
ROCKY MOUNTAIN
INSTITUTE

エネルギーの未来の破壊的変革

Disruptive Energy Futures

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自然エネルギー転換を加速する　　2022年3月2日　東京都

REvision 2022, Tōkyō, 1/2 March 2022

https://www.gloveworx.com/blog/simple-cup-of-tea-story/, but see http://www3.telus.net/public/sarlo/Oshobob/Nan%27in.htm

What can integrative design do by around midcentury?

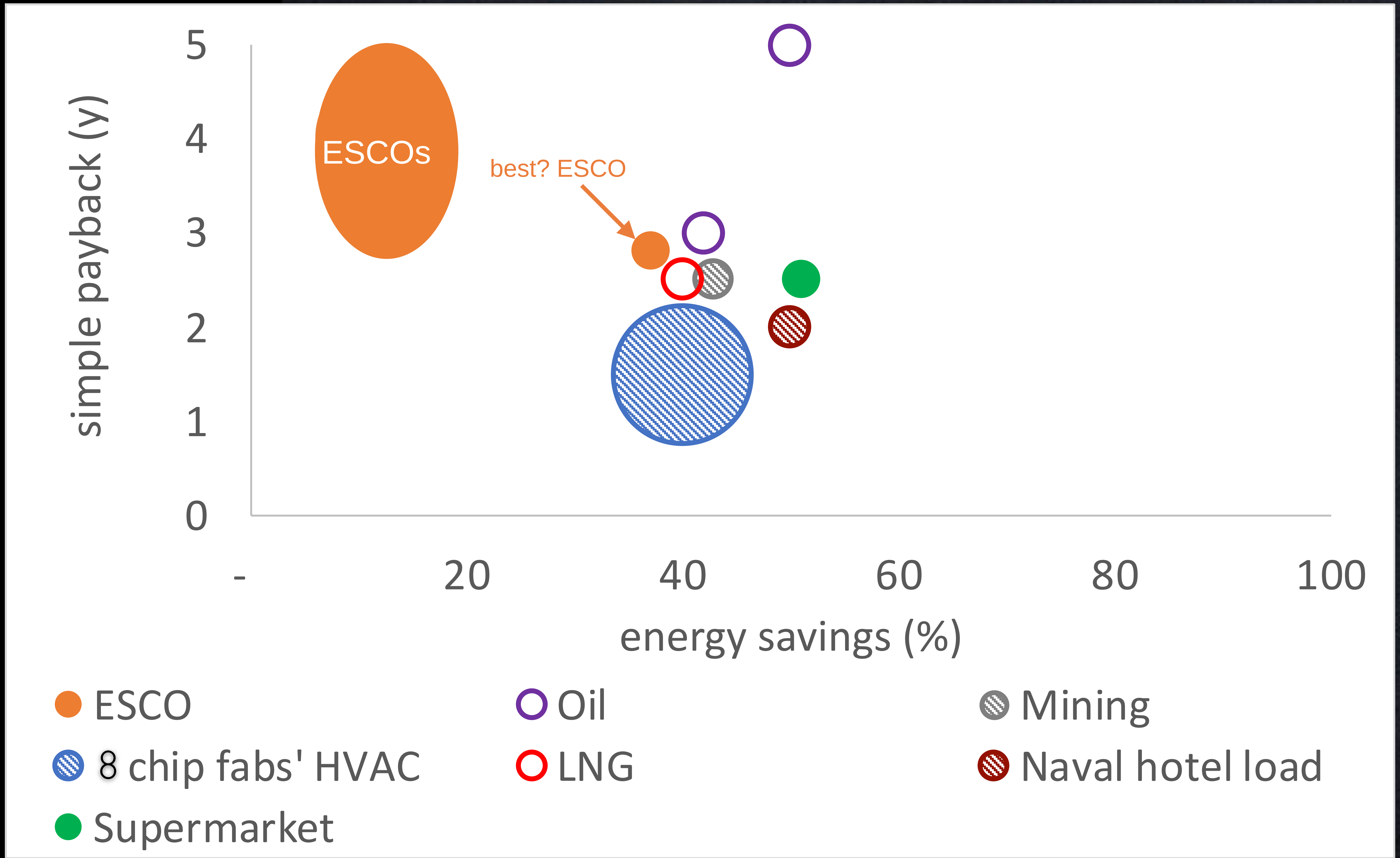
η = [normal] end-use efficiency

buildings: ~4–≥10η
automobiles: ~4–8η
trucks: ~3–4η
airplanes: ~3–8η
factories: ~2η old, ~2–10η new, →∞ if avoided
cement and steel: ~2–4η

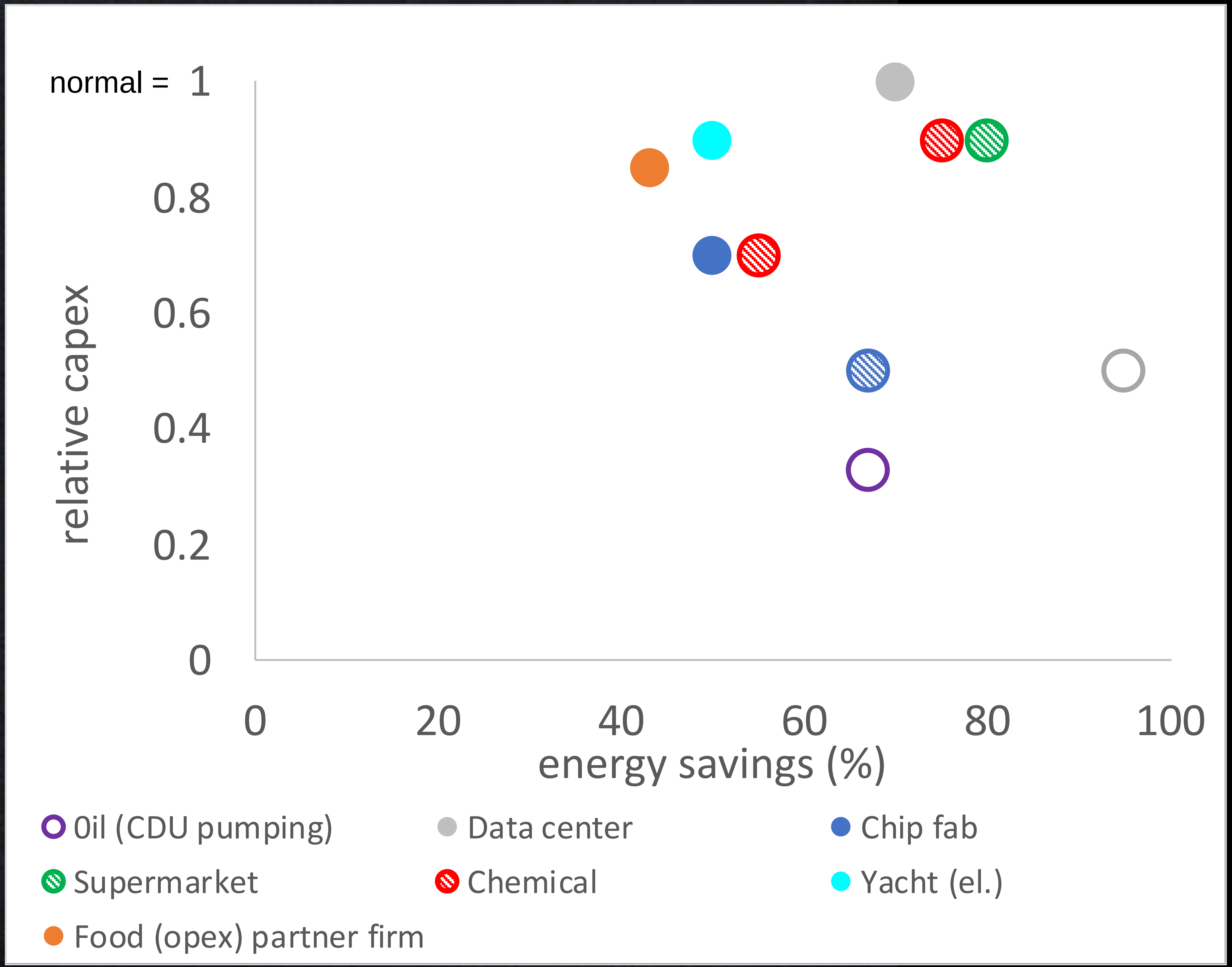
so…world economy: ≥5η?

RMI's latest >$50b worth of integrative design in diverse industrial projects—retrofits and newbuilds

(solid = built, shaded = incomplete data, circle = not yet built; ESCO = Energy Service Company; CDU = Crude Distillation Unit)



Retrofits



Newbuilds

A. Lovins, *Envtl. Res. Ltrs.* **13**:090401 (2018), https://doi.org/10.1088/1748-9326/aad965; — *et al.*, id. **14**:120201, https://doi.org/10.1088/1748-9326/ab55ab; — & K. Bond, *id.* **16**:020201, https://doi.org/10.1088/1748-9326/abc3f2

Decarbonize industrial process heat indirectly…
by elegantly frugal structural structural design

A. Lovins, "Profitably decarbonizing heavy transport and industrial heat," 2021, www.rmi.org/profitable-decarb/, and its *MIT Sloan Mgt Rev* companion paper

Tension structures—~80–90% less material

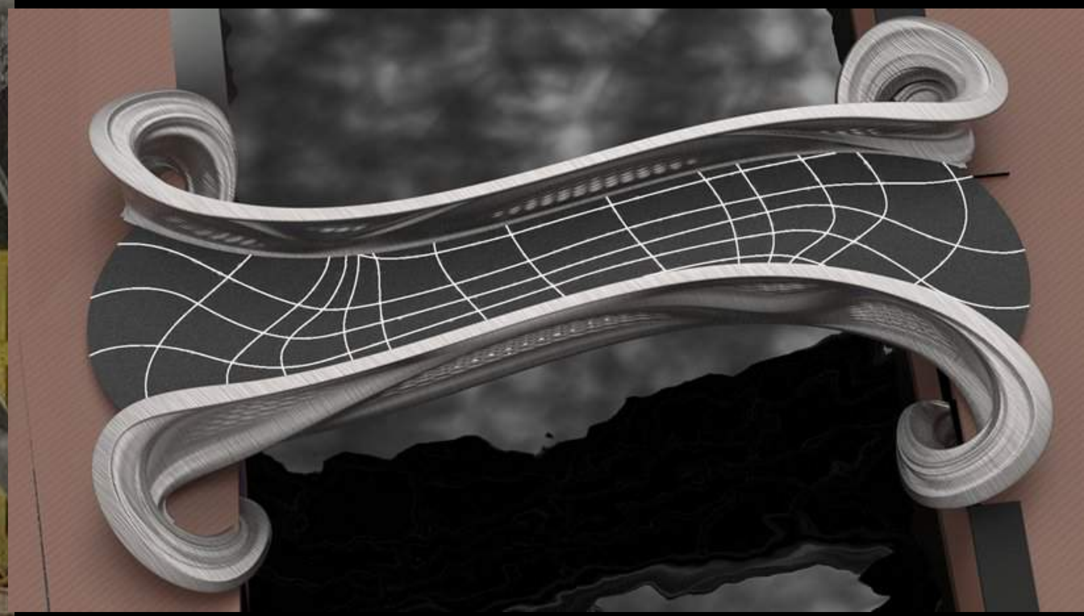
Schlaich Bergermann—see the remarkable book *Leicht Weit*

Fabric forms—≥50% less material

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

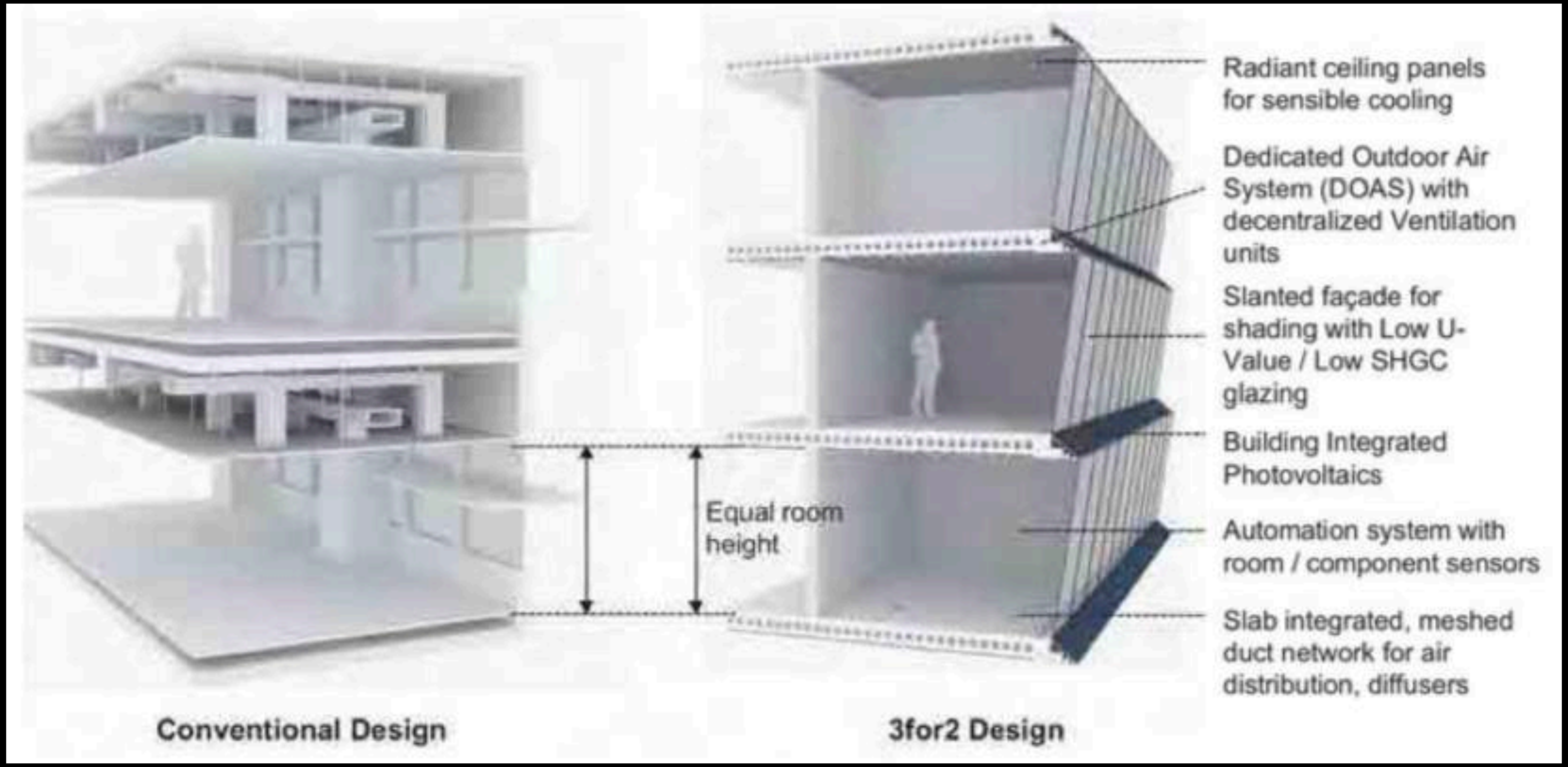
https://www.shapeways.com/blog/archives/35854-3d-printed-bridges-now.html (Joris Laarman Lab, MX3D)

