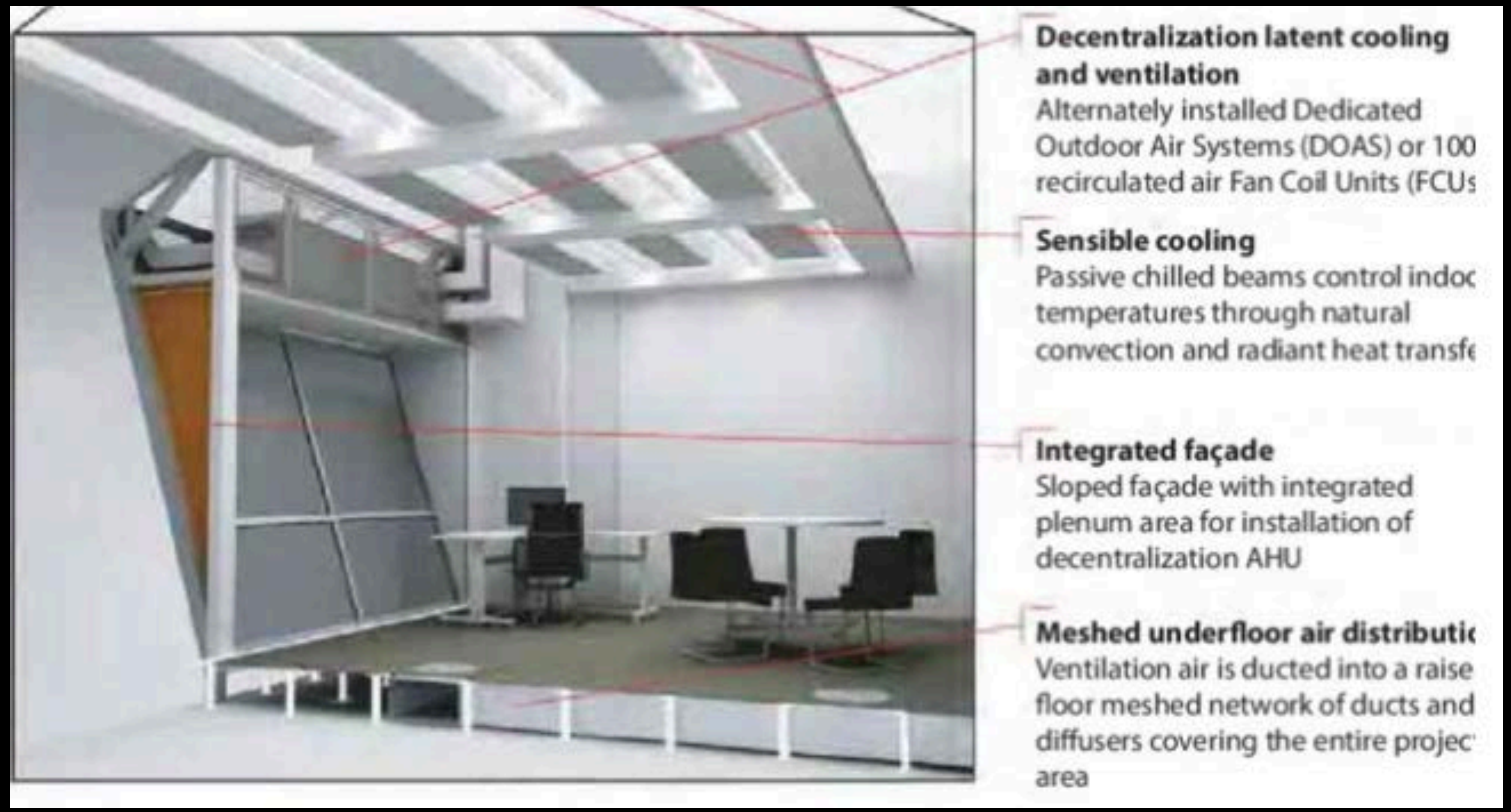
アムステルダムの運河にある3Dプリントされた芸術的な12.5mのステンレス鋼橋



Three stories in the height of two: the magic of the negaplenum

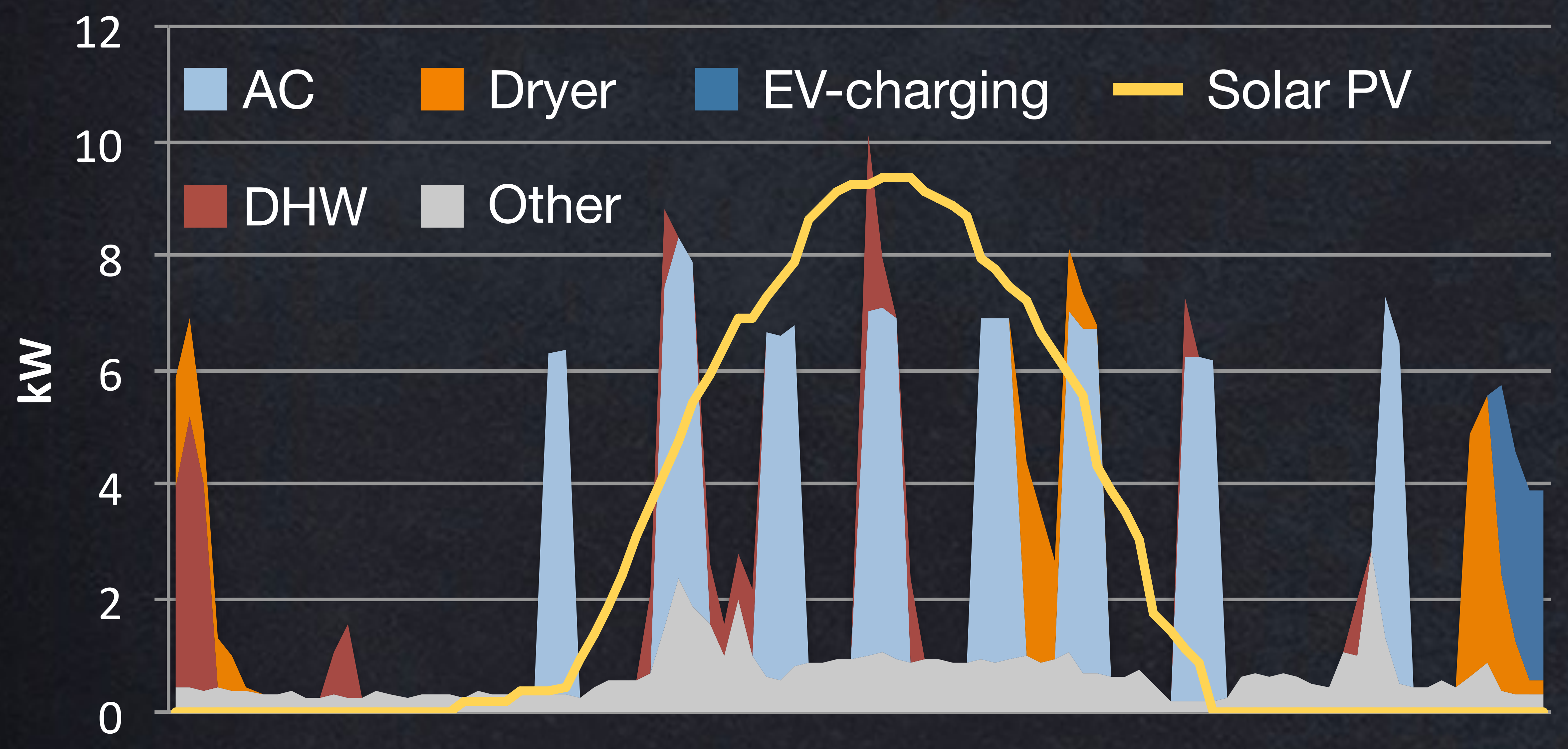


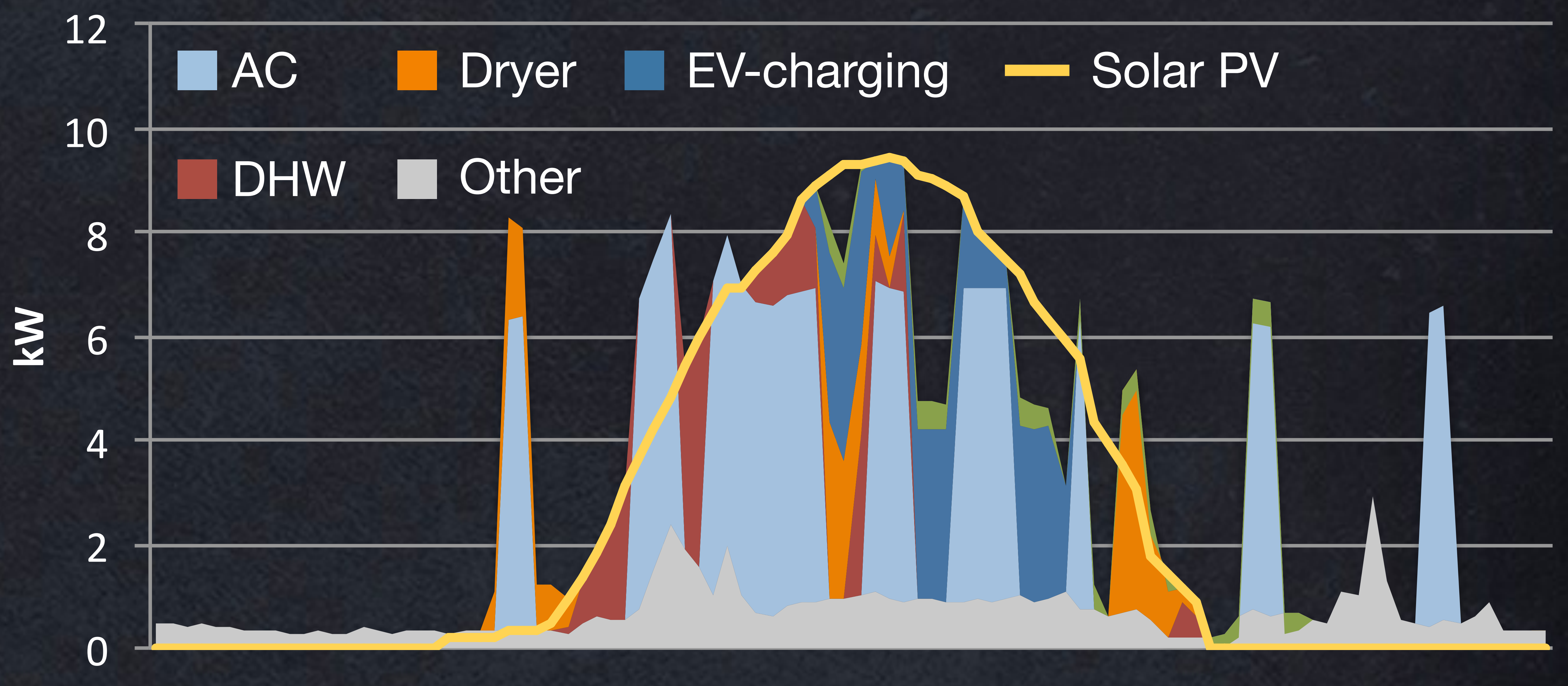
UCWSEA pilot installation, Singapore, 2015



A. Schlueter *et al.*, "3for2: Realizing Spatial, Material, and Energy Savings through Integrated Design," *CTBUH J.* **2016**(2):40–45, Council on Tall Buildings and Urban Habitat

