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INSTITUTE

Electricity revolution　電力革命

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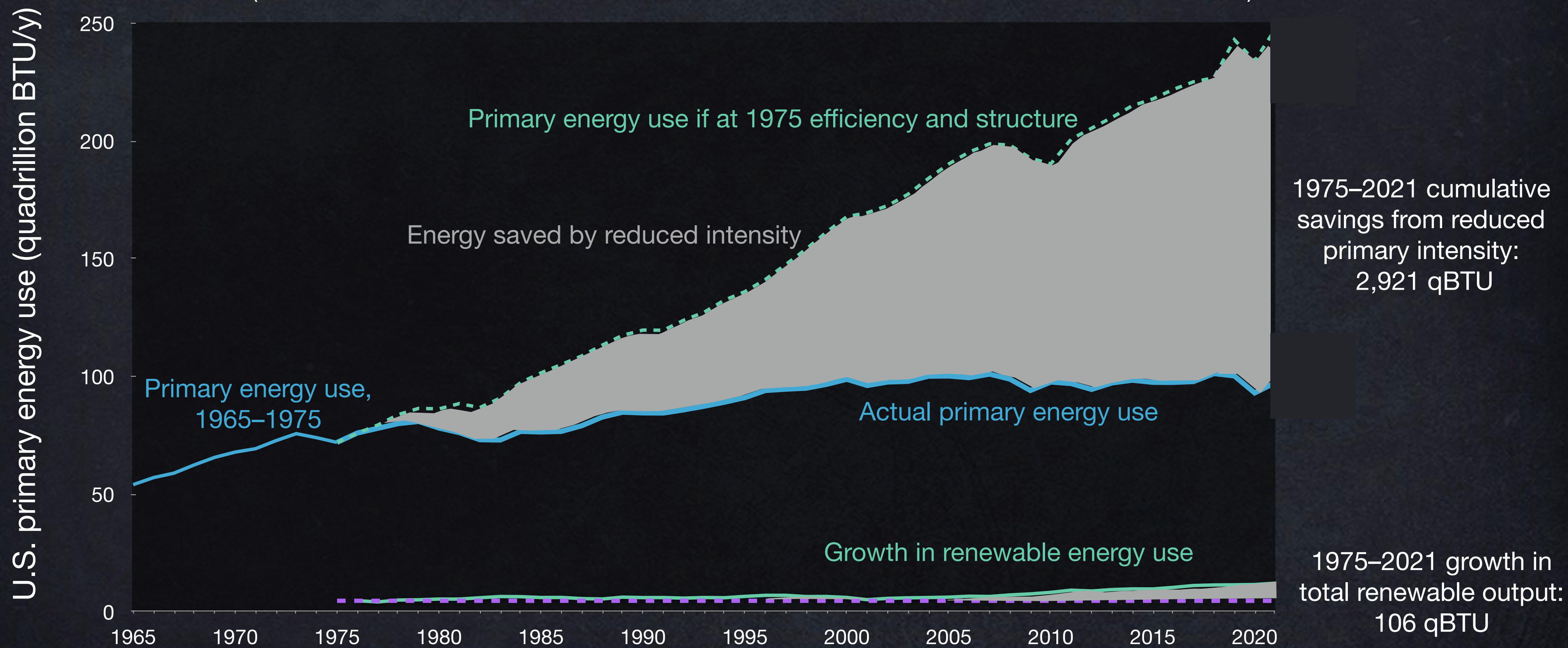
自然エネルギー転換を加速する　2023年3月8日　東京都