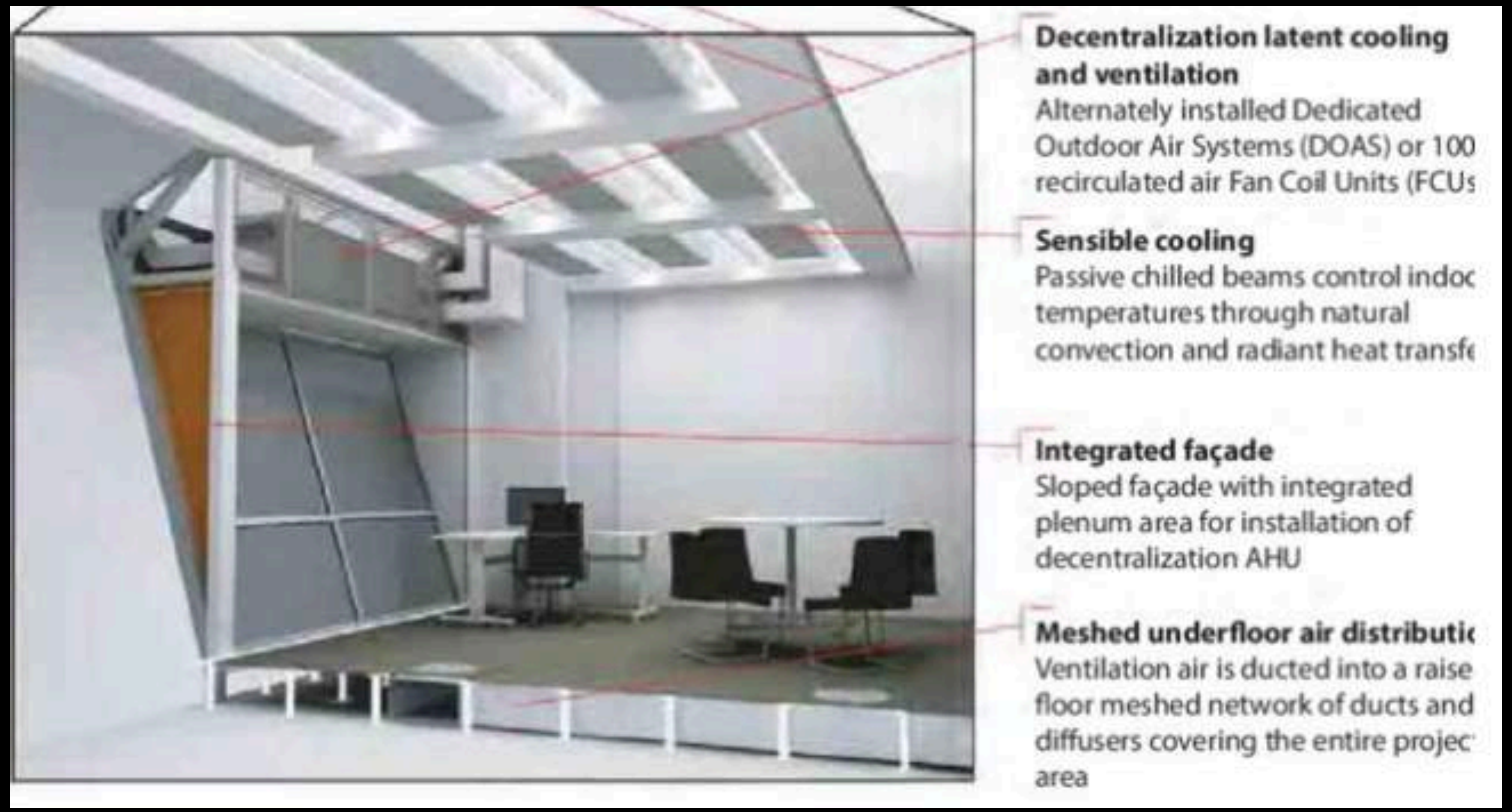
The artistic 3D-printed 12.5m stainless-steel bridge over Amsterdam's Oudezijds Achterburgwal canal



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

UCWSEA pilot installation, Singapore, 2015



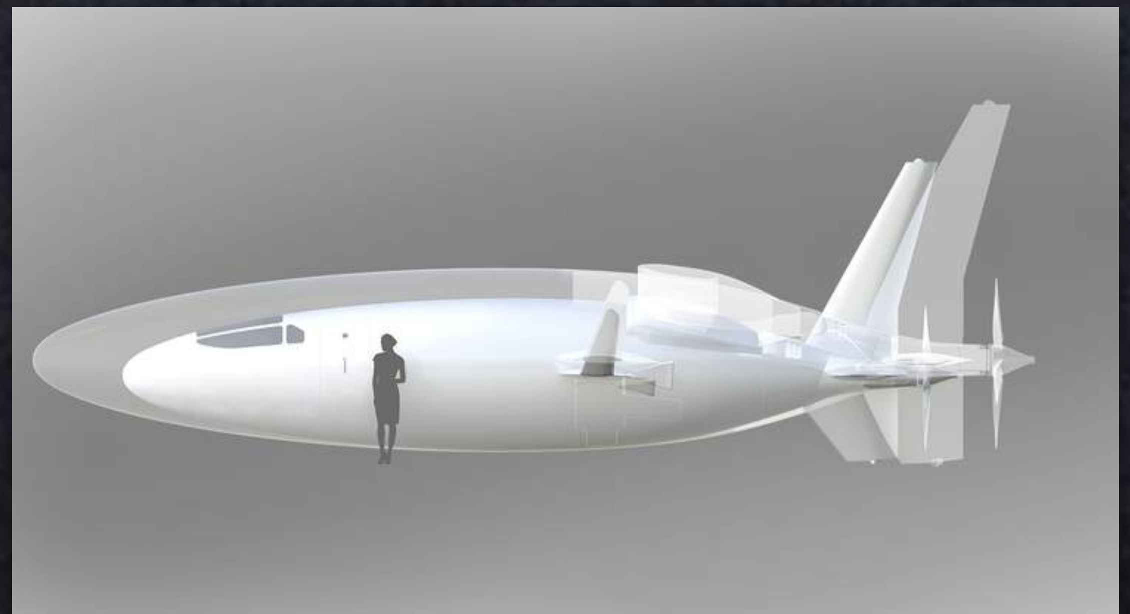


A. Schlueter *et al.*, “3for2: Realizing Spatial, Material, and Energy Savings through Integrated Design,” *CTBUH J.* **2016**(2):40–45, Council on Tall Buildings and Urban Habitat

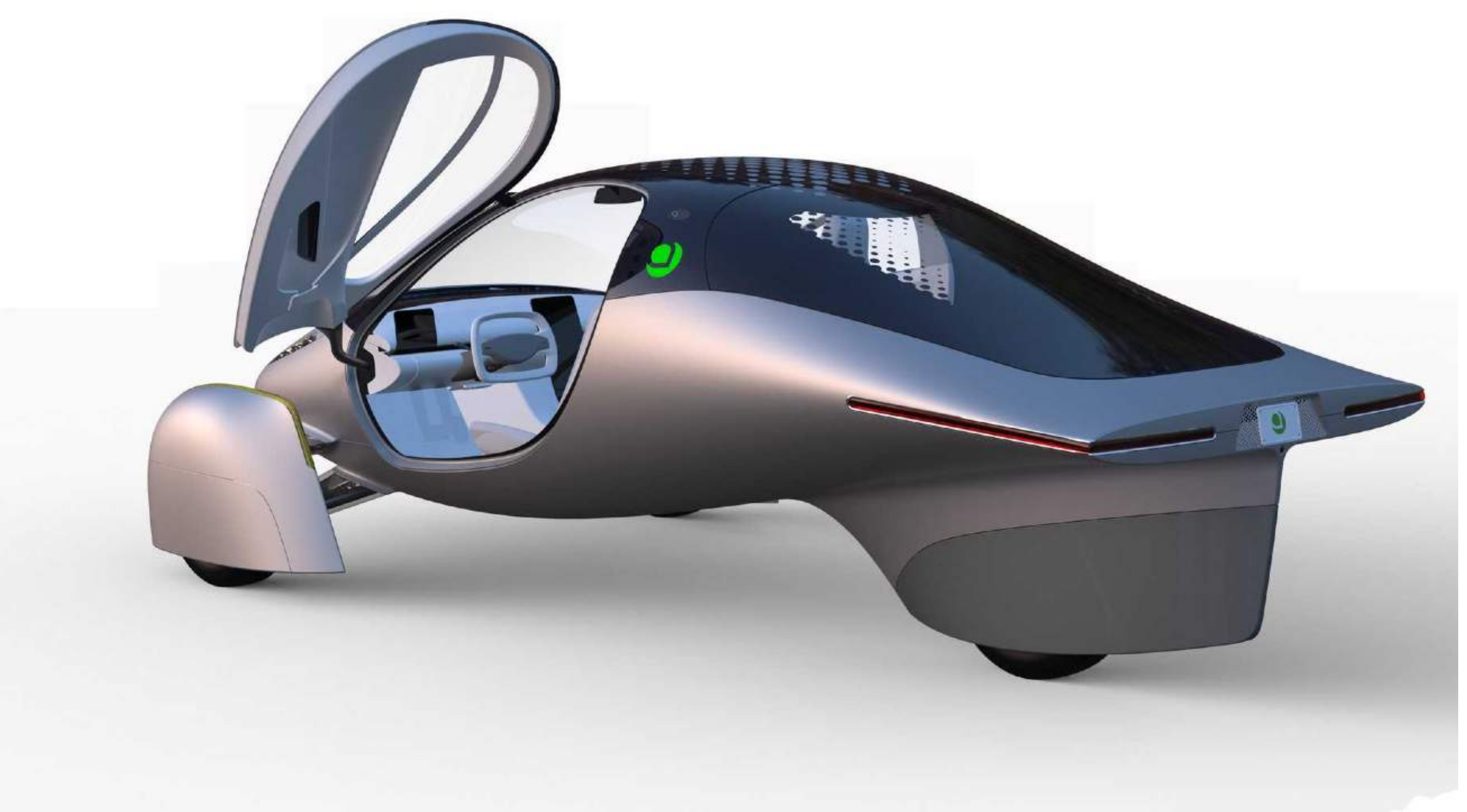
The revolution accelerates…

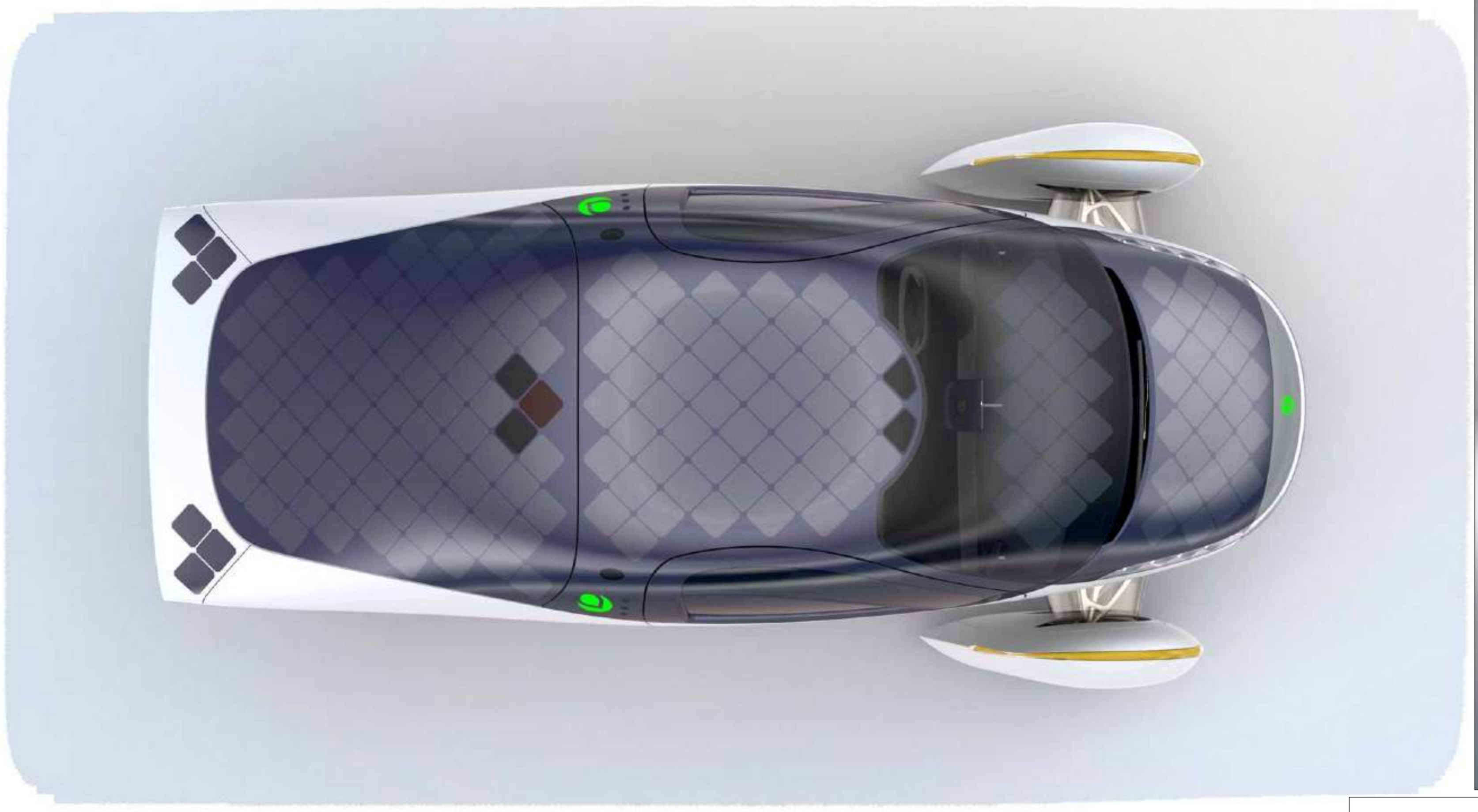
Tesla *Semi* Class 8 battery-electric truck (2023), >3× efficiency, 800-km full-load range (+ ~650 km w/30-minute recharge), 1.6-million-km warranty, 40% sleeker aerody-namics, unchanged payload, 3–5× faster acceleration, 1/3-faster hill-climbing (5% grade), 2-y payback at low US fuel prices (could be 0 in this decade)