Load control + PVs = grid optional





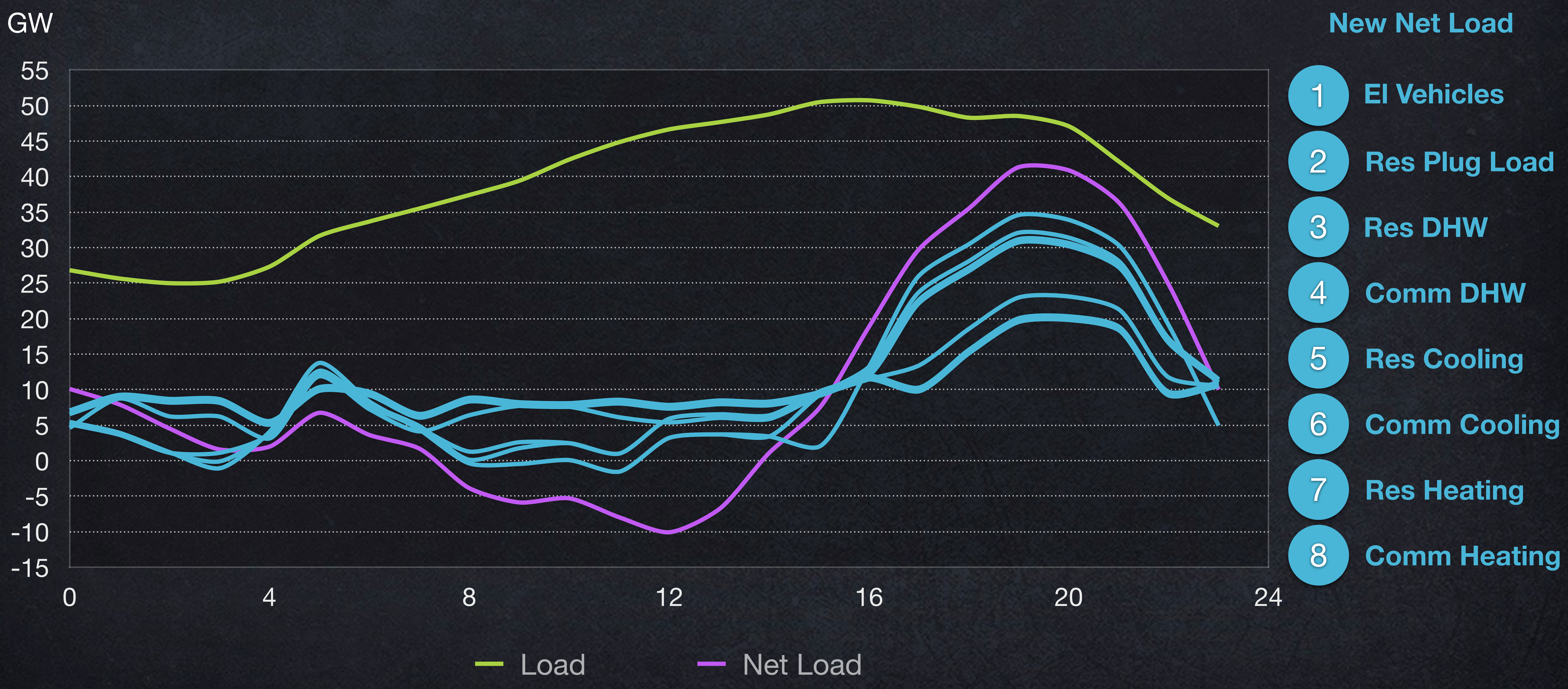
Uncontrolled: ~50% of solar PV production is sent to the grid, but if the utility doesn't pay for that energy, how could customers respond?

Controlled: flexible load enables customers to consume >80% of solar PV production onsite. The utility loses nearly all its windfall and most of its ordinary revenue.

Source: RMI analysis "The Economics of Load Flexibility," 2015

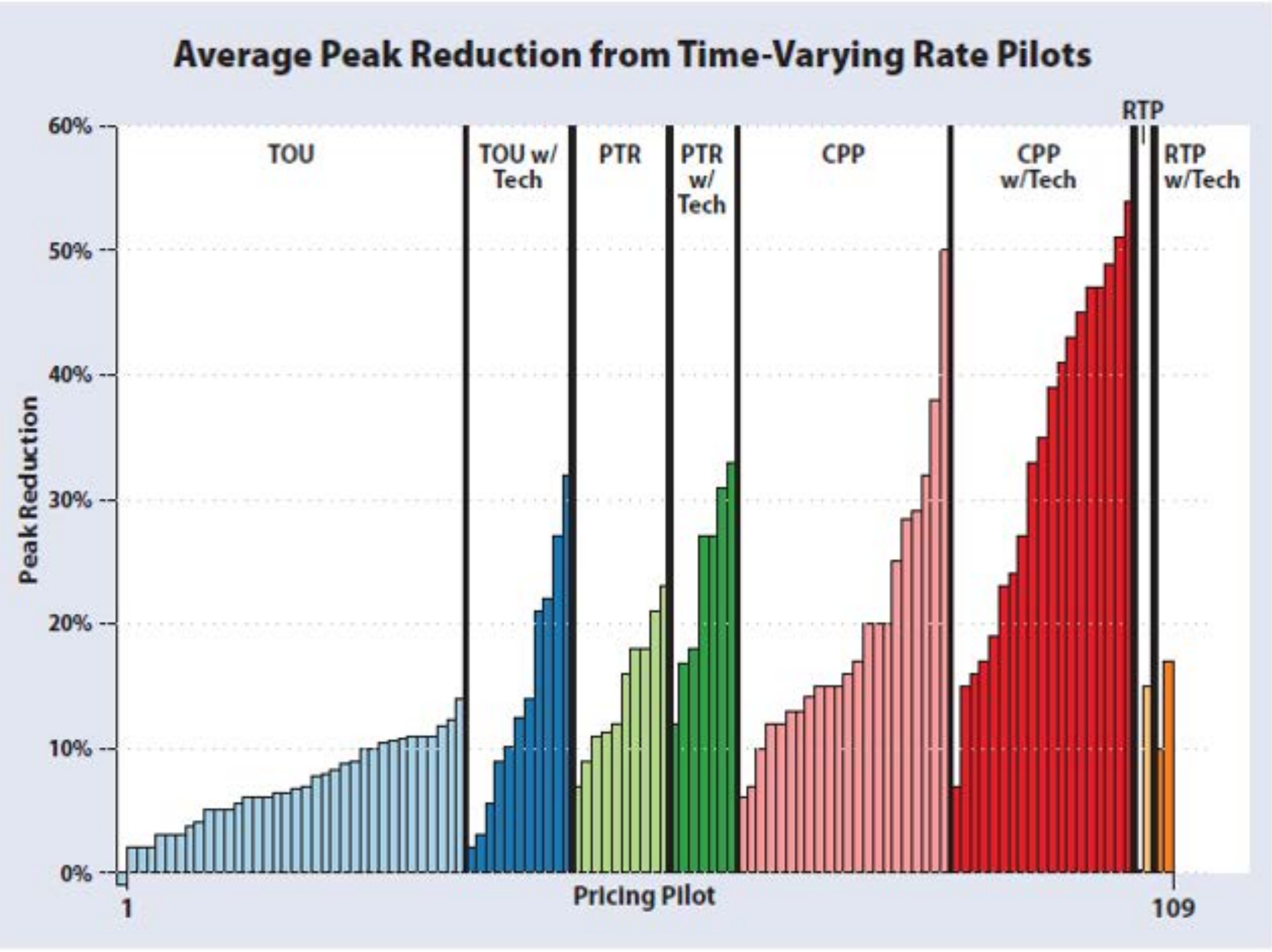
Flexible loads can dramatically smooth Texas loads

These eight levers combine to make net load far smoother and lower (ERCOT, summer 2050)



Source: analysis underlying Goldenberg, Dyson, & Masters, "Demand Flexibility," RMI, Feb 2018, https://www.rmi.org/wp-content/uploads/2018/02/Insight_Brief_Demand_Flexibility_2018.pdf

30–50+% peak-load reduction from 24 residential pilot projects in the US, EU, and Australia, 1997–2011



TOU = time-of-use tariffs
PTR = peak-time rebates
CPP = critical peak pricing
RTP = real-time pricing
Tech = smart thermostats, air-conditioner switches, etc.

These alter *when* people use electricity. H*ow much* they use depends on *average* price (https://eml.berkeley.edu//~saez/course/koichiroAER14.pdf) and on many other factors, including (importantly) barrier-busting so customers can respond to price.

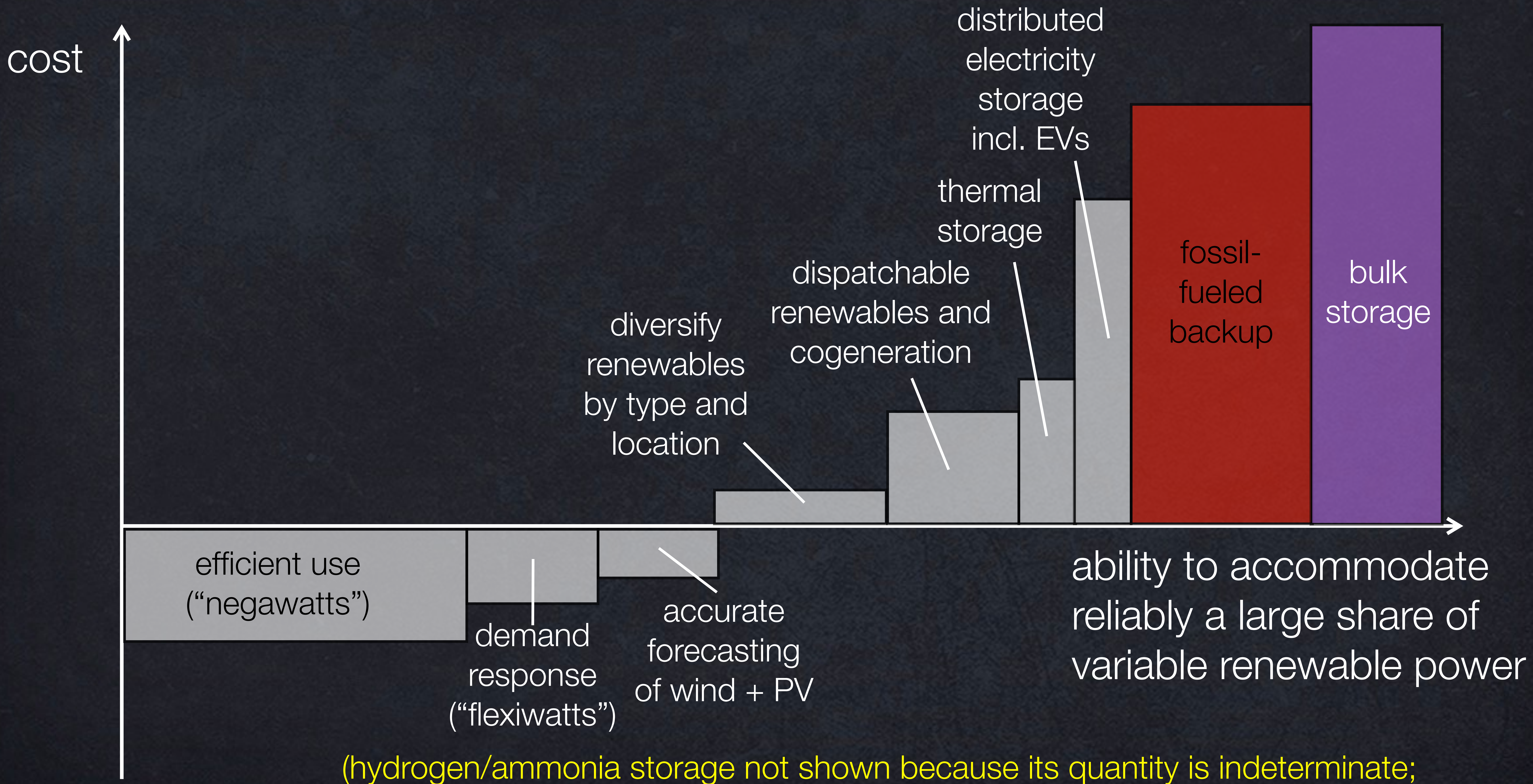
"Time-Varying and Dynamic Rate Design," 2012, Regulatory Assistance Project and The Brattle Group, https://www.raponline.org/knowledge-center/time-varying-and-dynamic-rate-design/

Renewables, efficiency, demand flexibility, and storage can provide all grid services traditionally provided by gas-fired power plants (1)

Source: RMI, *The Economics of Clean Energy Portfolios*, May 2018; these graphs show a West Coast US example

Grid flexibility resources

(all values shown are conceptual and illustrative)



(hydrogen/ammonia storage not shown because its quantity is indeterminate;
“bulk storage” combines batteries with pumped hydro, compressed air, gravity,…)

Source: The Mobility House

Stationary storage Johan Cruijff Arena

Flexibility Monetization Example

- **LOCATION:** Amsterdam, Netherlands
- **STORAGE PARAMETERS:** 3 MW / 2.8 MWh
- **BATTERIES**: 148 Nissan Leaf batteries (42% 2^{nd}-life)
- **EMISSION REDUCTION**: -116 tCO_2/10a
- **APPLICATION**: Multi-use stationary storage
- **PERFORMANCE OF TMH:** Development | operation | commercialization