REvision 2023, Tōkyō, 8 March 2023

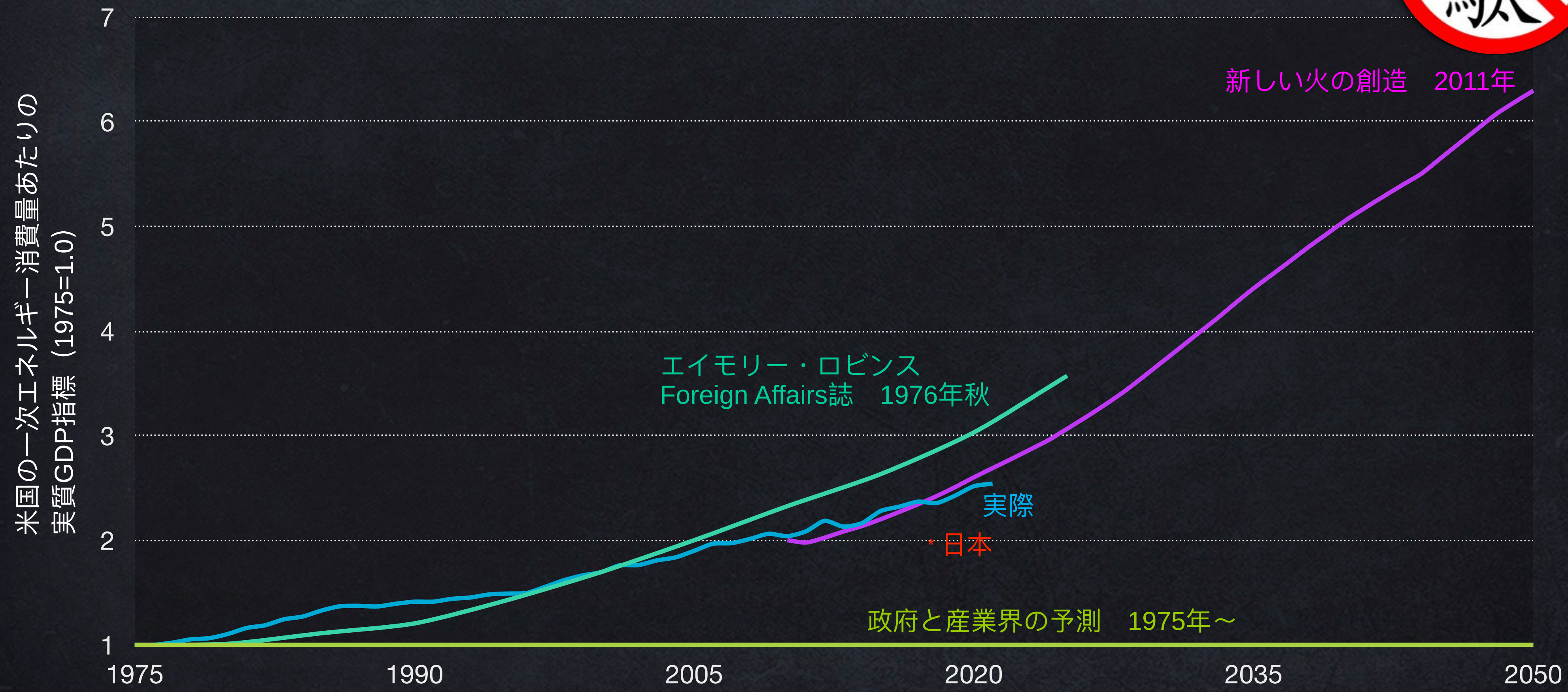
Reduced energy intensity has had 28× the impact of renewable growth

(United States, 1975–2021, not weather-normalized, USEIA data)



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）



US office buildings: >5–10× best-efficiency gains in 5 years

(site energy intensities in kWh/m²-y; US office median ~293)

…➞108 (–63%)
2010–11 new

…36 (–88%)
2015 new

…21 (–93%)
…and in Germany, 2013 new (office and flat)