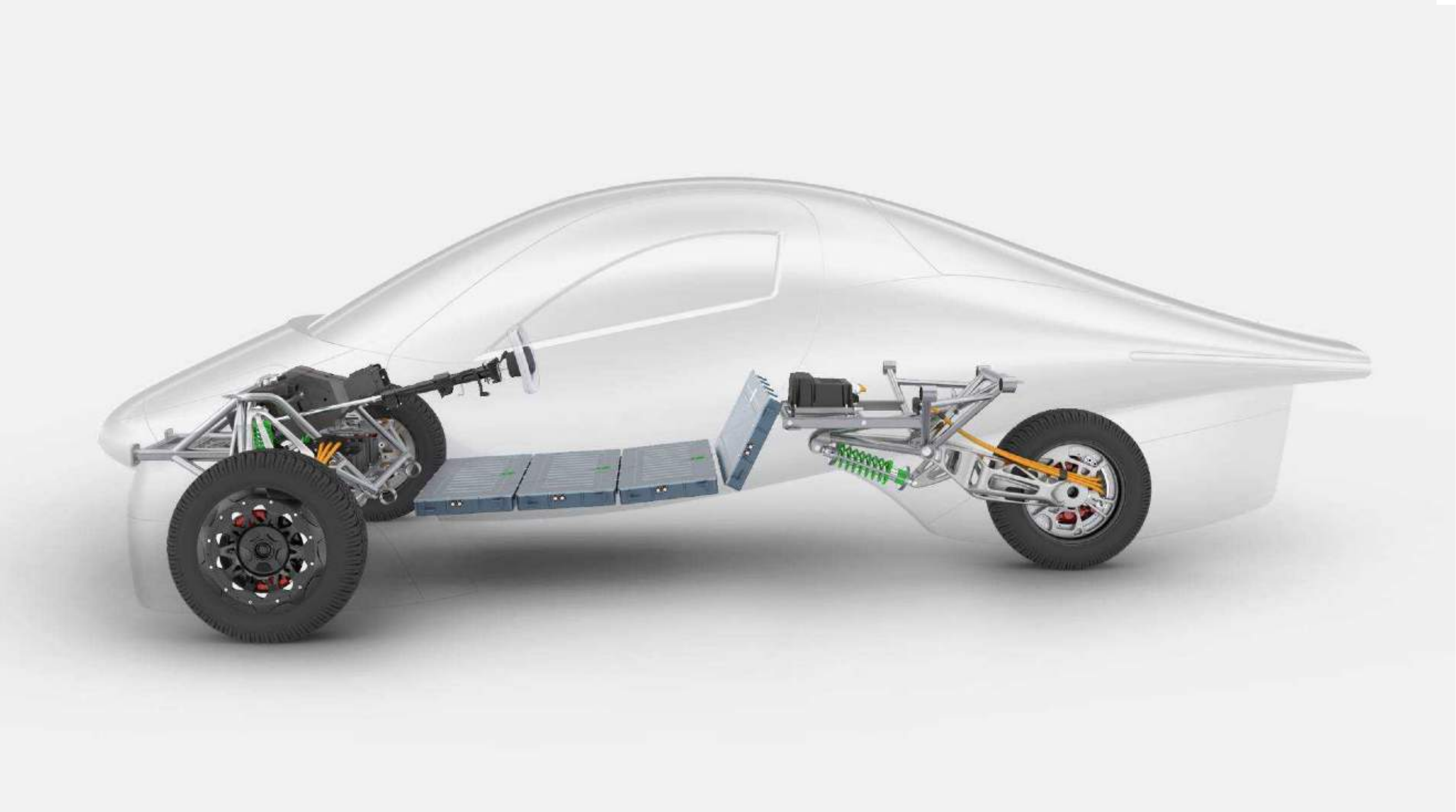
Celera *500L* (Otto Aviation 2020 prototype—the commercial version will add windows), *8× efficiency* (8–13 L/100 km *vs* ~78–118), >740 km/h, 8330-km range, 6× lower opex ($328/h); 6-seater can scale up to >20; good candidate for electrification

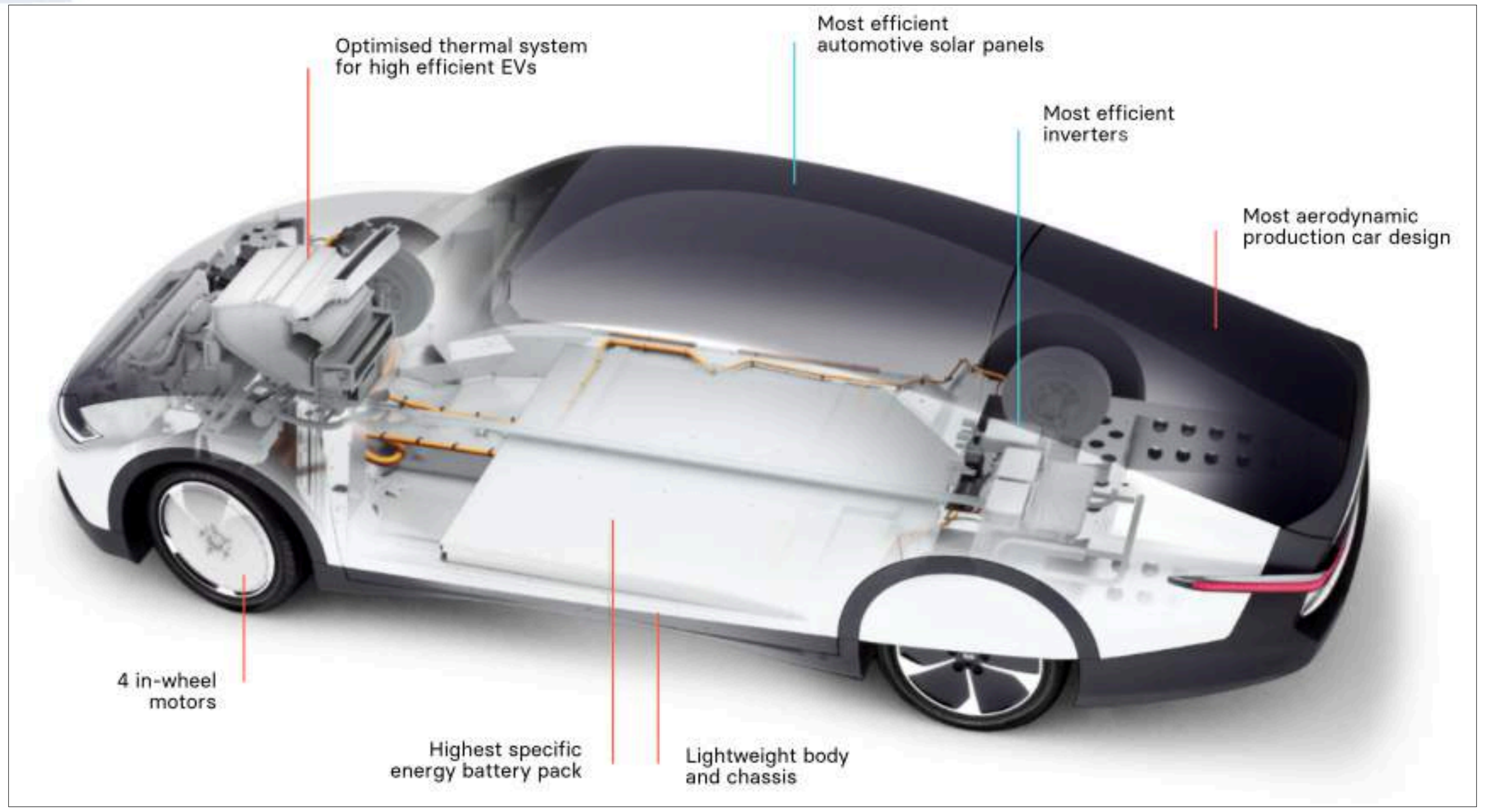


with more to come…









"NeverCharge" solar-powered Hypercar®-class 2-seat el. vehicle (aptera.us): up to 1,600-km range, but most drivers *will need no recharging*, because it's so efficient (≥146 km/L_{eq}) that its solar cells capture enough energy for ~18,000 km/y. It has half a Tesla's mass, and less air drag (C_d 0.13) than the wipers or side mirrors of a US pickup truck! 2022 release; $26–45k, depending on range.

"Lightyear One" mostly/all solar-powered (5 m^2, 21.5%-efficient, ~12 km charge/h) 5-seat 4-wheel sedan, 0.78–1.7 m^3 cargo, C_d <0.2, ~108 km/L_{eq}, 725-km range, 2022 release (lightyear.one).