Backup Power

Peak Shaving

Grid Services

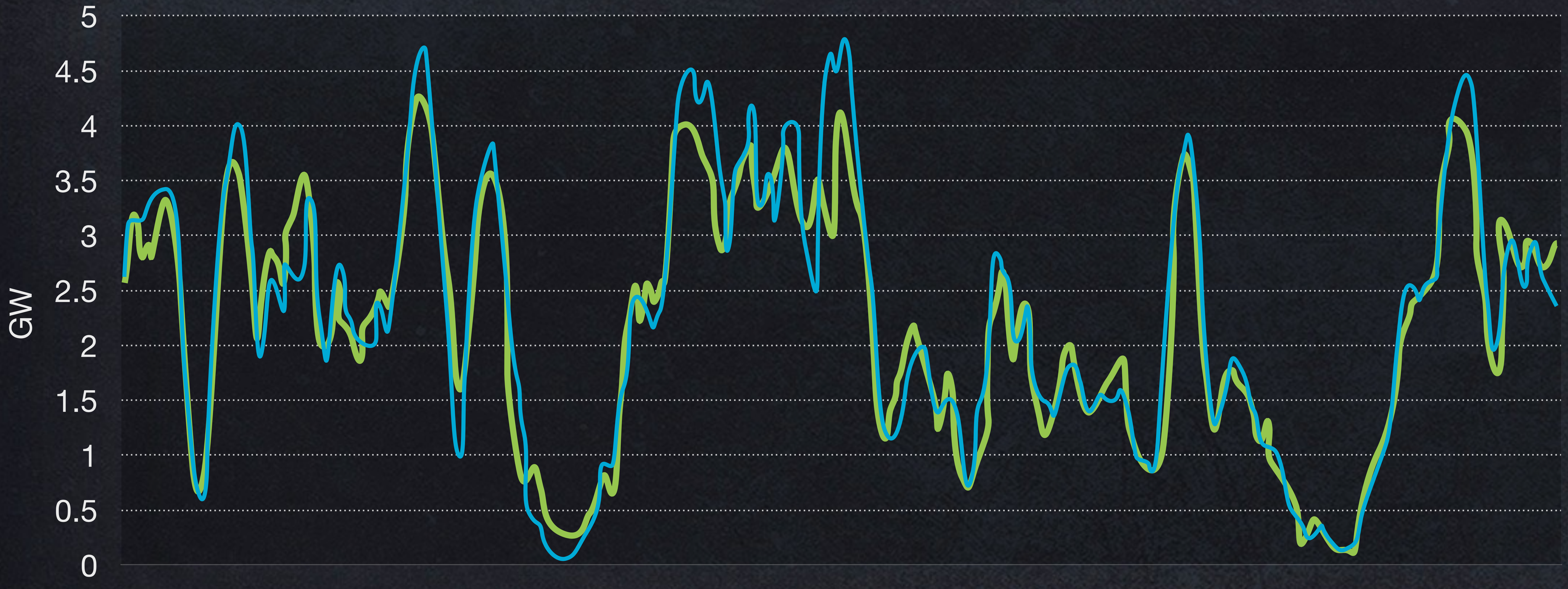
Optimized PV Integration

Vehicle-to-Grid

Smart Charging

Variable Renewables Can Be Forecasted At Least as Accurately as Electricity Demand

French windpower output, December 2011: forecasted one day ahead vs. actual

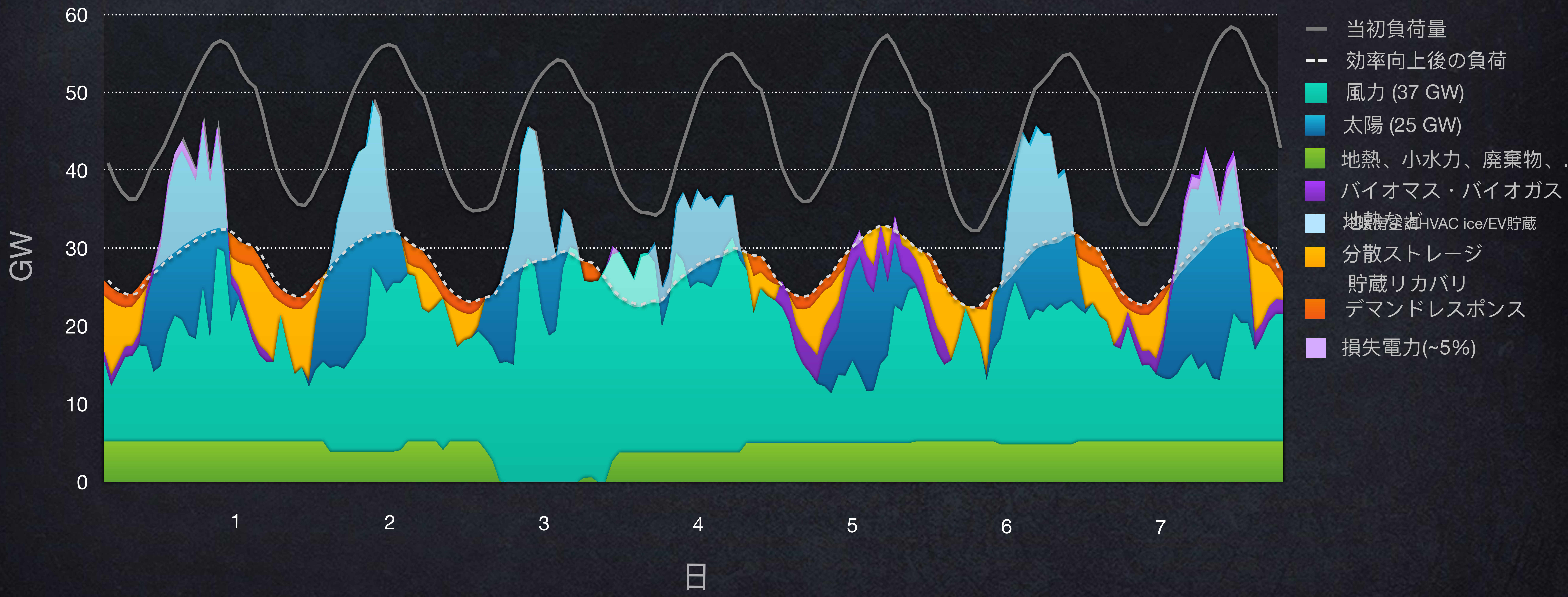


Source: Bernard Chabot, 10 April 2013, Fig. 7, www.renewablesinternational.net/wind-power-statistics-by-the-hour/150/505/61845/, data from French TSO RTE


12% Downtime
10% Downtime

変動型再生可能エネルギーの計画的発電

テキサス電力信頼度協議会（ERCOT）電力プール、テキサス州における２０５０年夏の１週間
（RMI による時間ごとのシミュレーション）



Choreographing Variable Renewable Generation

Europe, 2016–22 best annual renewable % of total electricity consumed

99%

Scotland 2020 (79% without hydro)

84%

Denmark 2022 (55% windpower)

52%

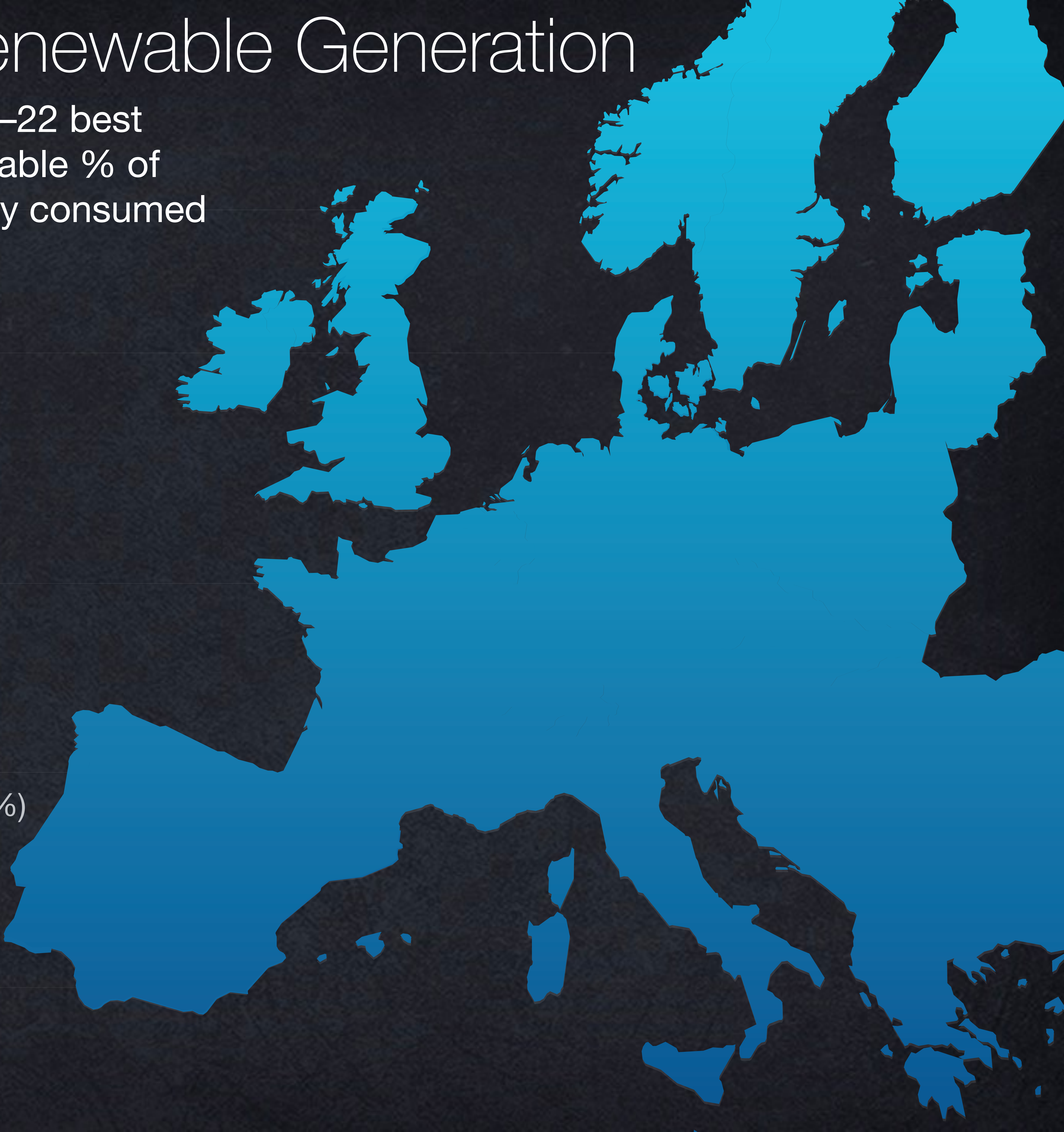
Germany 2020 (2016 peak 88%, 2018–20 ~90–100%, >100% for 12 h 27–28 Mar 2021)