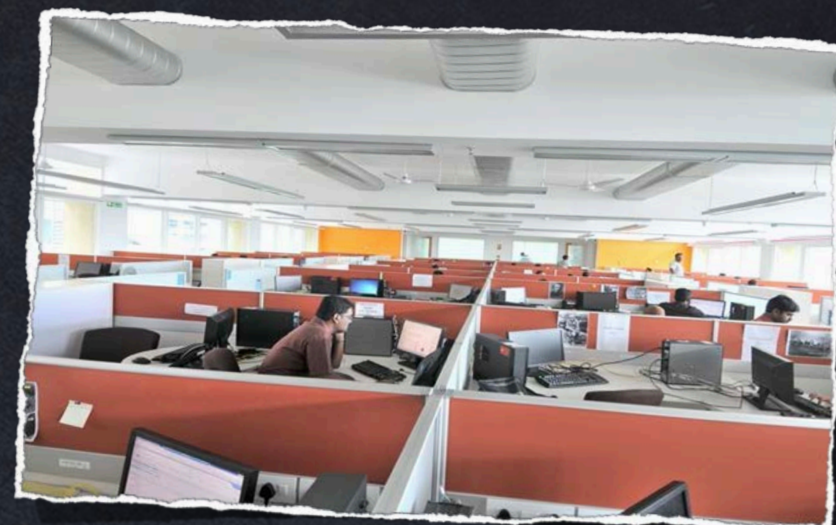
~277➞173 (–38%)
2010 retrofit

284➞85 (–70%)
2013 retrofit

386➞107 (–72%)
2015 Japan retrofit

Yet all these technologies existed well before 2005!