76

Flexible demand
Integrative design
Customer preferences
Utility blockchain
Resilience imperative
Efficiency
Distributed renewables
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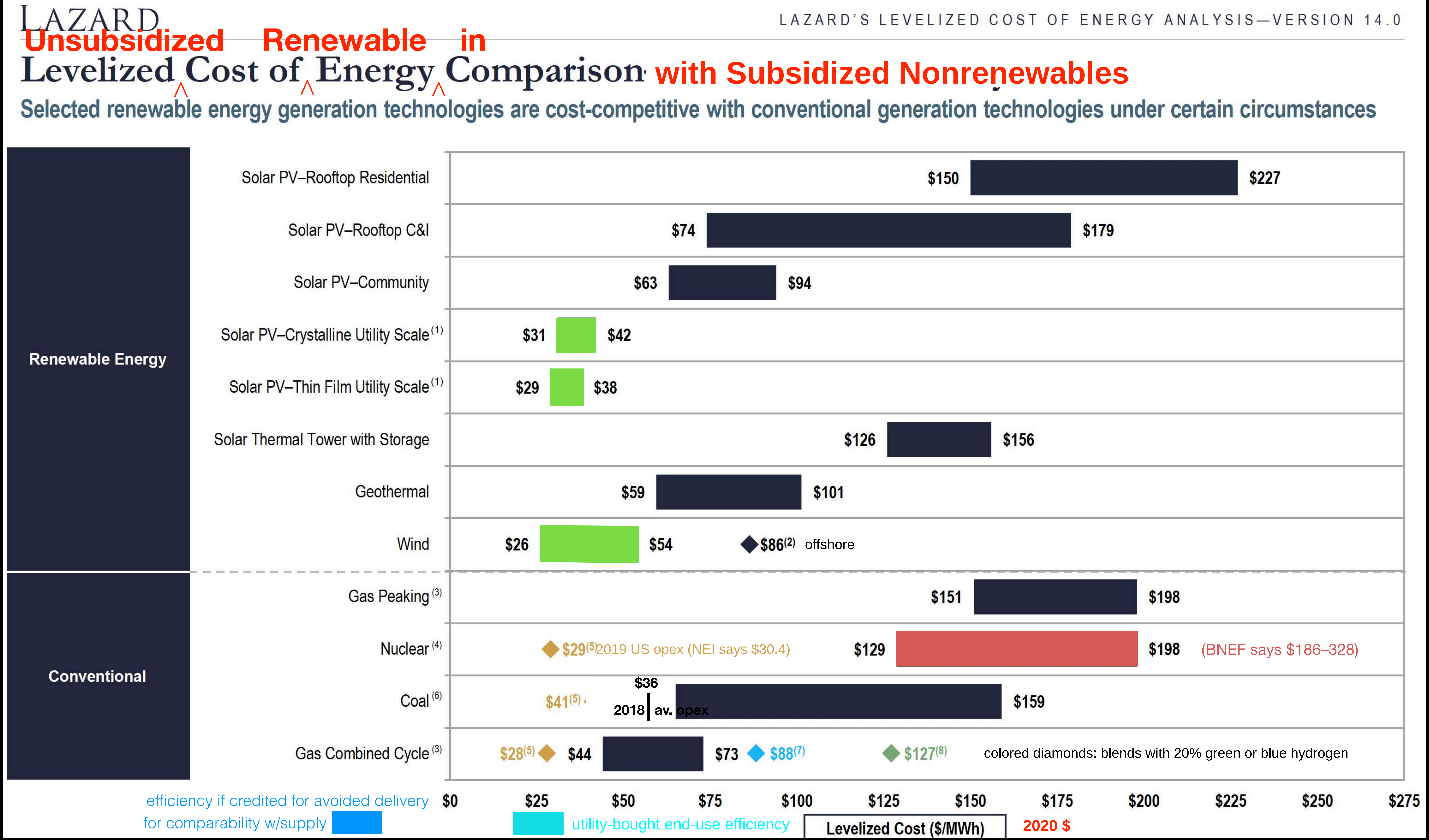
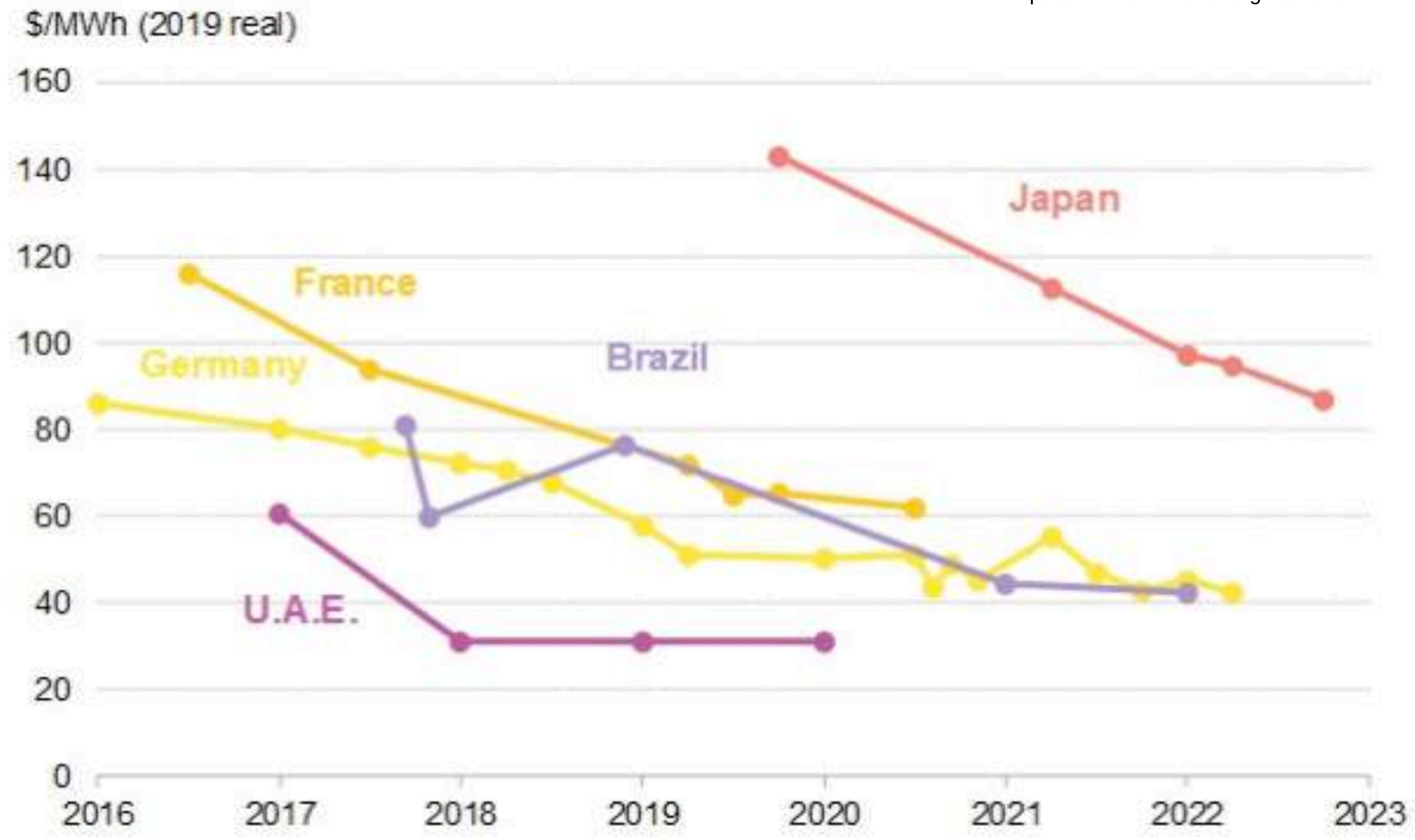
Utility revenues
Breakthrough batteries
No reactive power
Regulatory shifts
New financial & business models
Storage (including EVs)

Lazard's October 2020 view of new US electricity resources' costs



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

Levelized solar auction bids in select countries



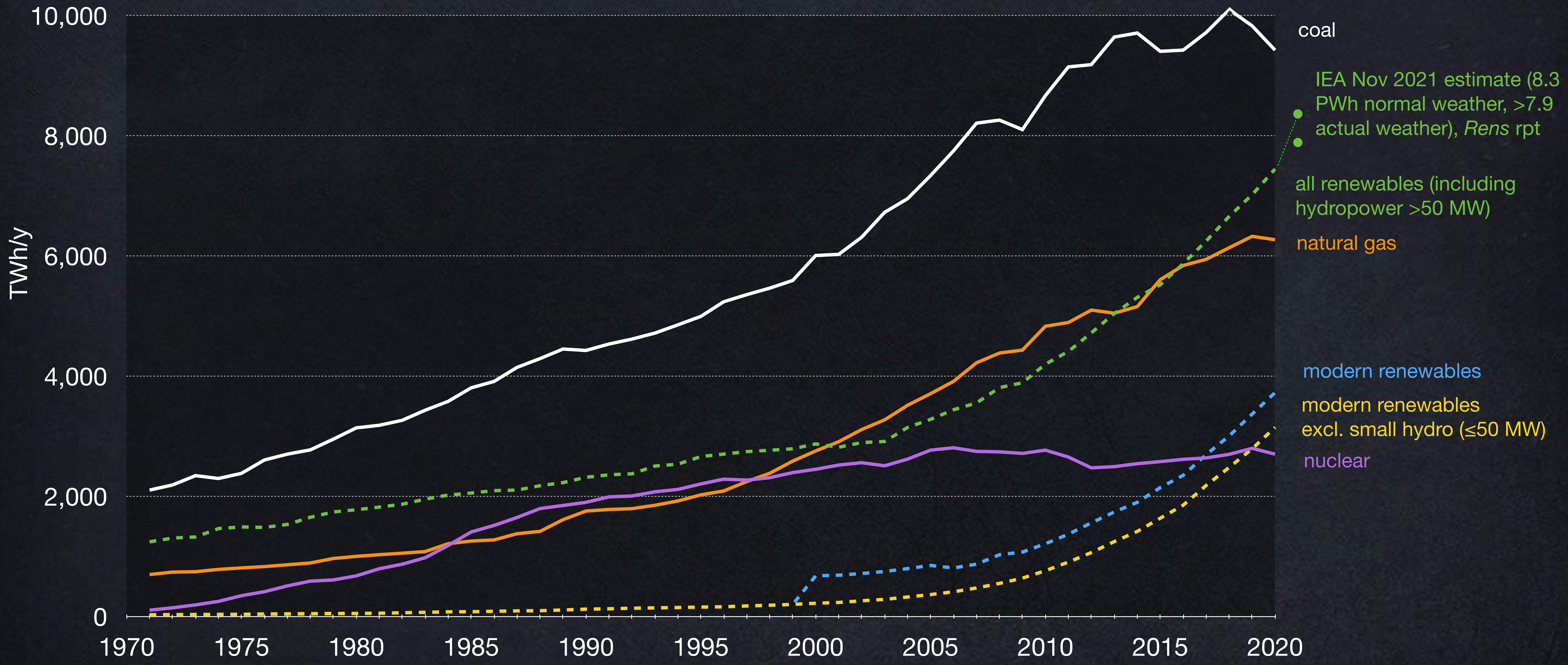
Source: BloombergNEF

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.

Worldwide electricity generation by source, 1971–2020

(These curves are separate, not stacked) (2020 total = 25,815 net TWh, BNEF)

(IEA in Nov 2021 forecasted 2026 renewables at 11.3 PWh, the largest source, w/37% share)



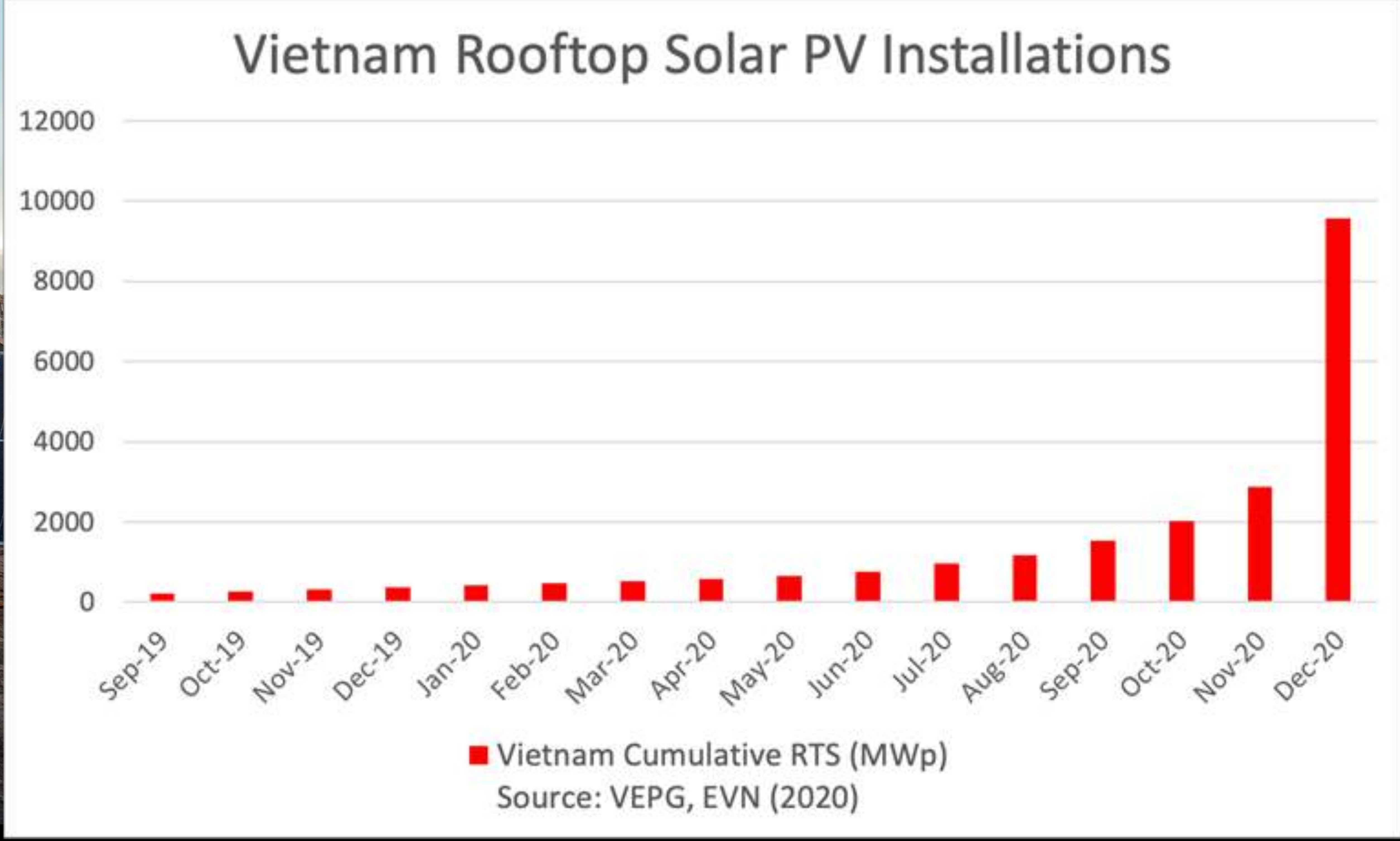
Updated 27 Oct 2021 from A B Lovins *et al.*, "Relative deployment rates of renewable and nuclear power: a cautionary tale of two metrics," *El. Res. & Soc. Sci.* **38**:188–192 (2018), doi:10.1016/j.erss.2018.01.05. 1971–2020 data reconciled from same BP *Statistical Review of Energy* (2021 edition), [slightly over]estimating small hydro share of hydro from BNEF data 2000–05 and adopting BNEF small-hydro data starting in 2006, omitted earlier. (BP data aggregate all hydro of whatever size; BNEF shows small hydro 2006–20 is 13–15% of total hydro generation.) Oil-fired generation (758 TWh in 2020) is not shown.

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

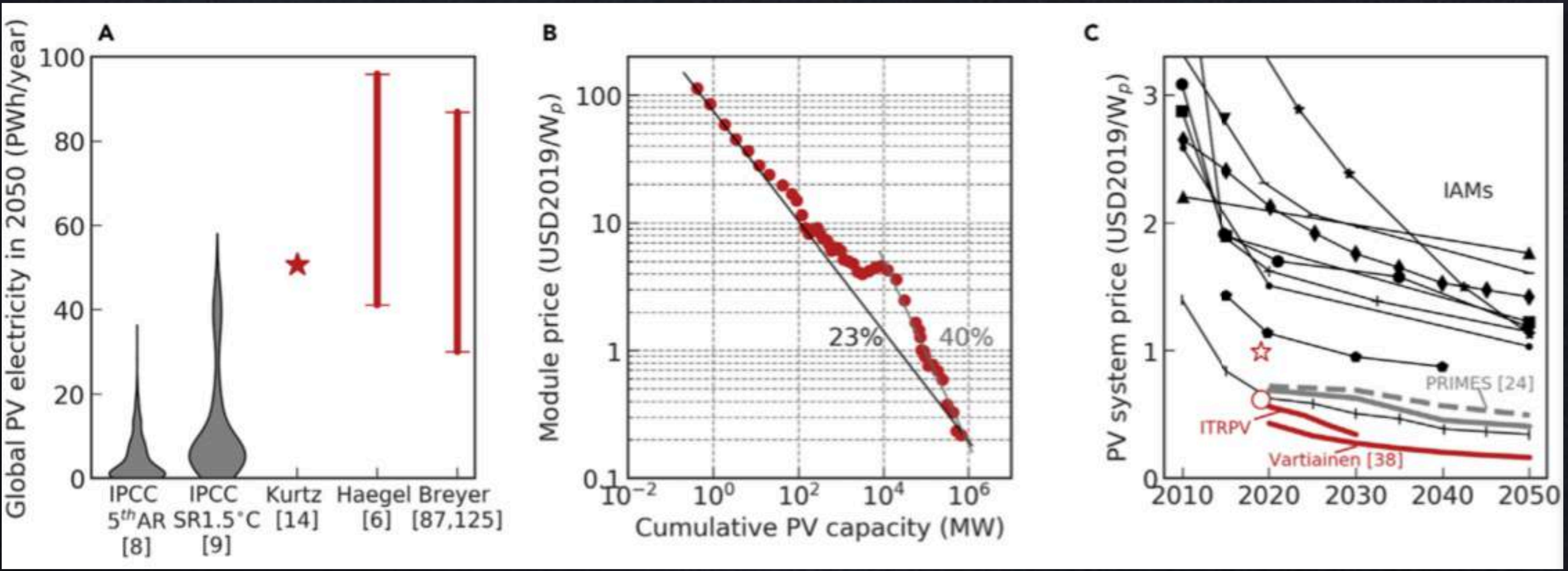
Year-end solar capacity: 2018: 0.1 GW, 2019: 5.5 GW, 2020: 16.5 GW;
of which rooftop solar added 9.3 GW (= 6 coal plants’ output) *in 2020*;
of which 6.7 GW was added *just in December 2020* (to get feed-in tariff).
Coal additions are trailing off, windpower additions rapidly rising.