66%

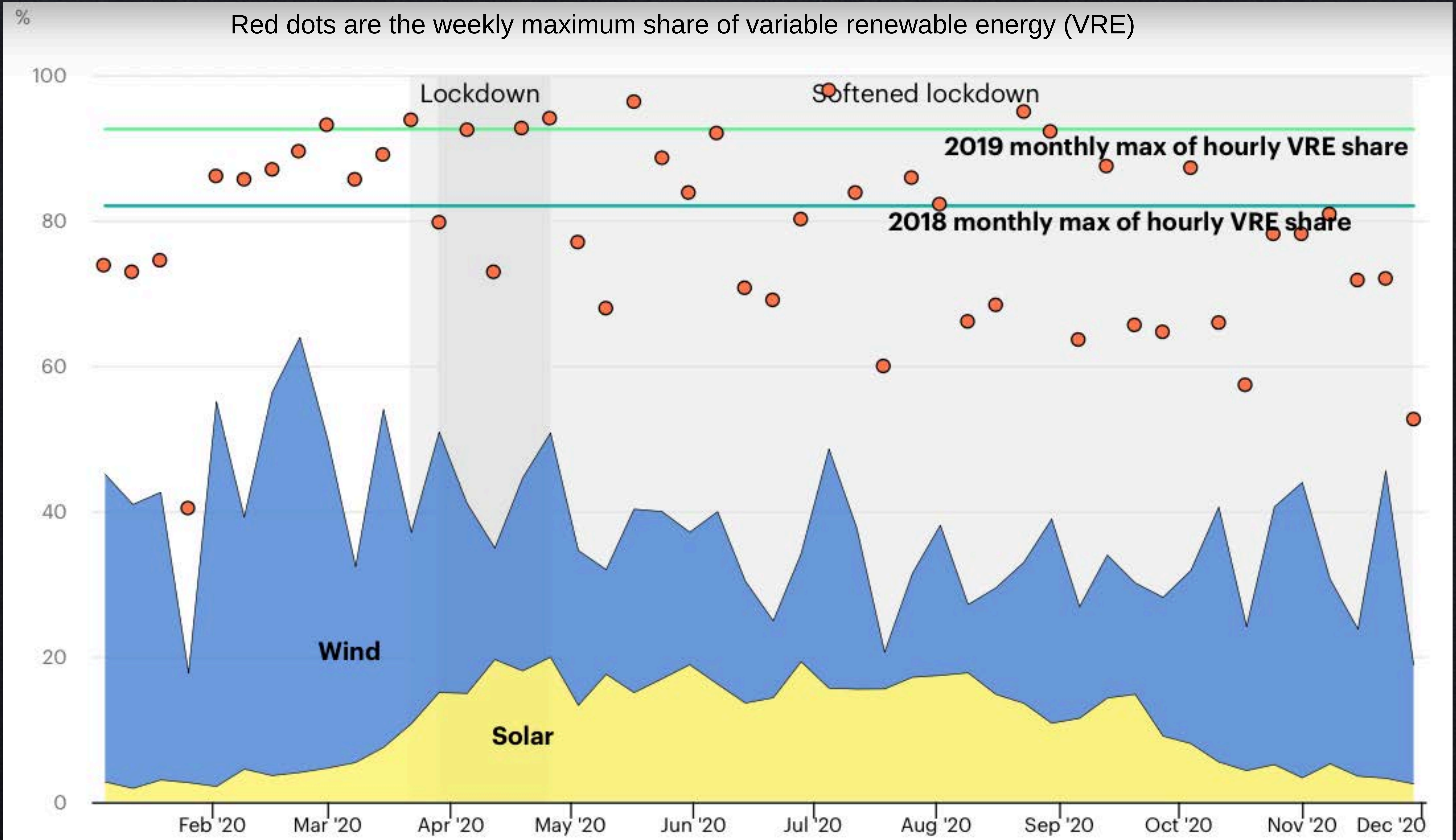
Portugal (2018, 42% without hydro) (2011 & 2016 peak 100%)

46%

Peninsular Spain (2016 & 2020, 27/33% without hydro)

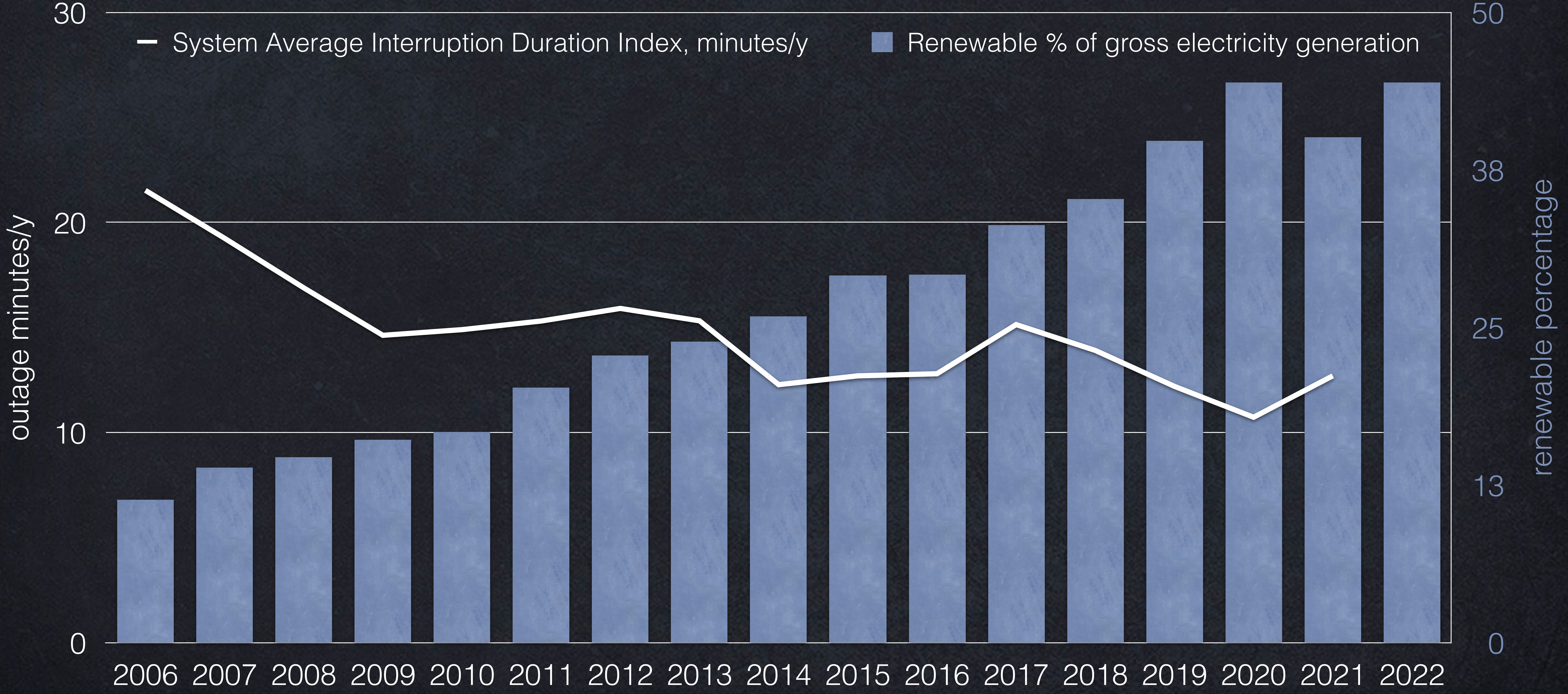


Germany’s variable renewable generation as % of demand, Jan–Nov 2020



https://www.iea.org/reports/electricity-market-report-december-2020/2020-global-overview-capacity-supply-and-emissions#abstract

Germany's renewable share quadrupled 2006–21 as power supplies became broadly more reliable

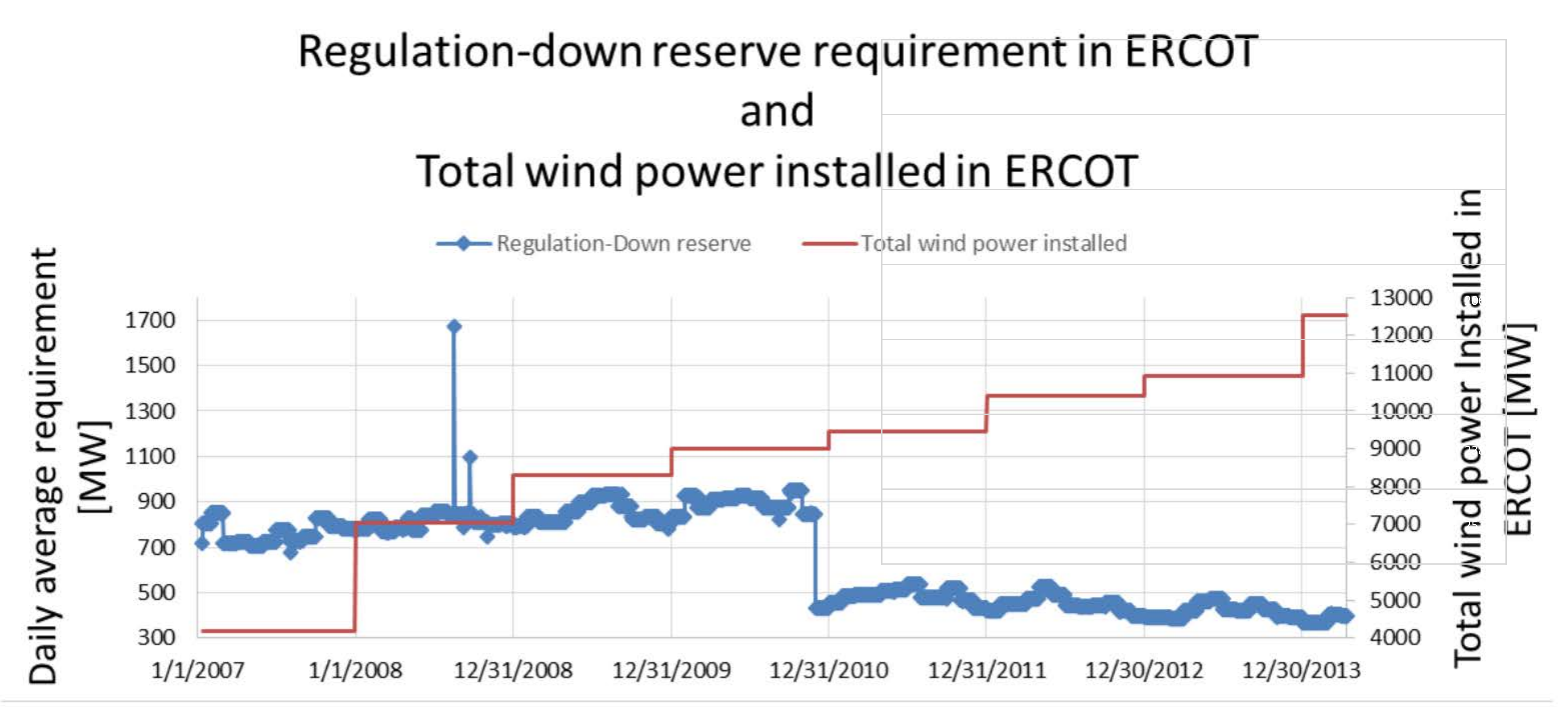


SAIDI data: Bundesnetzagentur, https://www.bundesnetzagentur.de/EN/Areas/Energy/Companies/SecurityOfSupply/QualityOfSupply/start.html

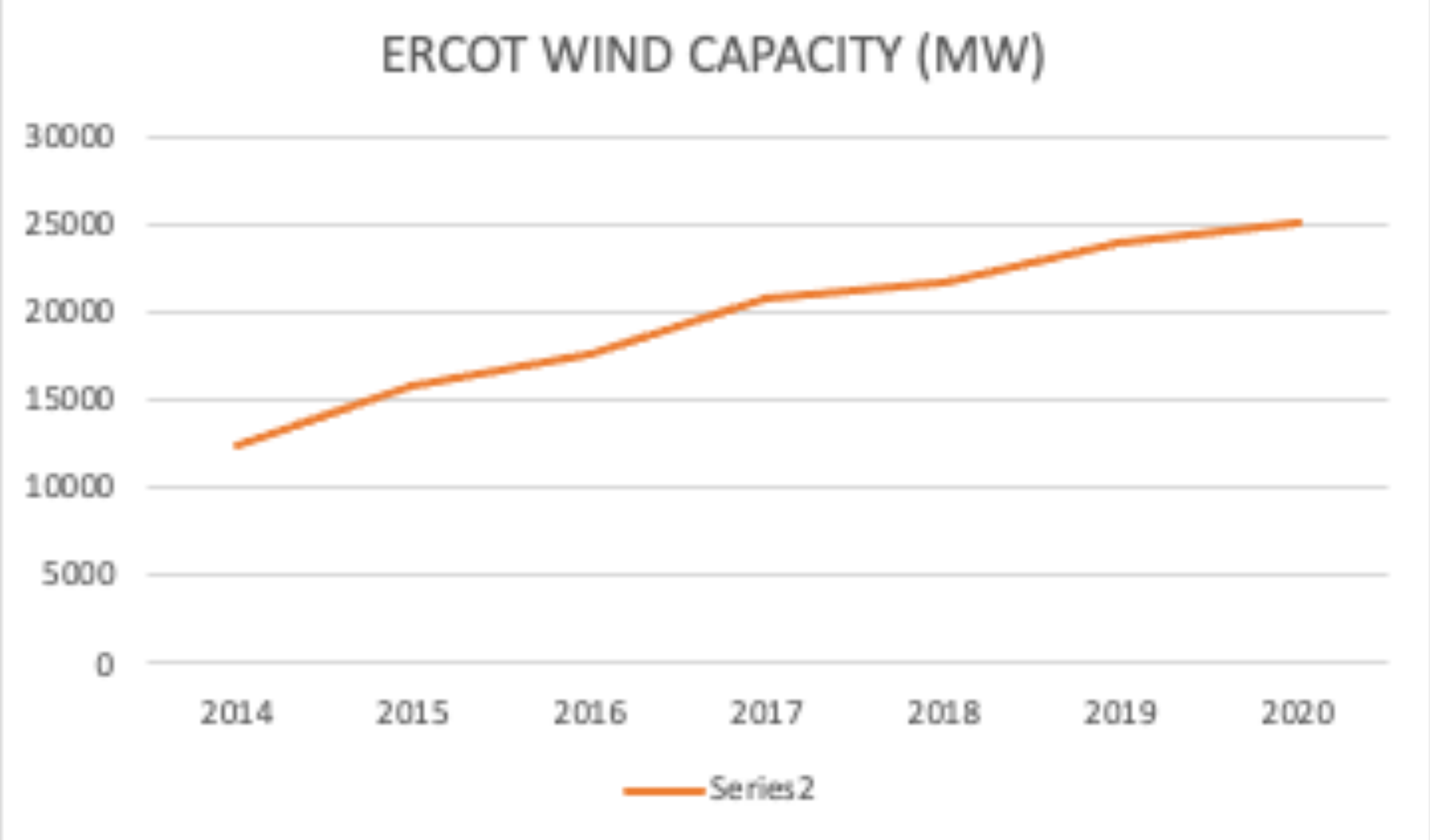
Renewable share data (gross generation): AG Energiebilanzen Bruttostromerzeugung in Deutschland ab 1990 nach Energieträgern, Dec 2020. https://www.ag-energiebilanzen.de; in net terms, 2022 share was 49.6%.