インドの新しい商業ビルは5倍以上の効率性

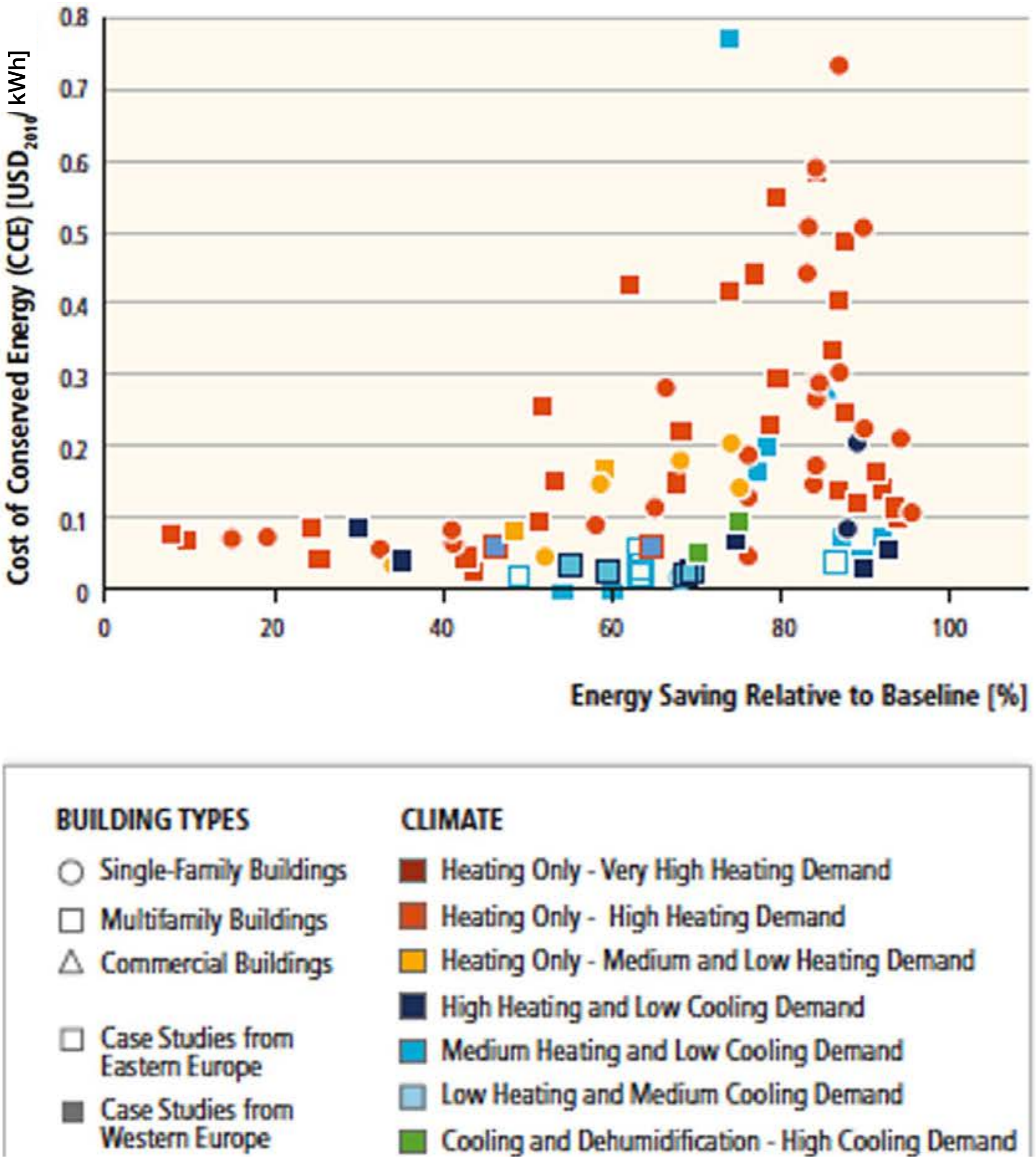


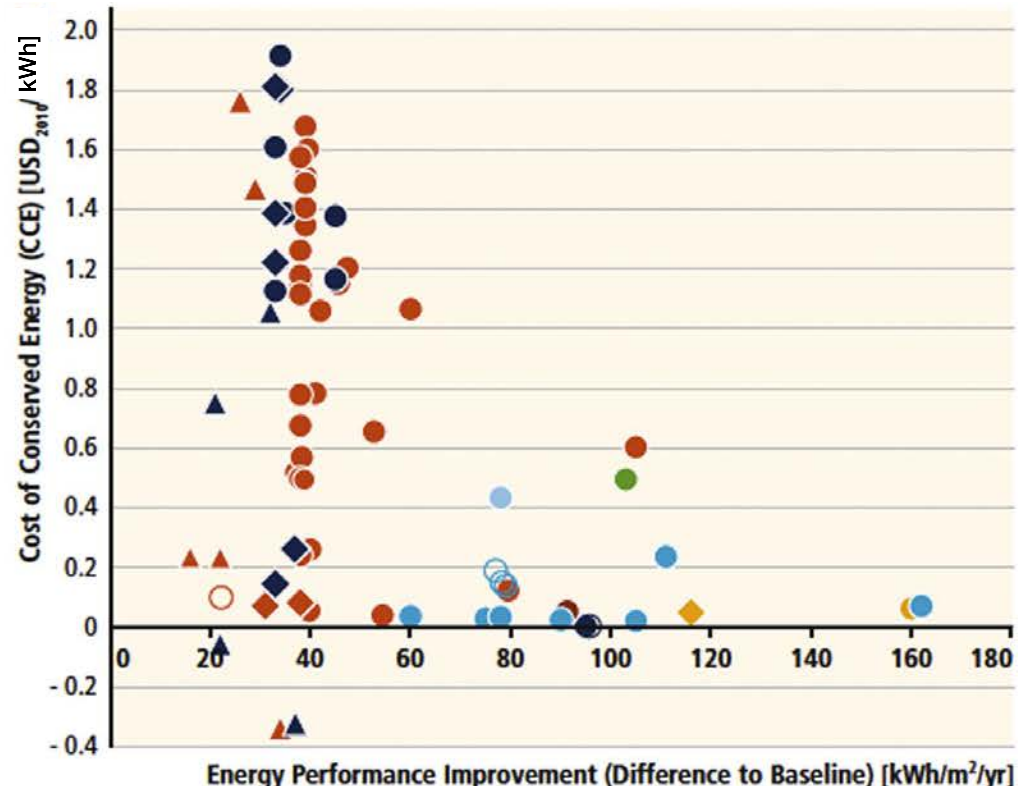
6つの街の22k㎡のオフィス地区にあるInfosysの150万㎡のオフィス（2009-2014）