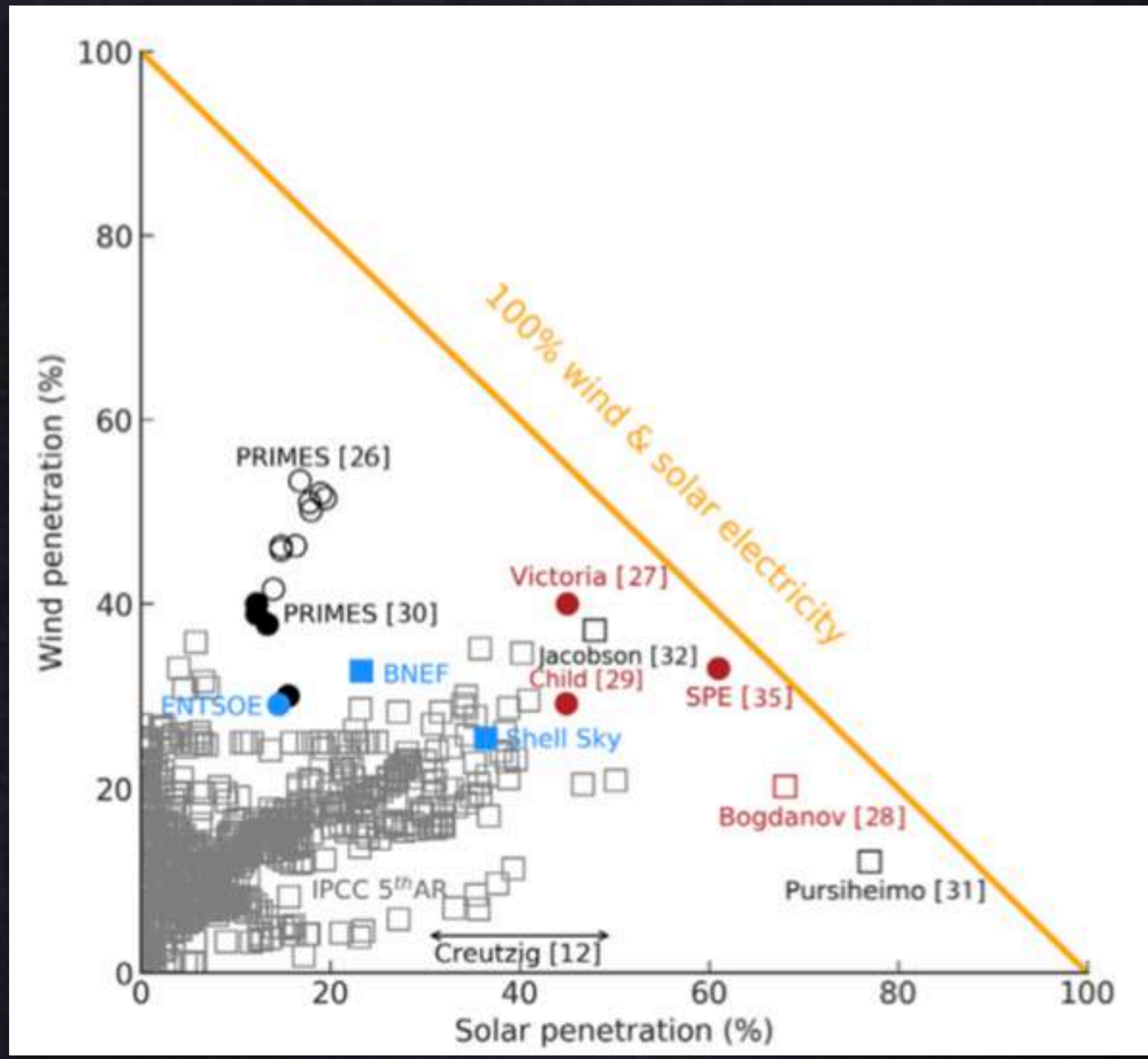
https://www.weforum.org/agenda/2021/02/viet-nam-solar-power-surge/viet-nam-solar-power-surge/

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



Forecasts of low 2050 PV contribution and high price reverse with proper modeling: modern grid integration, new PV cost/learning data, forming price *in* the model





890 IPCC AR5 simulations averaged **4.9** PWh/y PV output in 2050; 311 in the *1.5˚ Special Report* averaged **12.5**; the PV community finds **41–96** (red). Why?

PV modules' experience curve is 23% starting in 1976, but **40%** starting in 2007. Why keep using that 1976 origin today? And why not apply learning *in* the model?

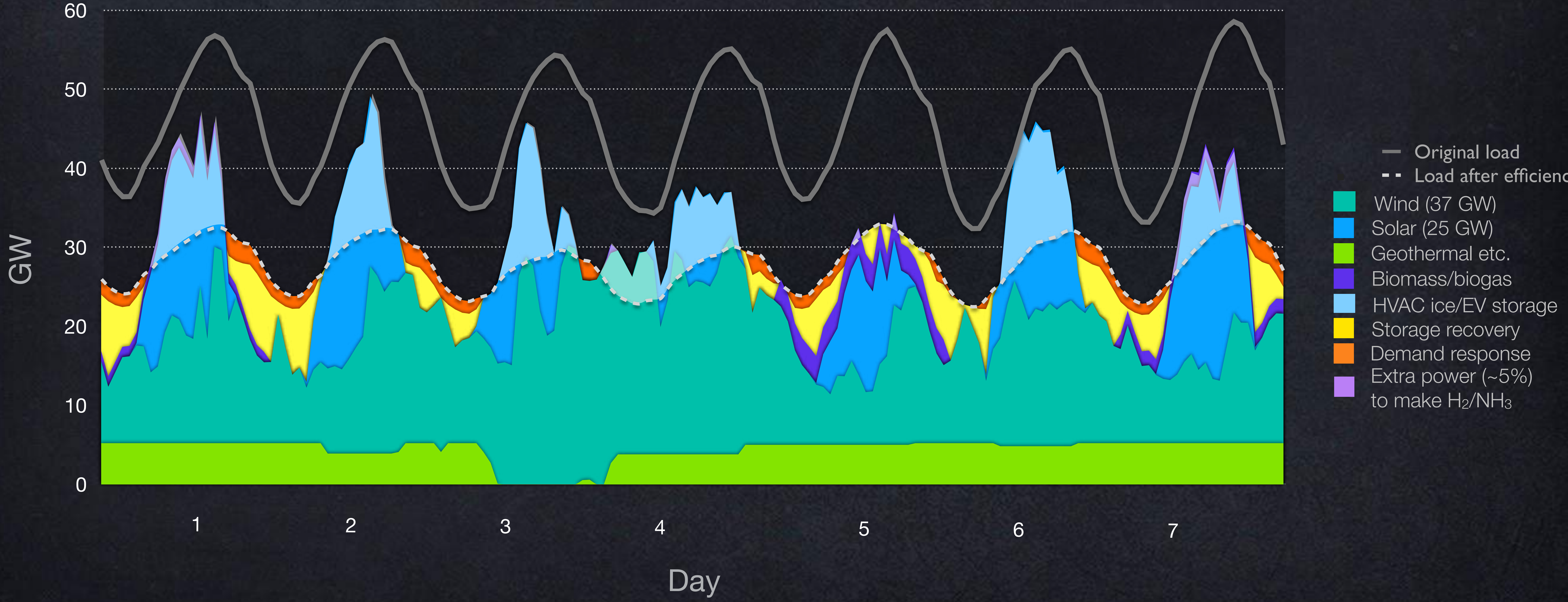
The EC's PRIMES model finds <20% optimal PV, but hourly resolution and modern grid integration find far lower PV prices (red).

European (circles) and global (squares) models—gray for AR5—show consensus forecasts of rather low 2050 renewables, *vs* red models with modern PV costs.

Figs. 2–3, M. Victoria *et al.*, "Solar photovoltaics is ready to power a sustainable future," *Joule* **5**:1041–1056 (19 May 2021), https://doi.org/10.1016/j.joule.2021.03.005.

Choreographing Variable Renewable Generation

ERCOT power pool, Texas summer week, 2050 (RMI hourly simulation, 2004 renewables data



Choreographing Variable Renewable Generation

Europe, 2016–20 best annual renewable % of total electricity consumed

99%

Scotland 2020 (79% without hydro)

79%

Denmark 2019 (BP), 50% wind+solar (2013 windpower peak 136%—55% for all Dec; 2020 data pending)

52%

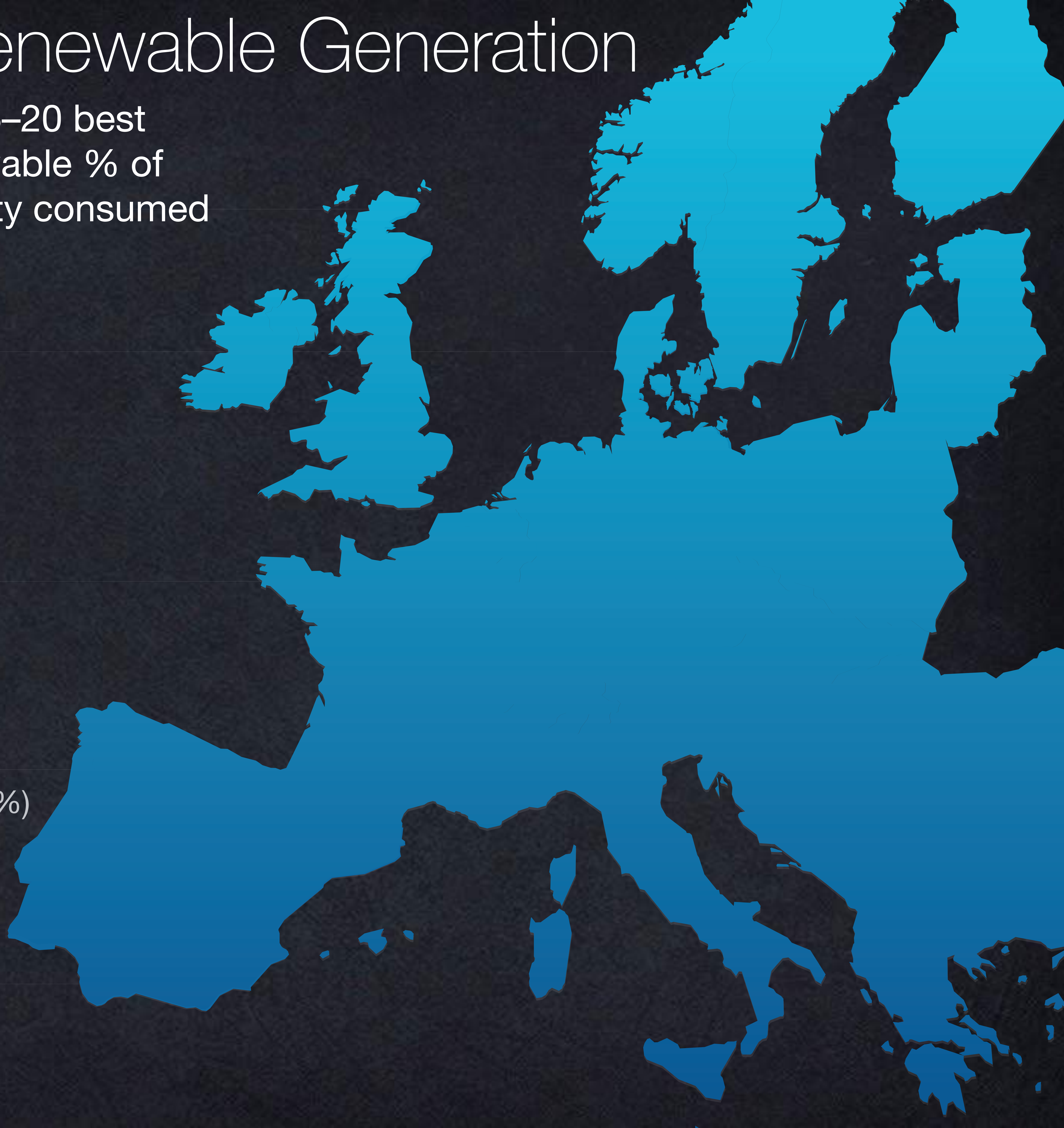
Germany 2020 (2016 peak 88%, 2018–20 ~90–100%, >100% for 12 h 27–28 Mar 2021)