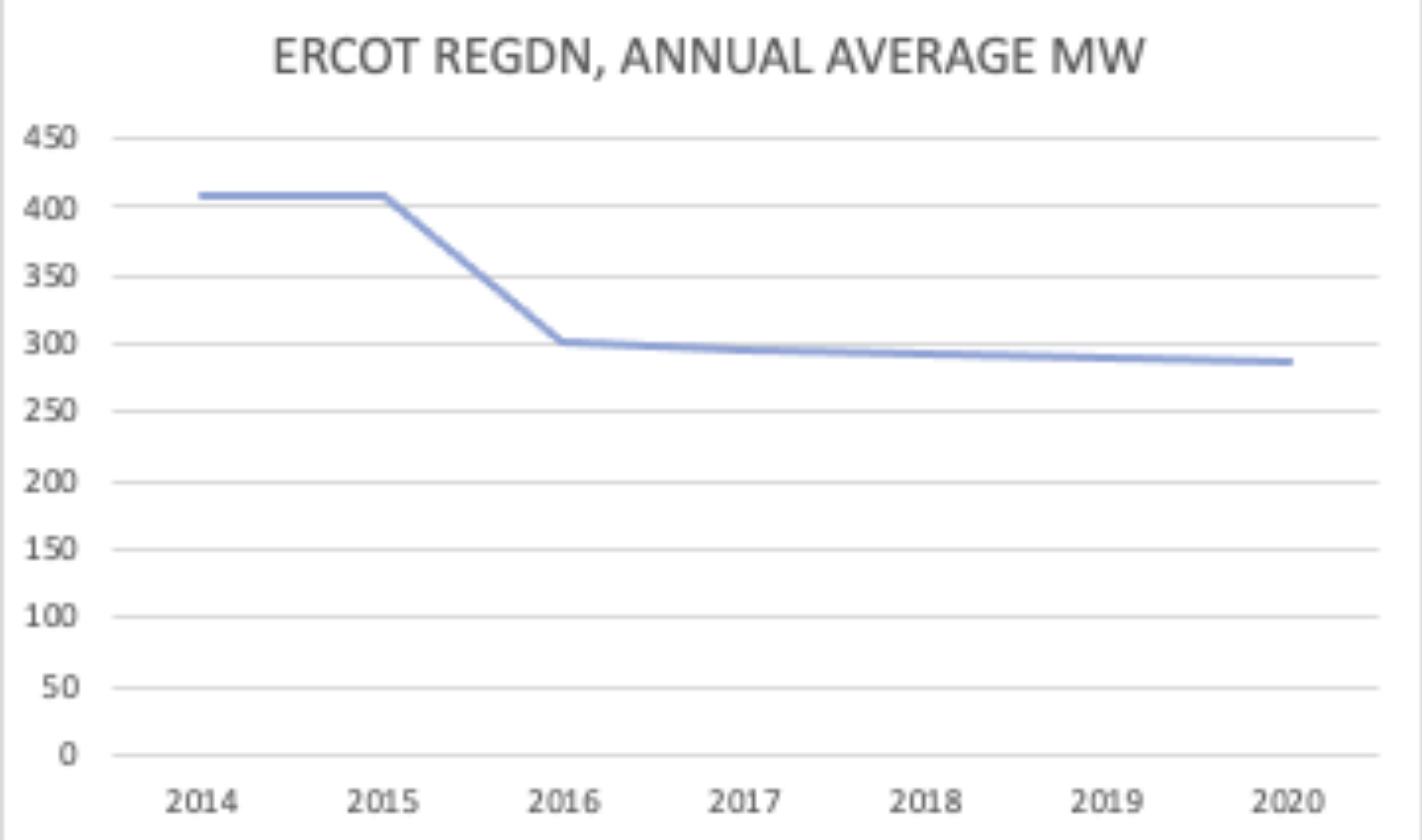
Texas grid's regulation-down procurements fell as windpower tripled and frequency stability (CPS1) improved by about one-sixth; then windpower doubled again while regulation-down fell by another 30%

Historical procured regulation-down reserves in ERCOT and end-of-year annual wind power capacity installed in ERCOT.



The Full Cost of Electricity (FCe-) Executive Summary: The Full Cost of Electricity, April 2018 | 28

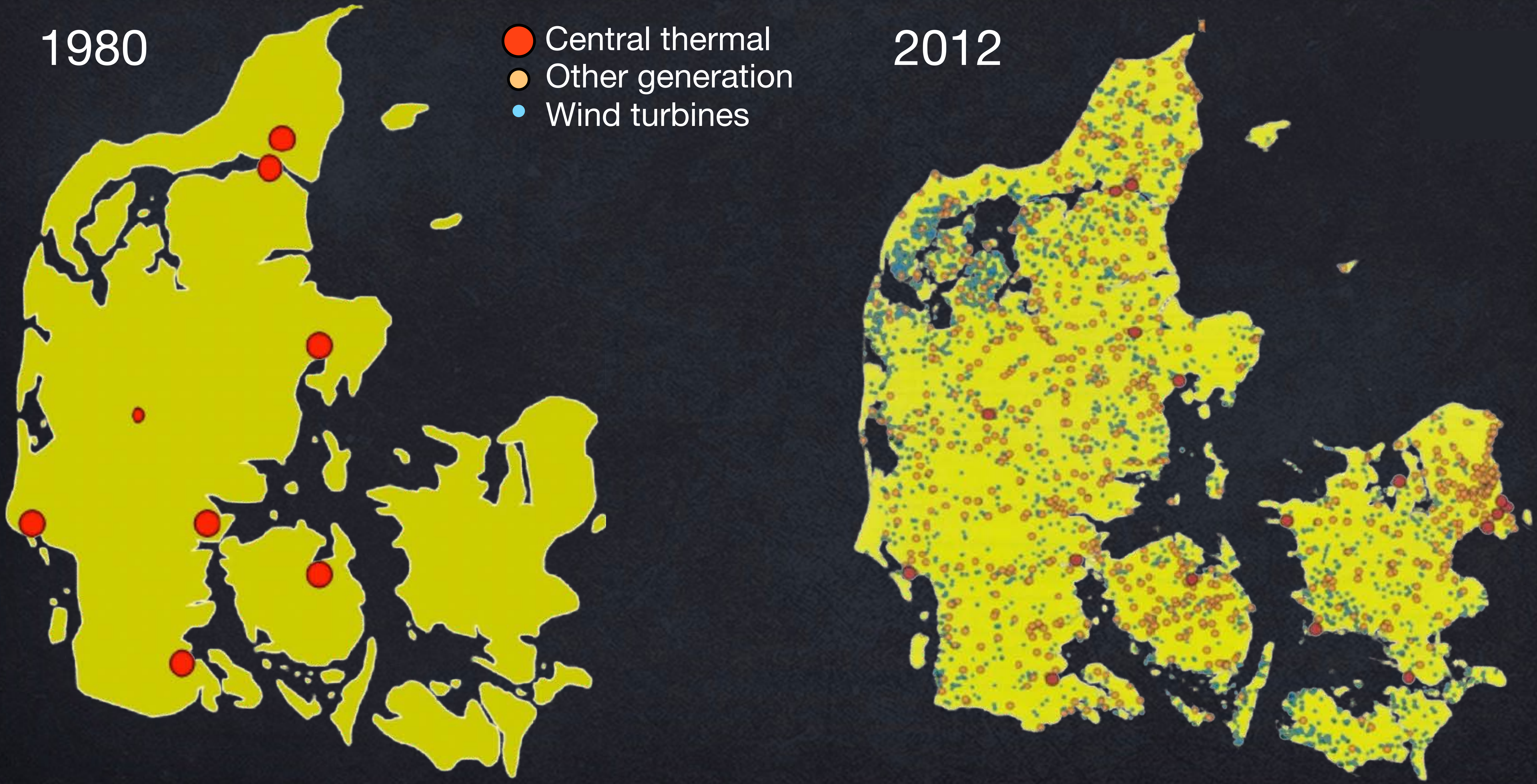




http://sites.utexas.edu/energyinstitute/files/2016/12/UTAustin_FCe_Ancillary-Services_2016.pdf

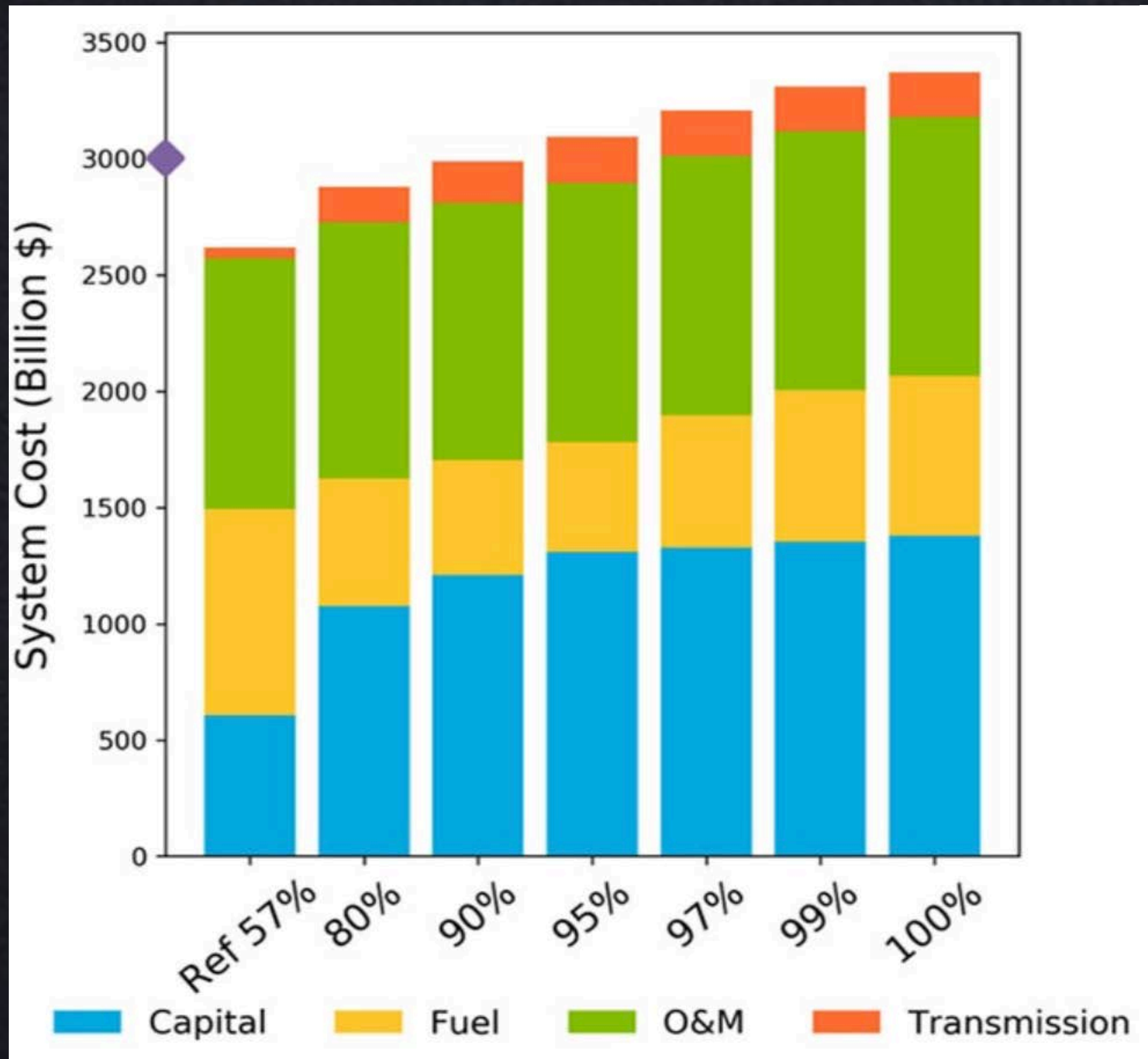
ERCOT.com; C. Bivens (Potomac Ecs.), pers. comm., 07 Sep 2021