環境パフォーマンス指数は66kWh/㎡・年に80%改善

初期投資は通常より10〜20%下がり、より快適に

Courtesy of Peter Rumsey PE FASHRAE (Senior Advisor, RMI) and Rohan Parikh (then at Infosys in Bengaluru, now at McBERL)



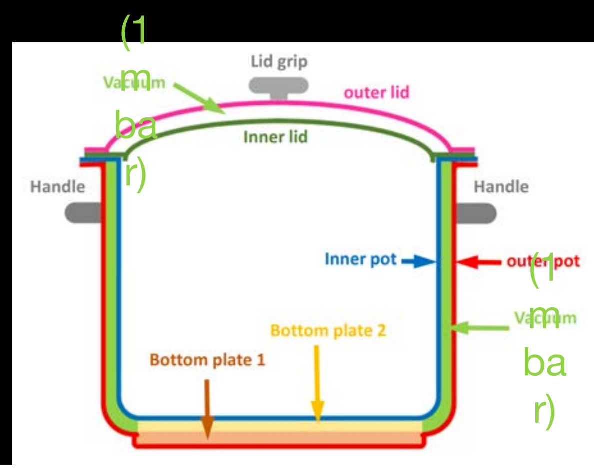


IPCC第5次評価報告書（2014）によると、効率を意識したヨーロッパの新築（左）および改修（右）の建物では、90%以上の節約まででは節約エネルギーのコストが大幅に増加しないことを報告している。表中のいくつかのデータではより高いコストを示しているが、本来はそうした必然性はない。

電気を節約し、ガスを置き換える
最先端の超効率的な家電製品
スイスの2つの例

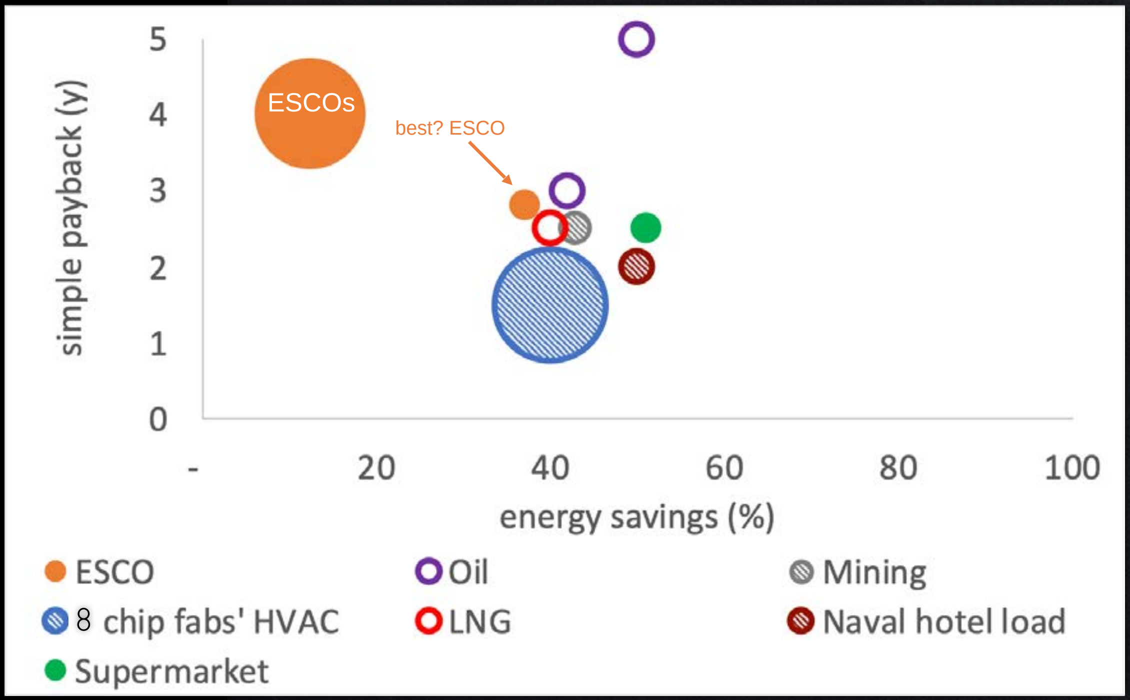
9〜20 kWt、200 krpm DHWヒートポンプ
直径約8cm、カルノー効率60%以上で
COP ＝ 6〜15（△T ＝ 13〜31℃）
例： 13〜31℃から必要な44℃に加熱した場合