66%

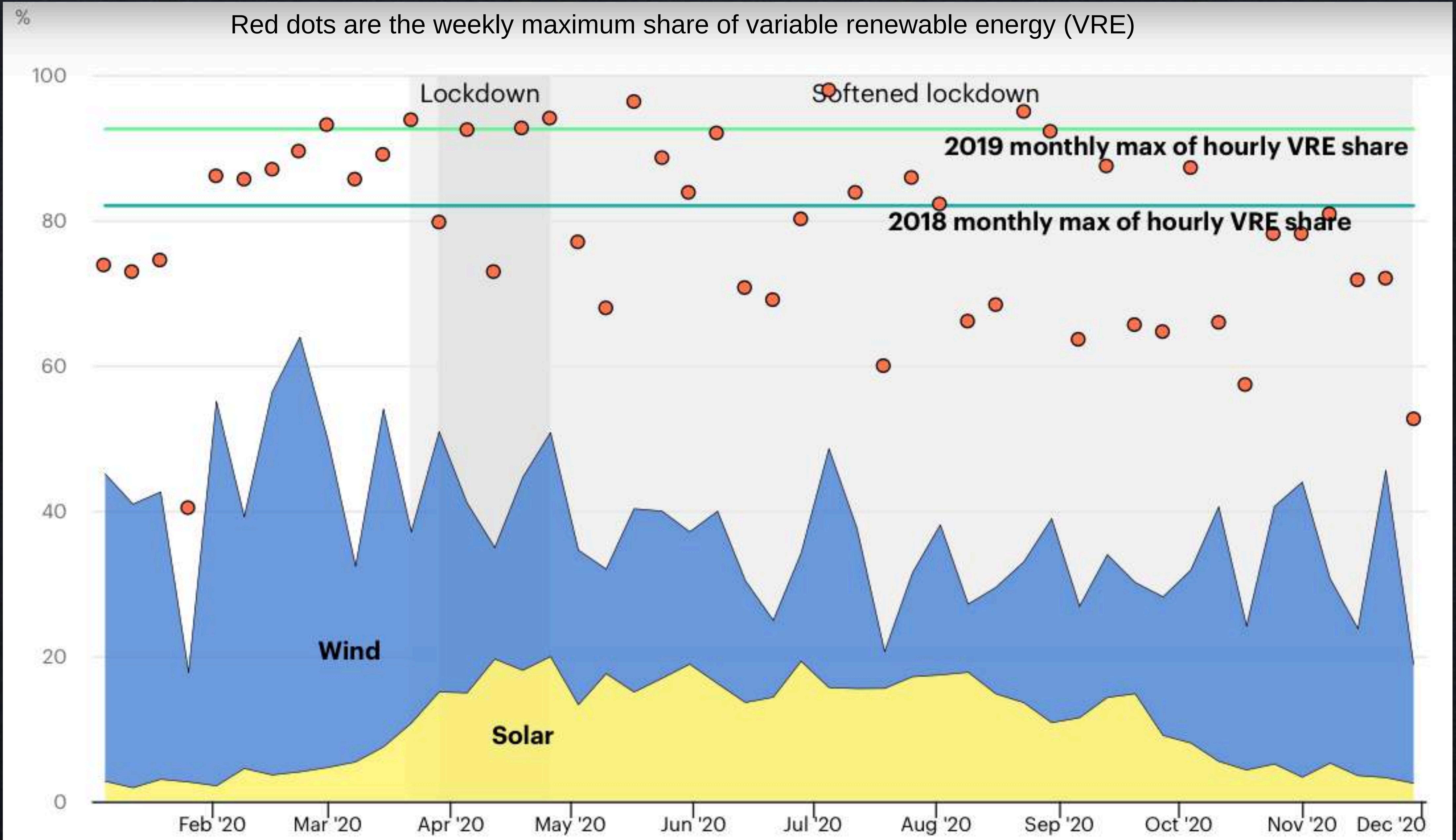
Portugal (2018, 42% without hydro) (2011 & 2016 peak 100%)

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

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)

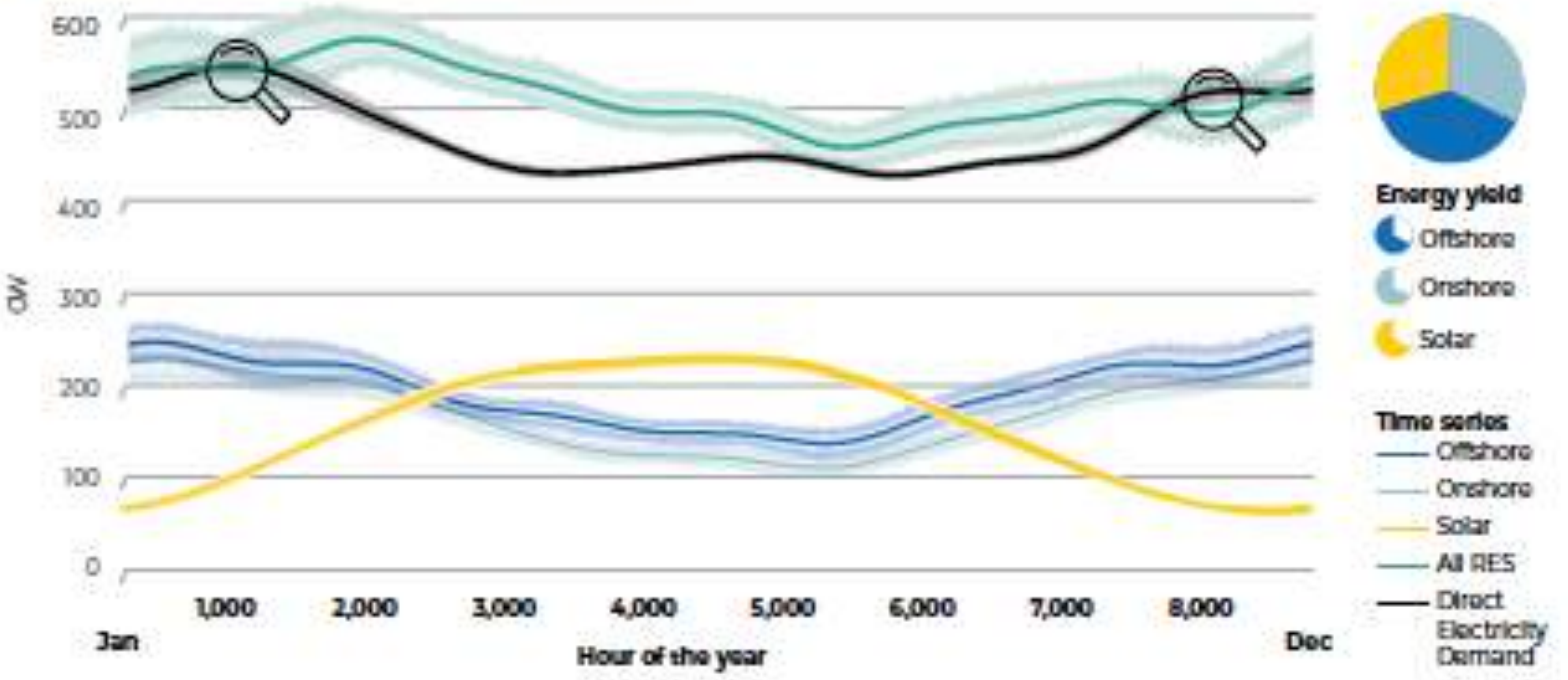
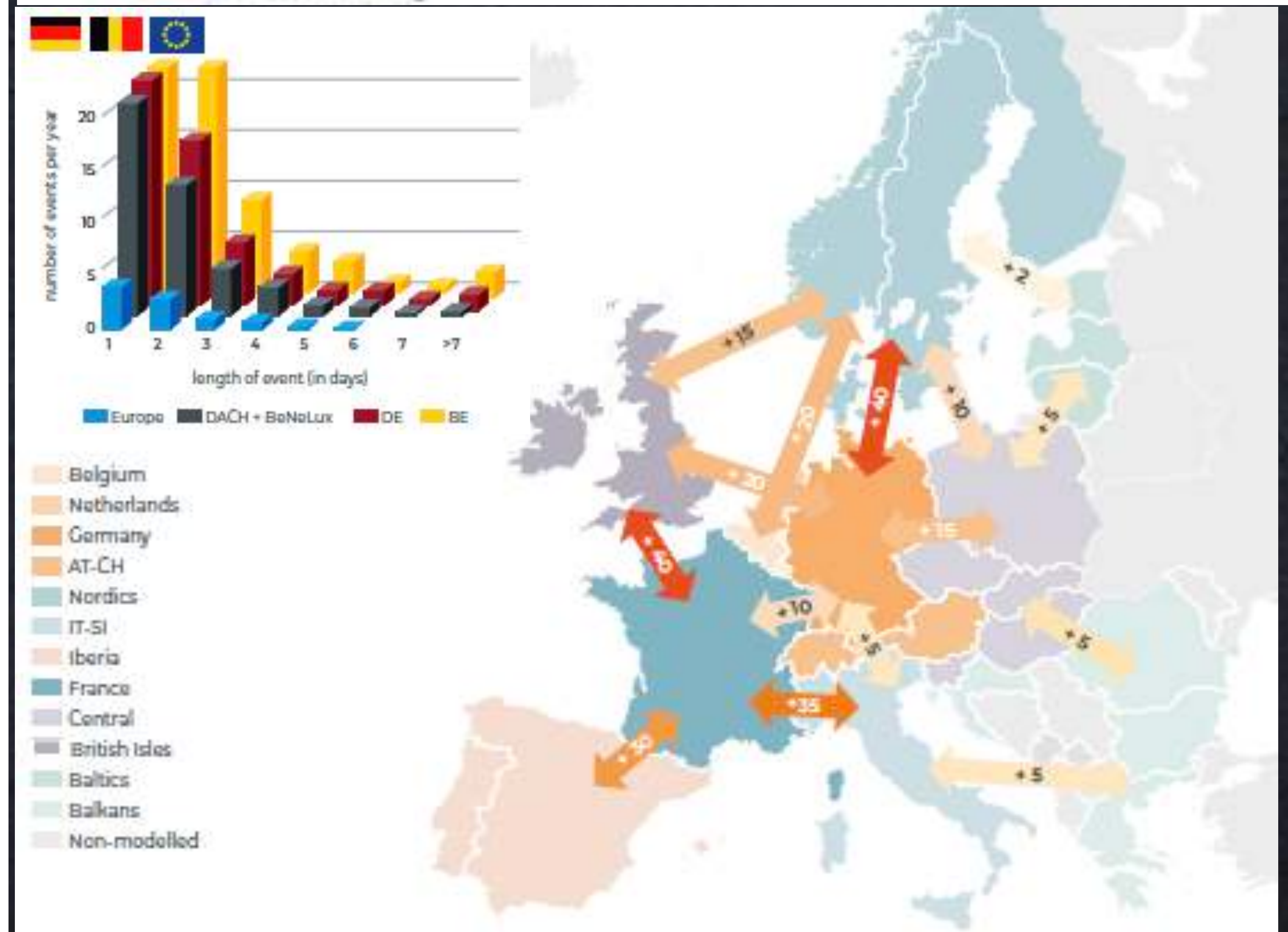


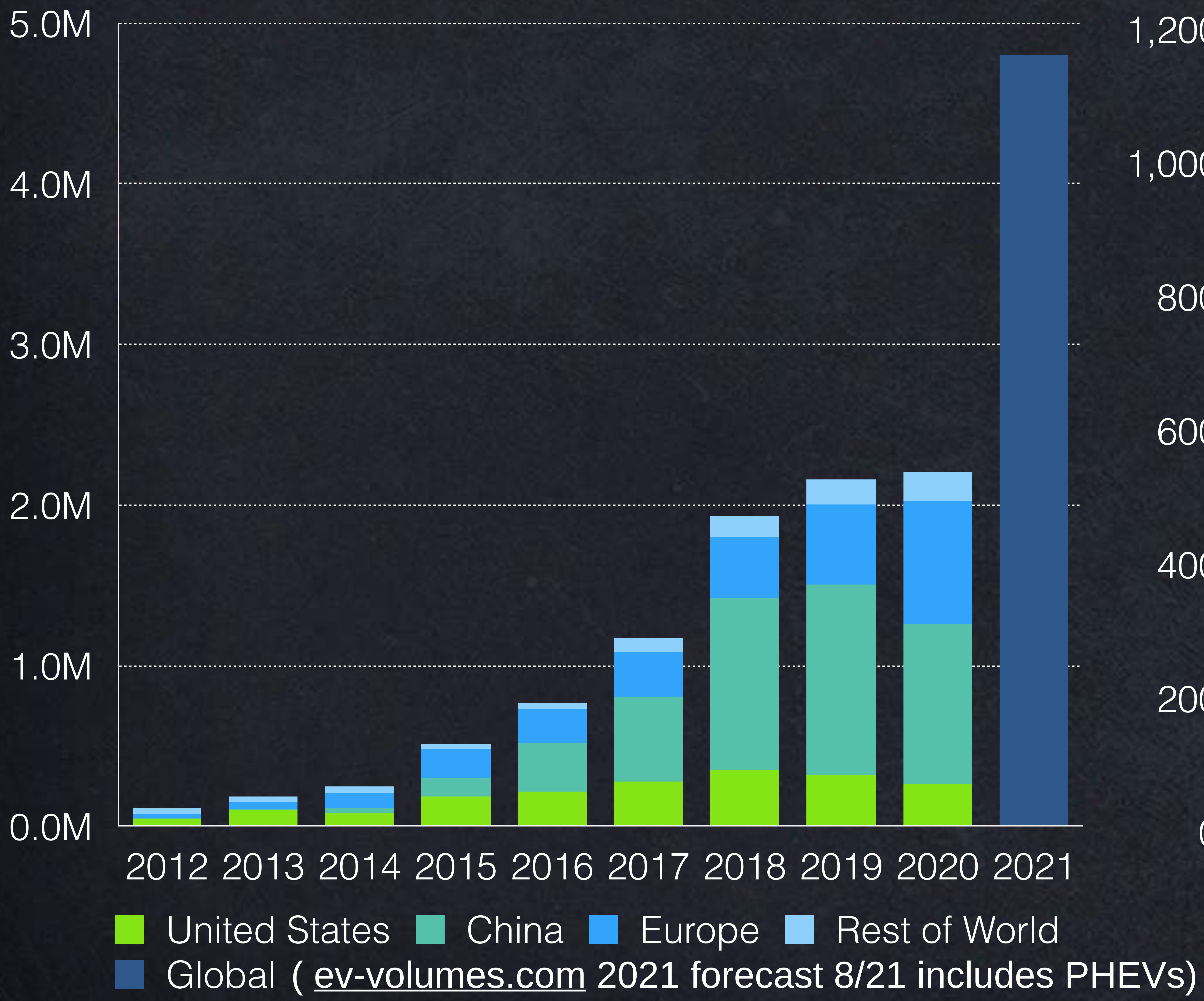
FIGURE 2: STRONG ELECTRIFICATION OF END USE (AS UNDER THE ELEC-PATHWAY) SAVES UP TO 1,800 TWH AT THE EUROPEAN LEVEL COMPARED TO THE MOL-PATHWAY. DIRECT ELECTRICITY DEMAND UNDER THE ELEC-PATHWAY INCREASES BY 70% COMPARED TO TODAY'S DEMAND. A TRIPLING OF TODAY'S RES EXPANSION RATE IS NEEDED TO MEET THIS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