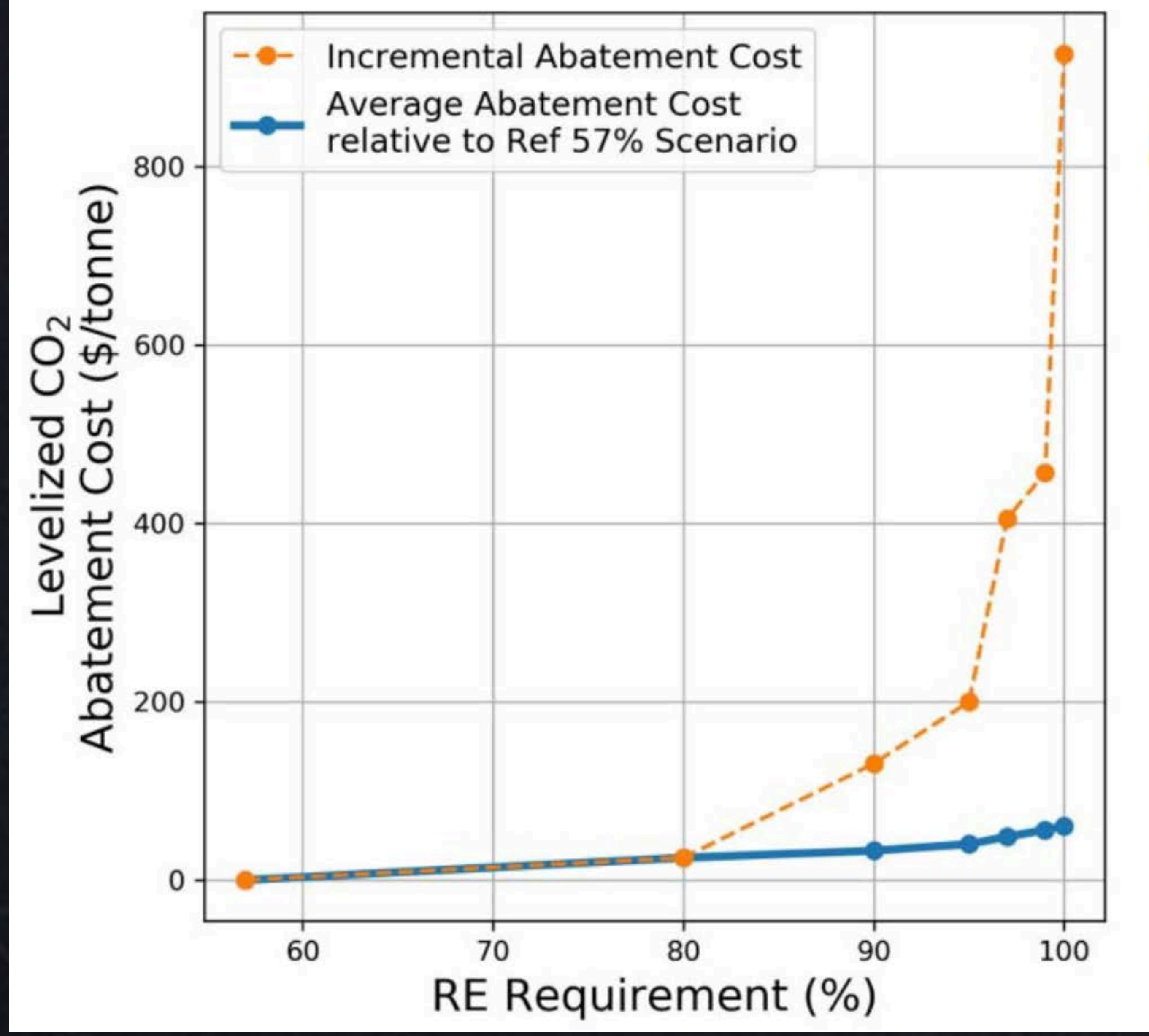
Transitioning to distributed renewables in Denmark

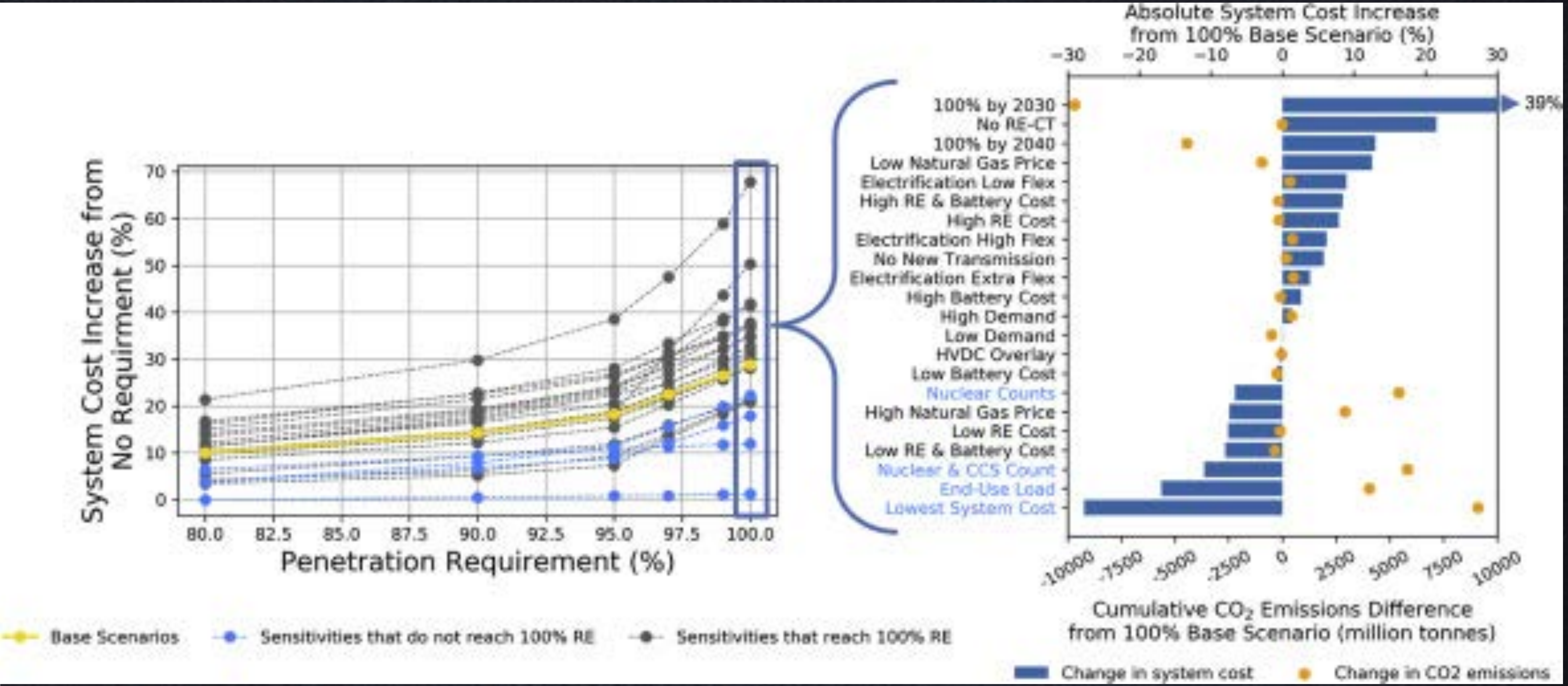


Source: Risø

U.S. electricity can even be 100% renewable…at what cost?







The last few percent's high marginal cost, which has little effect on average cost, reflects a constrained resource portfolio and assumed high curtailment of variable renewables. Electricity demand is assumed to nearly double from the base case. Better integration with unelectrified sectors, and inclusion of end-use efficiency and greater flexibility, should abate that steep rise and might even reverse it.

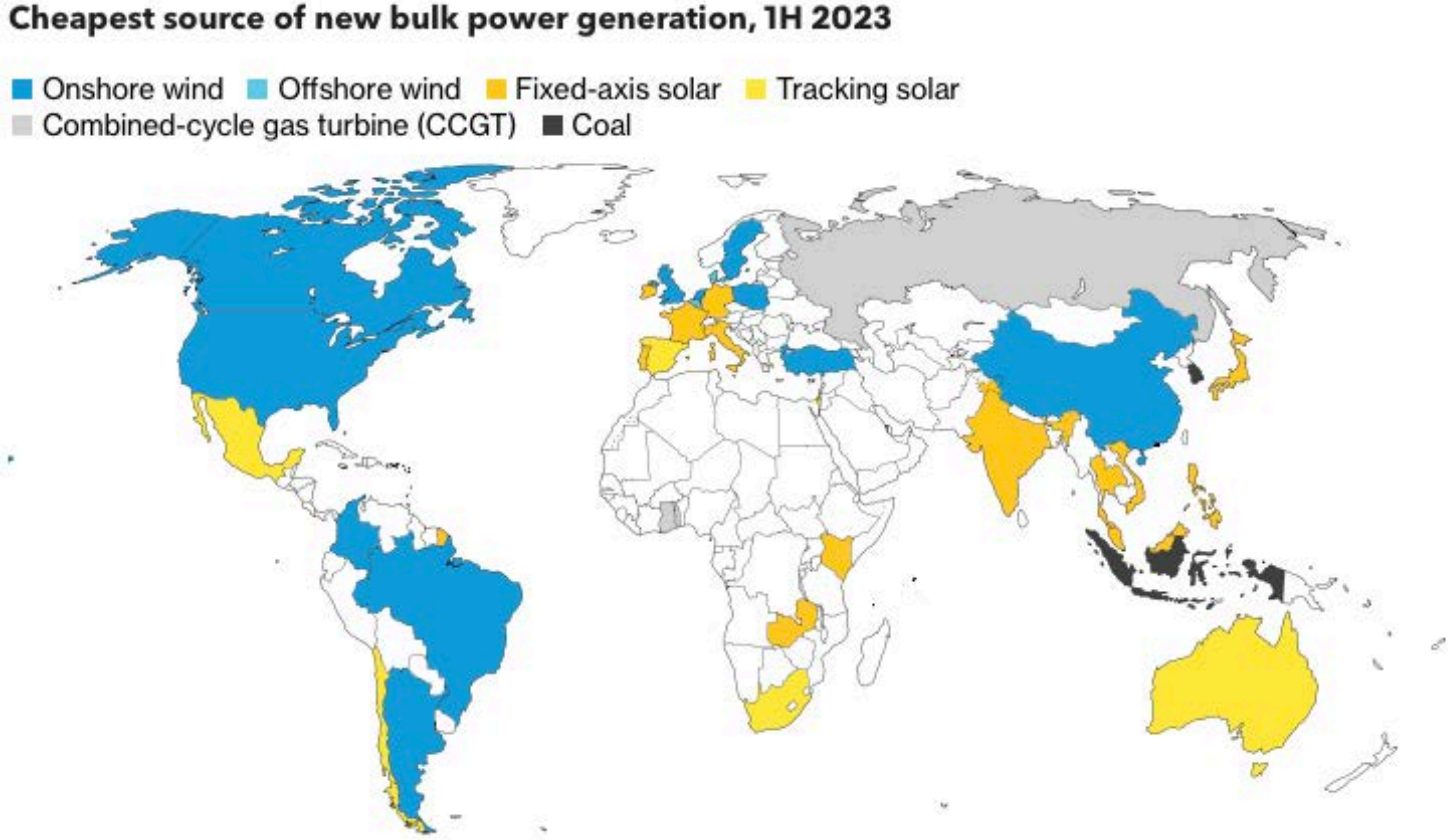
W. Cole *et al.*, "Quantifying the challenge of reaching a 100% renewable energy power system for the United States," *Joule* **5**(7):1732–1748 (21 July 2021), https://doi.org/10.1016/j.joule.2021.05.011

Energy-efficient buildings displace and outcompete electricity storage

Retrofitting conventional building efficiency, plus extra renewables in an optimal mix, largely displaces H_2 long-term storage, *cutting investment by ≥1 order of magnitude*. This "can eliminate the need for long-duration energy storage for U.S. regions" defined by" the Gulf Coast, the desert Southwest, and the Intermountain W & NW.