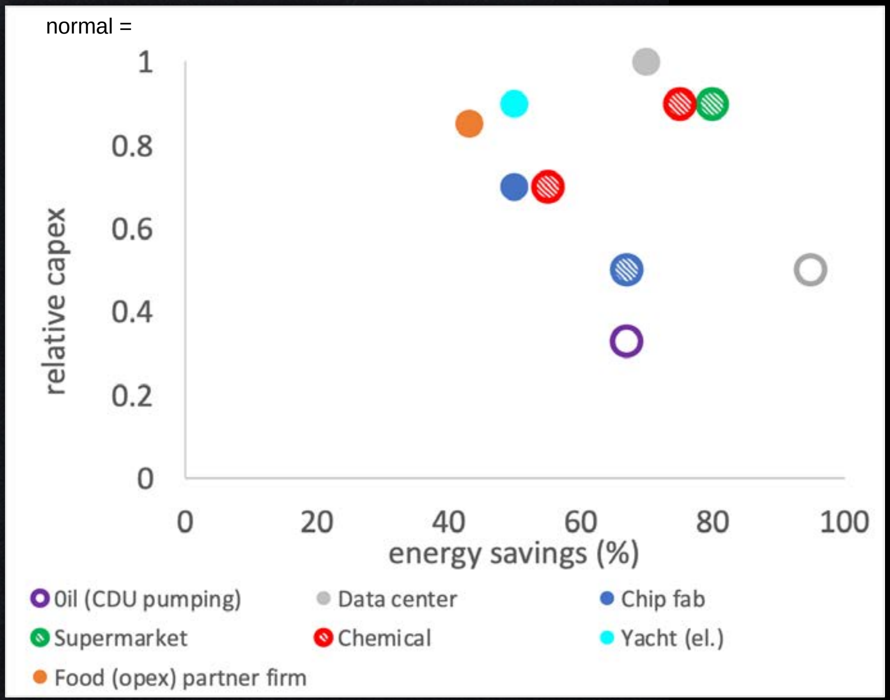
吸引式真空鍋よりも2–4.5倍効率的な
優れた電気伝導調理システム



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

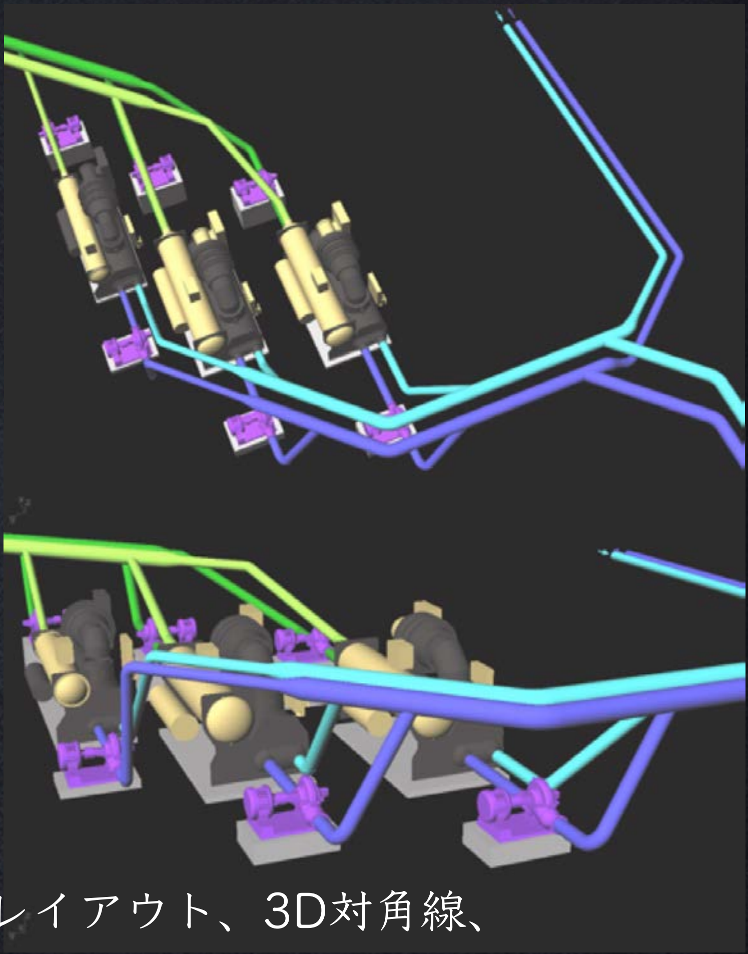
薄く、長く、曲がっている

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
ー太く、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

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 • © 2018 The Author(s). Published by IOP Publishing Ltd