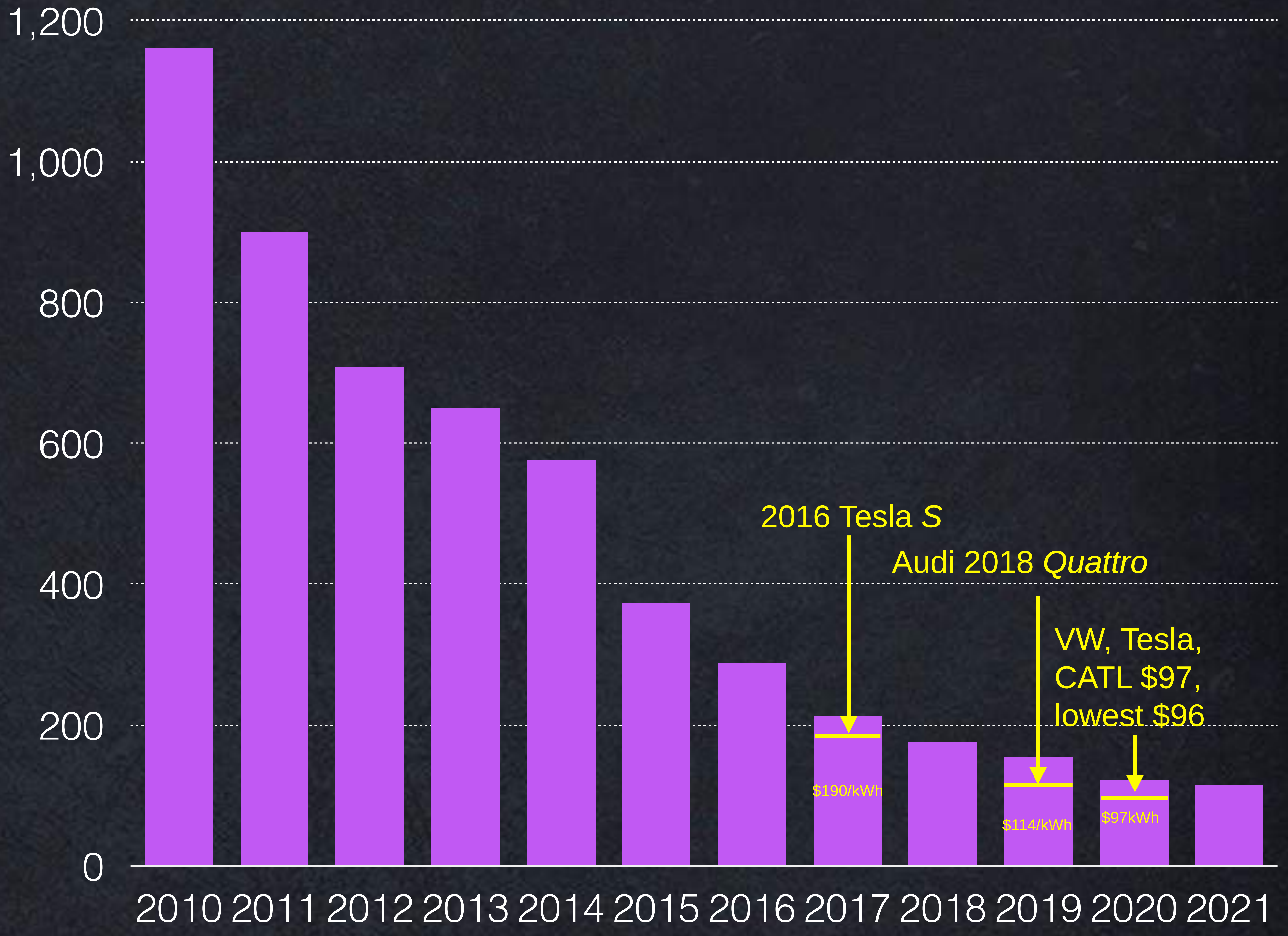
Elia Group/50Hertz, *Roadmap to Net Zero*, 19 Nov 2021, p 7, https://www.50hertz.com/en/News/FullarticleNewsof50Hertz/11597/elia-group-publishes-roadmap-to-net-zero-our-vision-on-building-a-climate-neutral-european-energy-system-by-2050. "RES" ≡ renewable energy supply.

Global electric vehicle sales are growing at a ~65% CAGR, with best battery pack prices falling below the magic $100/kWh (2020 $)

BEV (no PHEV) annual sales, 2012–2021



Battery pack price, 2010–2021 (2018 $/kWh)

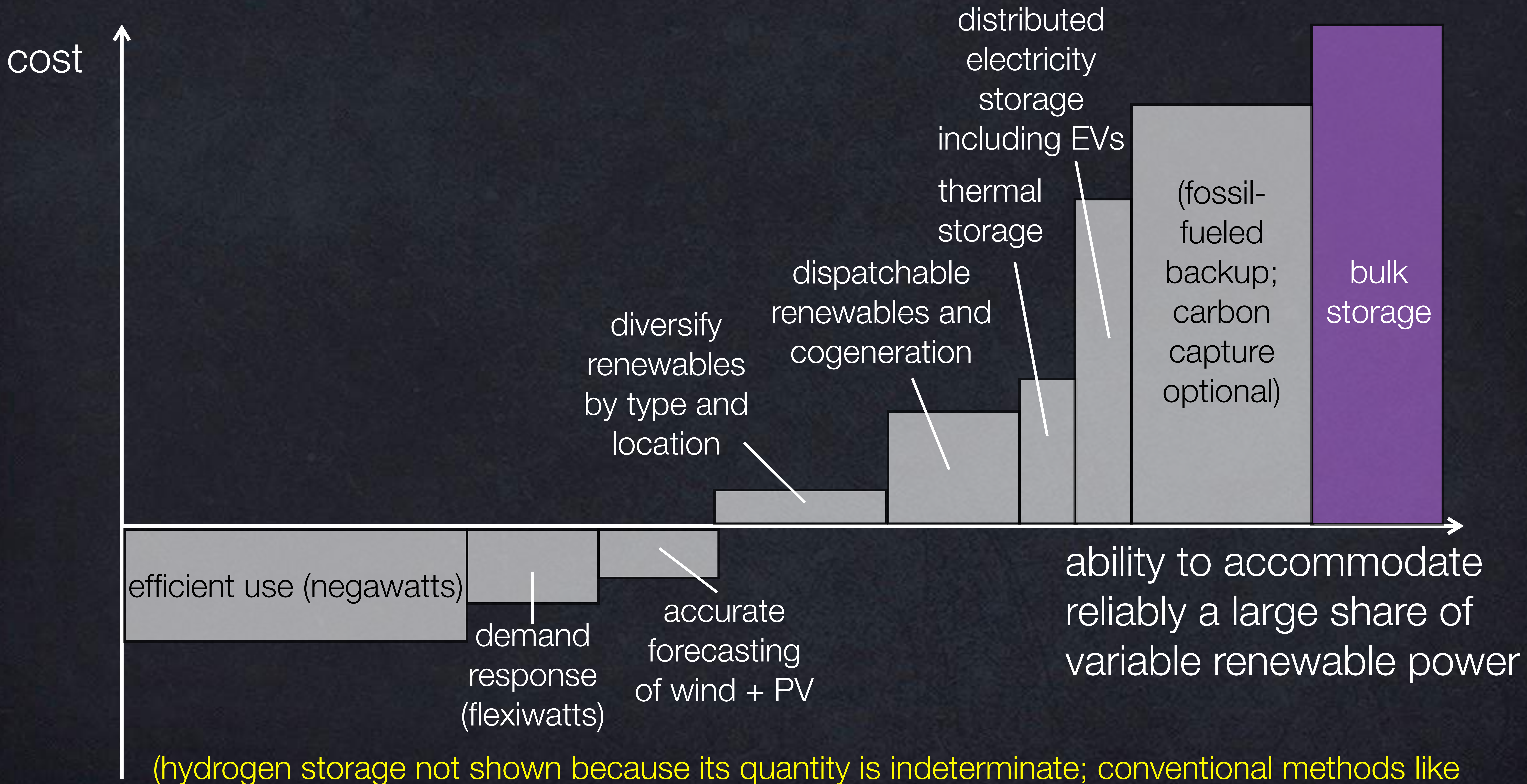


(BNEF in August 2021 forecasted $58/kWh by 2030, with 1 TWh/y of capacity sales in 2025 and >2 in 2029)

Sources: BNEF (but https://insideevs.com/news/396177/global-ev-sales-december-2019/ puts 2019 sales slightly higher at 2.21M, and https://www.ev-volumes.com/country/total-world-plug-in-vehicle-volumes/at 2.268M), then 4.8M in 2021. Tesla *S*: https://www.greencarreports.com/news/1103667_electric-car-battery-costs-tesla-190-per-kwh-for-pack-gm-145-for-cells *Quattro*: https://electrek.co/2017/06/28/audi-electric-car-battery-cost/for-2016-145kwh-cell-cost-volt-margin-improves-3500; 2020: https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/. 2021: https://www.bnef.com/insights/27865.

Grid flexibility resources

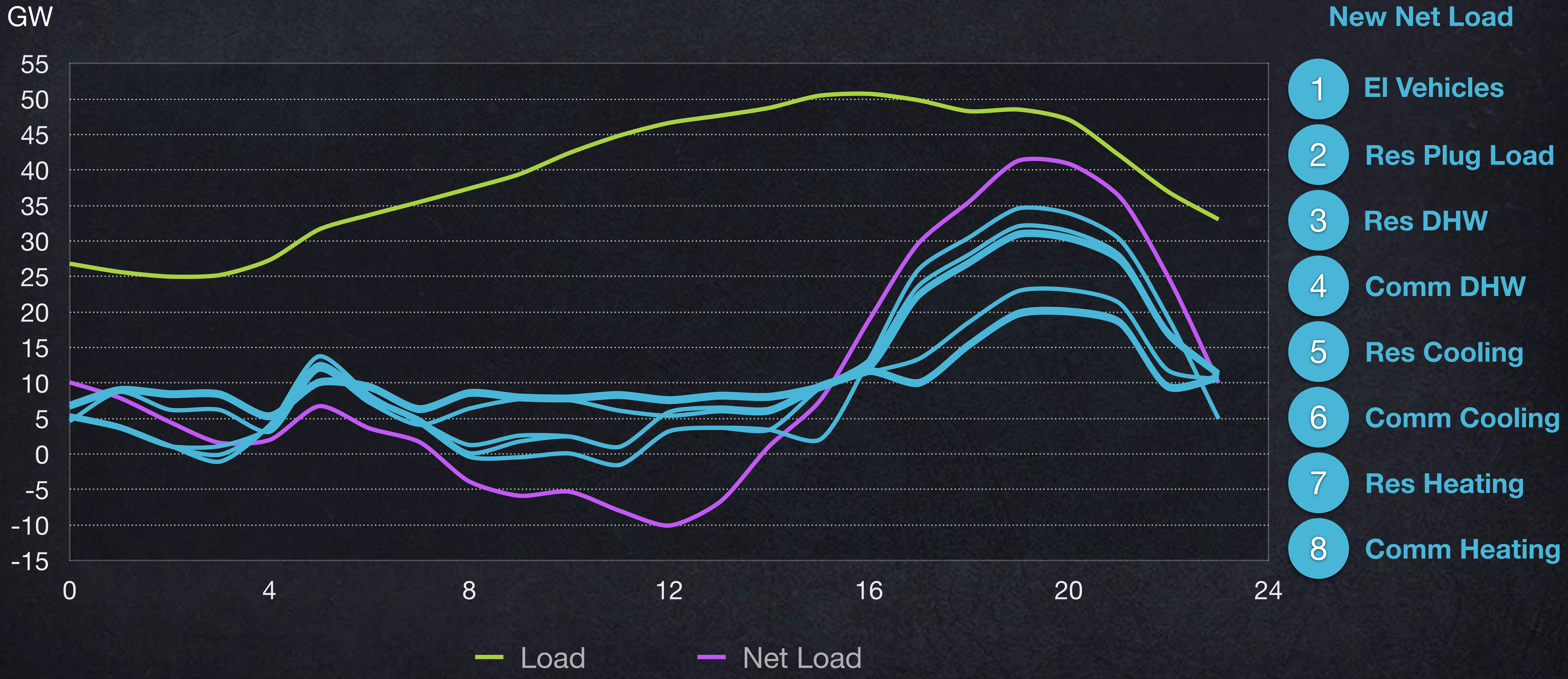
(all values shown are conceptual and illustrative)



(hydrogen storage not shown because its quantity is indeterminate; conventional methods like pumped hydro included in bulk storage; thus ten carbon-free methods in total)