S. Hussainey & W. Livingood, "Optimal strategies for a cost-effective and reliable 100% renewable electric grid," *J. Ren. Sust. En.* **13**, 066301 (2021), https://doi.org/10.1063/5.0064570, 2 Nov 2021

Sun &/or wind are now the cheapest source of new bulk electricity in countries with 85% of world GDP and 82% of electricity generation—including Japan



Source: BloombergNEF

Note: Shows the technology with the lowest LCOE (or auction bid for recent delivery) for new-build plants in each market where BNEF has data. LCOEs exclude subsidies, tax credits and grid connection costs, and include a carbon price where applicable.

v1.0.0 (07 June 2023): Initial release.

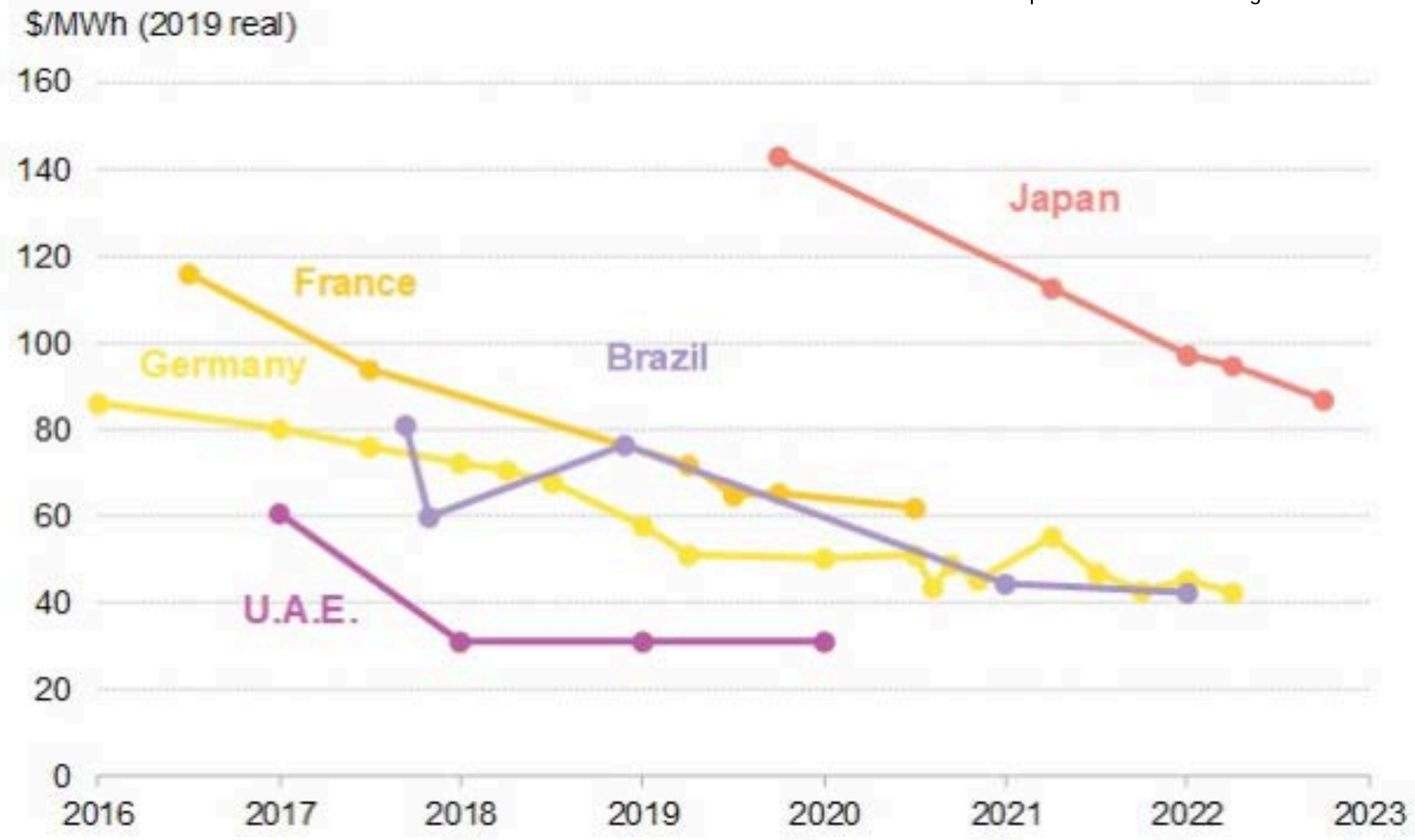
“Variable renewables and back-up are the cheapest new-build option to meet a flat load.” The backup can be demand-side, storage, other renewables, or nonrenewables (generally the costliest).

Estimated mid-2022 learning curves (% cost reduction per doubling of cumulative capacity) were 28.8% for PV modules, 12% for onshore wind projects (13.6% for turbines), ~18% for lithium battery packs (to ≥2030), 0 for coal and gas-fired CCGT, negative for nuclear.

Bloomberg New Energy Finance, 04 June 2023, https://www.bnef.com/insights/31487, based on actual costs of 31,000 projects worldwide

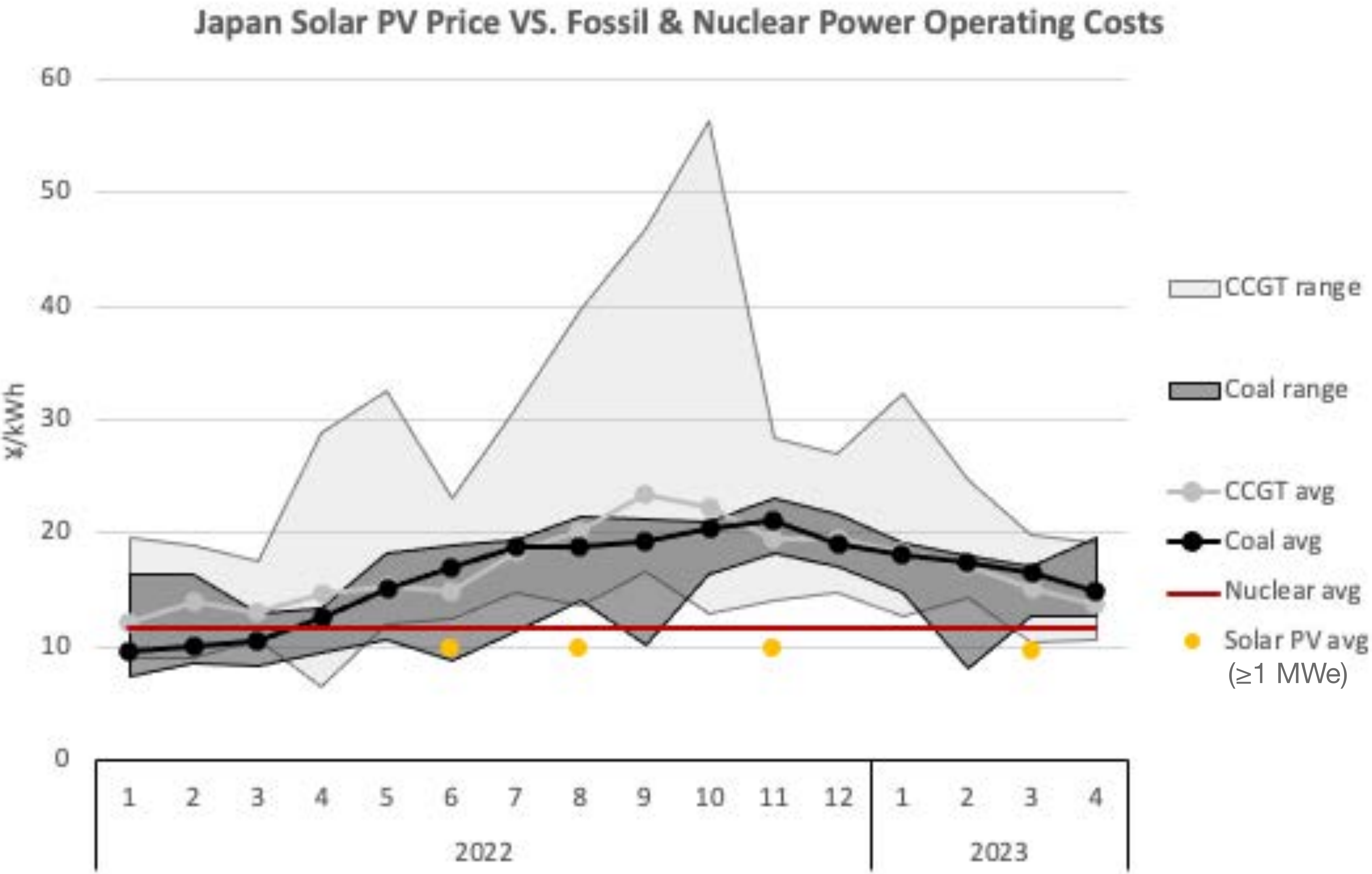
Levelized solar auction bids in select countries

I. Kikuma, "Endgame Starts in Japan Solar Feed-in Tariff Auction," BNEF, 9 Nov 2020, https://www.bnef.com/insights/25231



Source: BloombergNEF

Note: For Japan, we assumed a project tenor of 25 years. In years 21-25 the project gets paid the average January 1, 2019 – December 31, 2019 spot system power price. Projects are assumed to be built 2 years after the auctions.



• For existing coal and CCGT power plants: the operating cost is essentially the fuel cost observed (i.e., imported steam coal and LNG). Operation & maintenance cost is ¥3/ kWh for coal and ¥1/kWh for CCGT. Electrical conversion efficiency is 40% for coal and 55% for CCGT. Capacity factor is 75% for both coal and CCGT. No carbon cost is included (because it is currently negligible in Japan). Initial investment is assumed fully amortized.

• For nuclear power plants: based on restarted reactors. Operating cost includes restart cost (i.e., safety upgrades), fuel cost, and operation & maintenance cost. Capacity factor is 70%. Initial investment is assumed fully amortized. Lifetime extensions included when granted.

• For solar PV: based on auctions for projects ≥ 1 MW. Price includes total cost and profit. After auctions, solar PV power plants should typically start operation within 3 years.

Steam coal and LNG from Japan MoF, nuclear from Professor K. Oshima (Ryukoku University), and solar PV from OCCTO.