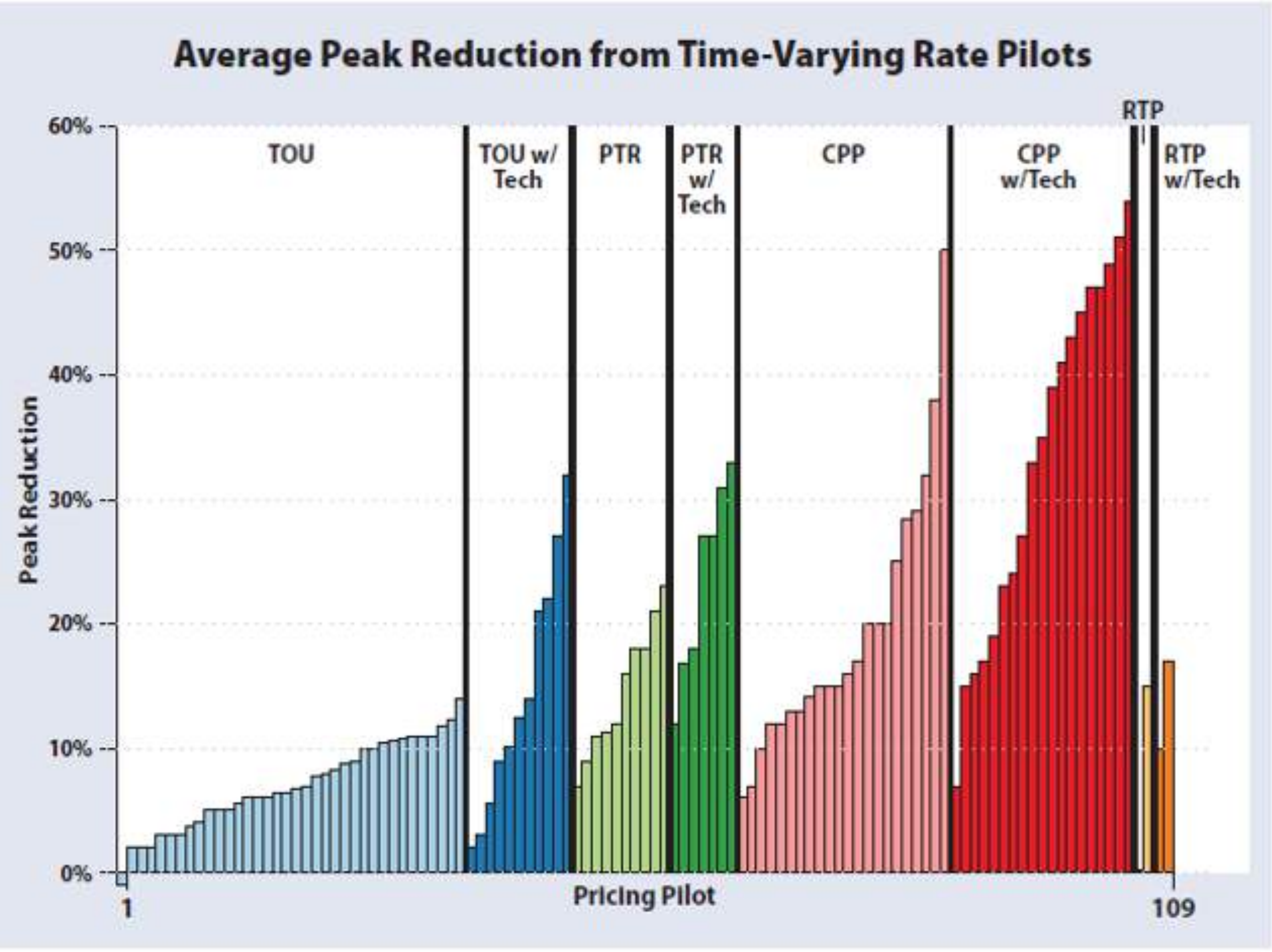
Flexible loads: goodbye “duck curve”

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. *How 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.

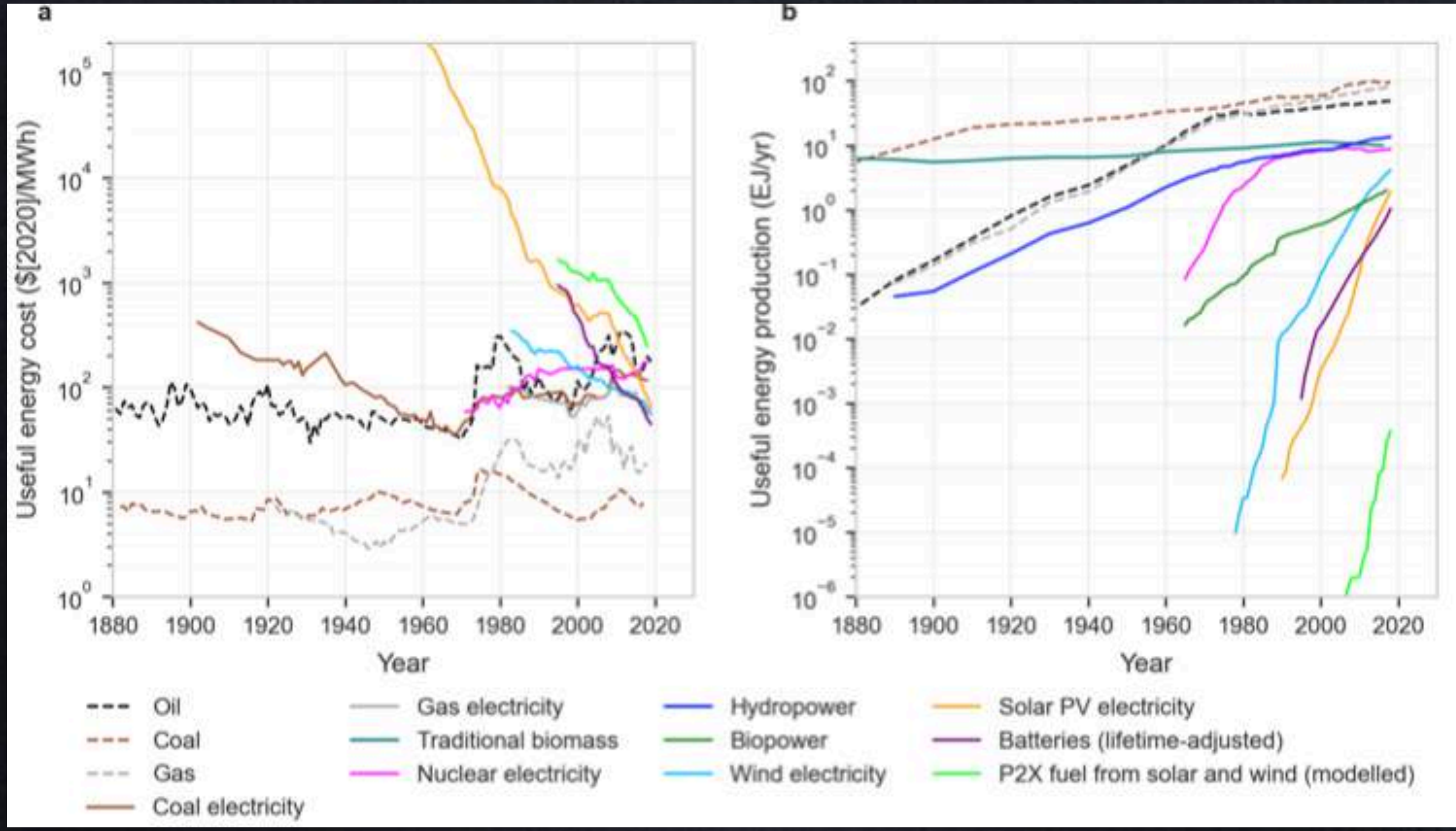
"Time-Varying and Dynamic Rate Design," 2012, Regulatory Assistance Project and The Brattle Group, https://www.raponline.org/knowledge-center/time-varying-and-dynamic-rate-design/

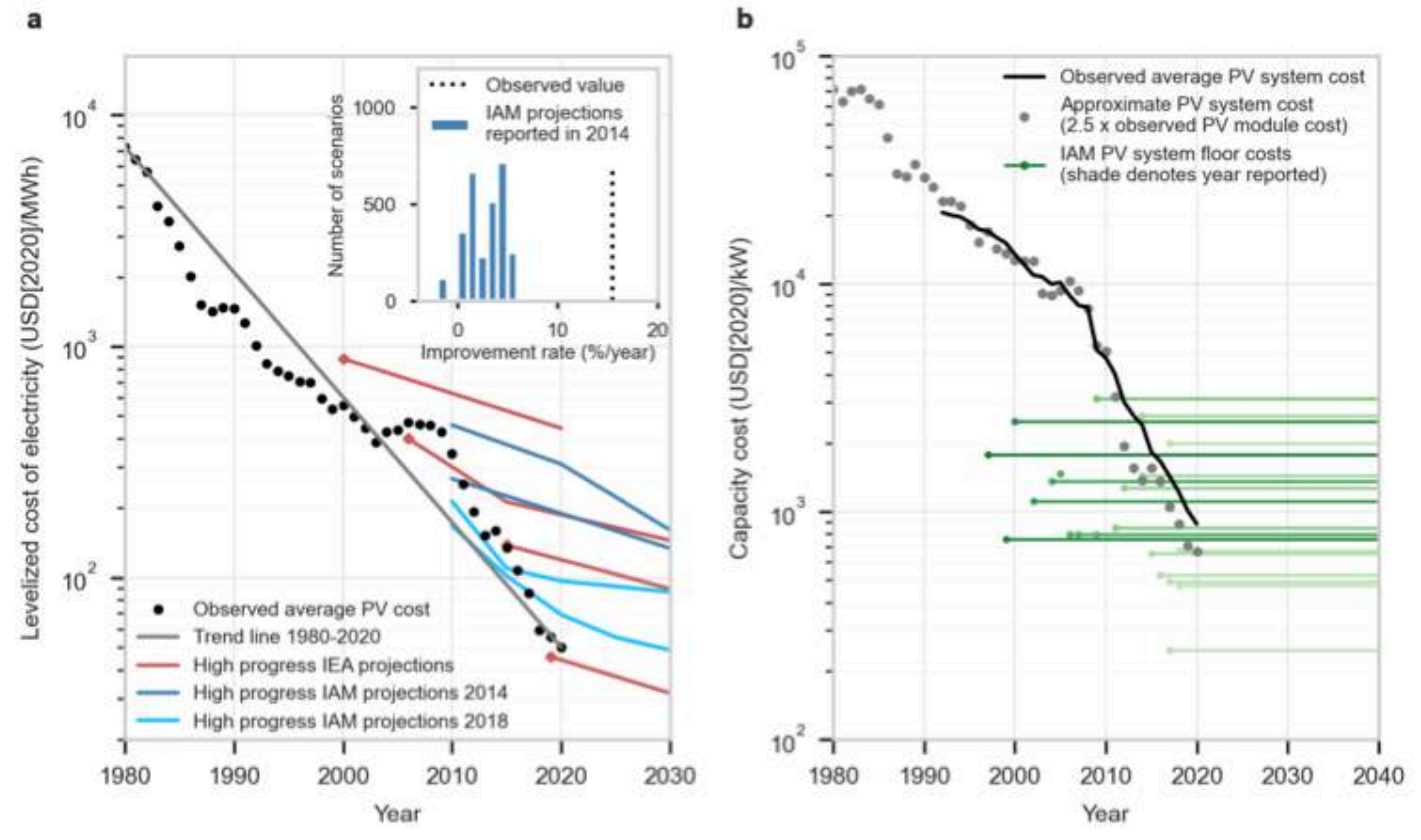
Energy-efficient buildings displace and outcompete electricity storage

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

Forecasts of low 2050 PV contribution and high price reverse with proper modeling using *empirical* costs





Real costs or prices of useful energy by technology, 1880–2020.

No wonder PV output has grown 44%/y for past 30 y, wind 23%/y.

Histogram: 2,905 Integrated Assessment Models predicted PV costs in 2010–20 would fall by 2.6%/y mean, <6% max. *Actual: 15%/y*. Only the fastest-growth IAM and IEA projections are graphed (colored lines).

PV “floor costs” in diverse IAMs from 1997 (dark green) to 2020 (light green) constrained price drops modeled, and utterly failed to predict actual behavior (black). Virtually the entire literature was systematically, comprehensively wrong—yet it still drives policy.

Almost all climate-choice models’ solar forecasts diverge sharply from reality.

Figs. 1–2, R. Way *et al.*, “Empirically grounded technology forecasts and the energy transition,” INET Oxford 2021-01 (14 Sep 2021), https://www.inet.ox.ac.uk/files/energy_transition_paper-INET-working-paper.pdf.

Easter Parades on Fifth Avenue, New York, 13 years apart

1900: where's the first car?

1913: where's the last horse?

Images: L, National Archive, www.archives.gov/research/american-cities/images/american-cities-101.jpg; R, shorpy.com/node/204.
Inspiration: Tona Seba's keynote lecture at AltCar, Santa Monica CA, 28 Oct 2014, http://tonyseba.com/keynote-at-altcar-expo-100-electric-transportation-100-solar-by-2030/

Challengers with just a few percent market share routinely trigger capital flight from incumbents

Incumbent peaked…	*…at challenger % market share…*
UK steam	3%
UK gas lighting	2%
US non-farm horse sales	3% (1910)
European utilities	3%
Peabody Coal	4%
Nokia	1%
Kodak	3%

K. Bond, "Myths of the energy transition: Renewables are too small to matter," Analyst Note, Carbon Tracker Initiative, Oct 2018, http://carbontracker.org/wp-content/uploads/2018/10/CTI_Myths_Series_1_Renewables-too-small.pdf; horse-sales data point from Tony Seba

Recent world energy peaks

Peak nuclear power output	2006
Peak coal use	2013
Peak automobile sales	2017
Peak fossil-fueled electricity generation	2021
Probably peak oil, fossil fuels, and CO_2 emissions	2019

A. Lovins & K. Bond, “Can a virus and viral ideas speed the world’s journey beyond fossil fuels?,” *Environ. Res. Letts.* **16** (2021) 020201, https://doi.org/10.1088/1748-9326/abc3f2