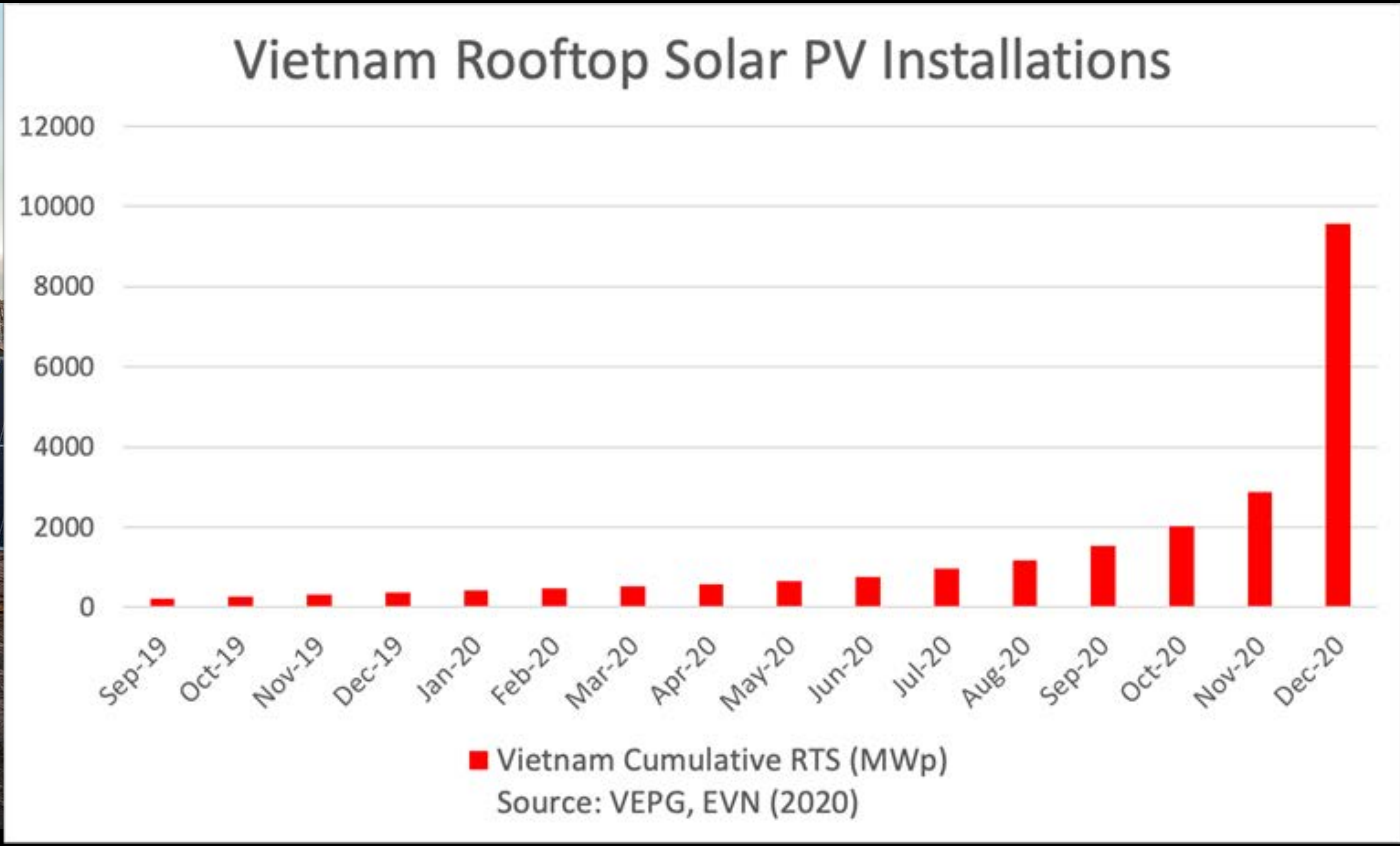
Courtesy of Dr Romain Zissler, Renewable Energy Institute, Tōkyō, 18 June 2023. Consistent with https://www.bnef.com/flagships/lcoe, 11 June 2023.

Vietnam’s solar power revolution:  a world record in 2020?

Year-end solar capacity: 2018: 0.1 GW, 2019: 5.5 GW, 2020: 16.5 GW;
of which rooftop solar added 9.3 GW (= 6 coal plants’ output) *in 2020*;
of which 6.7 GW was added *just in December 2020* (to get feed-in tariff).
Coal added 1.2 GW in 2020. Windpower added 3.7 GW in 2018–21.

https://www.weforum.org/agenda/2021/02/viet-nam-solar-power-surge/viet-nam-solar-power-surge/

https://www.pv-tech.org/vietnam-rooftop-solar-records-major-boom-as-more-than-9gw-installed-in-2020/



An EU analysis finds no structural seasonal deficit in a 2050 net-zero power system: 70% el. use growth to 2050 needs only 240–400 dispatchable GW for 1–2 *weeks*/y

A WELL-BALANCED RES MIX DOES NOT CAUSE A STRUCTURAL SEASONAL MISMATCH BETWEEN DEMAND AND RES SUPPLY

Complementarity of wind and solar power

The generation patterns of wind and solar energy in Europe are complementary: wind energy production is most abundant in winter, whilst around 40% of solar energy is produced between June and August. Figure 4 shows the long-term fluctuations (over a time scale of 1 to 12 months) in the BAUx3 RES supply in Europe in 2050, and of the direct electricity demand (ELEC-pathway). Achieving the right balance between wind and solar production in the energy mix avoids a structural seasonal mismatch between supply and demand in summer (e.g. oversupply of solar energy) and winter (e.g. undersupply because of low solar infeed).

No need for large-scale volumes of green molecules to cope with seasonality in the power sector

The BAUx3 RES expansion scenario does not reveal a structural seasonal mismatch between supply and demand on a European level under the ELEC-pathway in 2050. This means that there is no need in the power system for large-scale seasonal storage via green molecules. The role of green molecules will be limited to covering periods of 1 up to 2 weeks with exceptionally low RES infeed. Belgium and Germany can achieve a balanced RES mix by building interconnectors with countries with a complementary RES mix.

FIGURE 4: SEASONAL PATTERN OF ELECTRICITY GENERATION AND DEMAND (FLUCTUATIONS 1 TO 12 MONTHS). THE RIGHT MIX OF WIND AND SOLAR POWER AVOIDS A SEASON-LONG MISMATCH BETWEEN ELECTRICITY DEMAND AND SUPPLY IN EUROPE IN 2050 (BAUX3 RES, ELEC-PATHWAY)

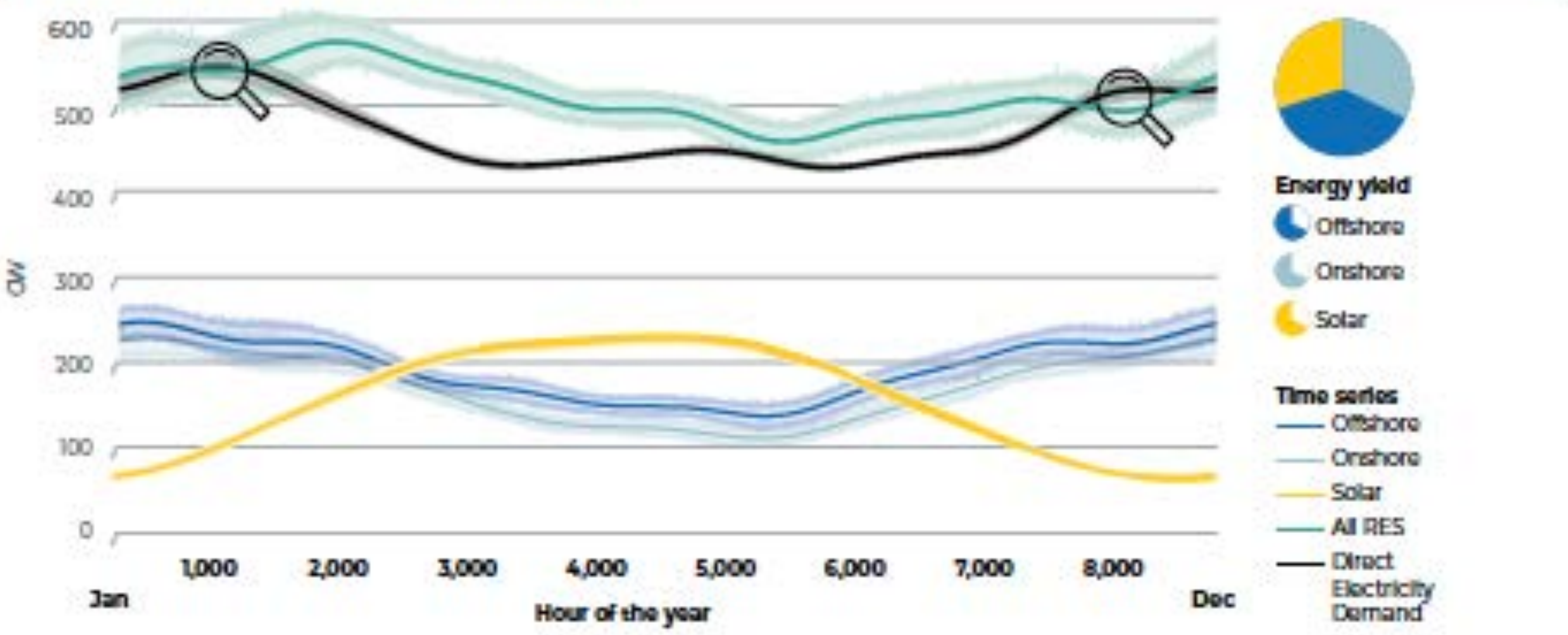
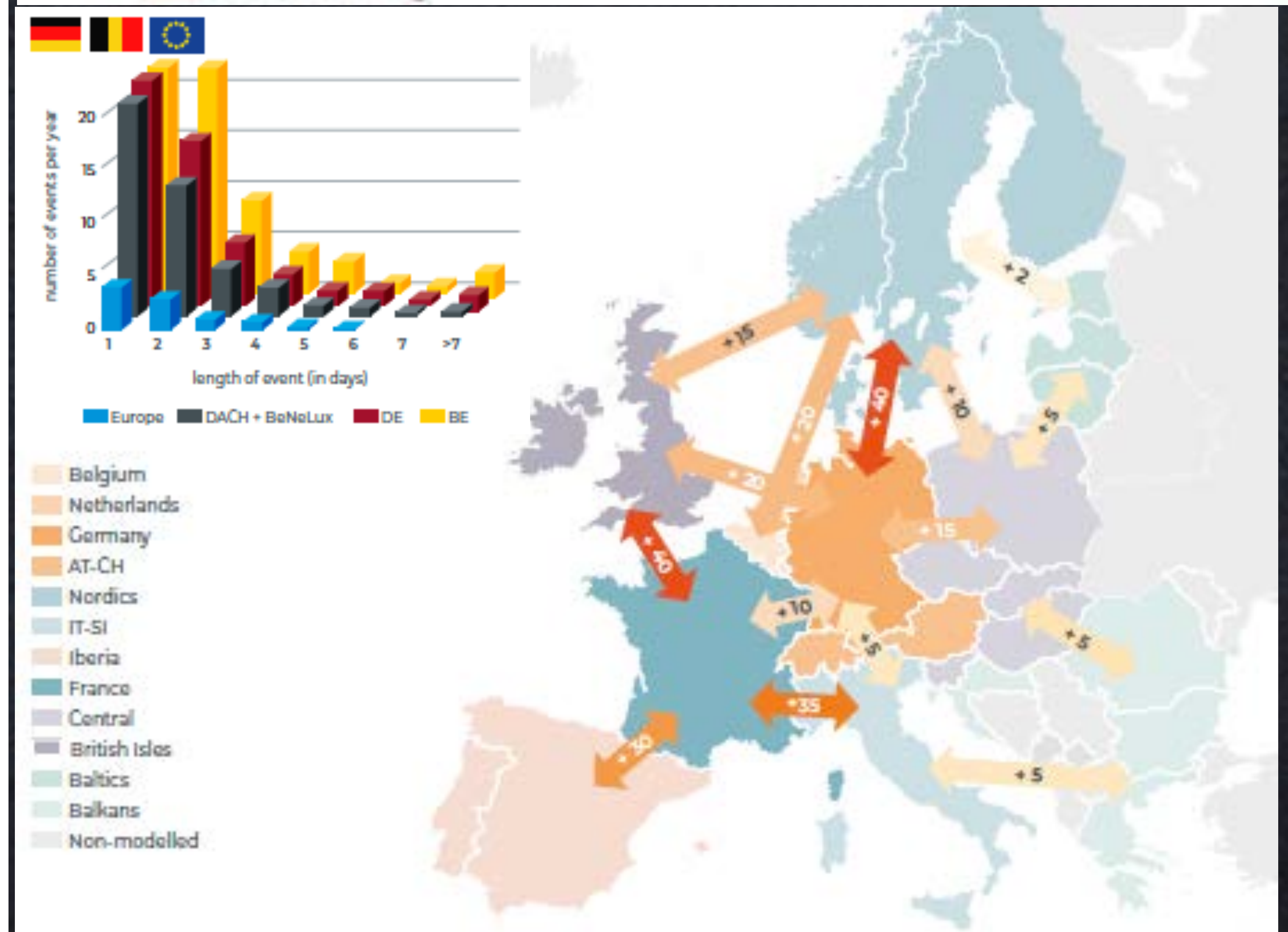


FIGURE 2: STRONG ELECTRIFICATION OF END USE (AS UNDER THE ELEC-PATHWAY) SAVES UP TO 1,800 TWH AT THE EUROPEAN LEVEL COMPARED TO THE MOL-PATHWAY. DIRECT ELECTRICITY DEMAND UNDER THE ELEC-PATHWAY INCREASES BY 70% COMPARED TO TODAY'S DEMAND. A TRIPLING OF TODAY'S RES EXPANSION RATE IS NEEDED TO MEET THIS DIRECT ELECTRICITY DEMAND



Elia Group/50Hertz, *Roadmap to Net Zero*, 19 Nov 2021, p 7, https://www.50hertz.com/en/News/FullarticleNewsof50Hertz/11597/elia-group-publishes-roadmap-to-net-zero-our-vision-on-building-a-climate-neutral-european-energy-system-by-2050. "RES" ≡ renewable energy supply.