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 by around midcentury?

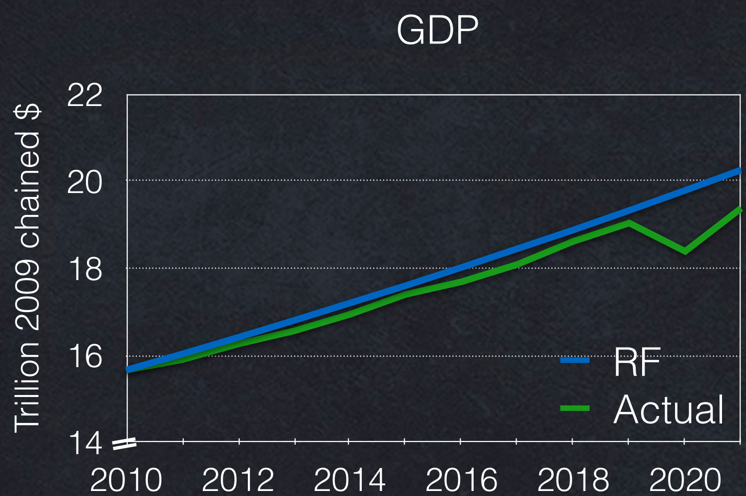
η = [normal] end-use efficiency

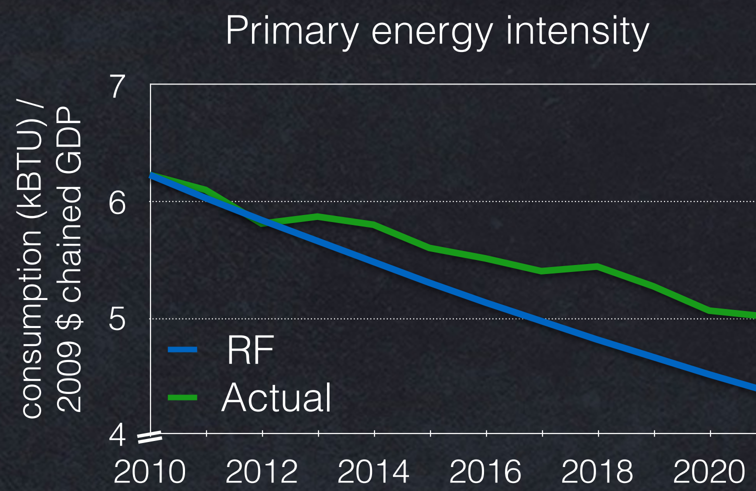
buildings: ~4–≥10η
automobiles: ~4–8η
trucks: ~3–4η
airplanes: ~3–8η
factories: ~2η old, ~2–10η new, →∞ if avoided
cement and steel: ~2–4η

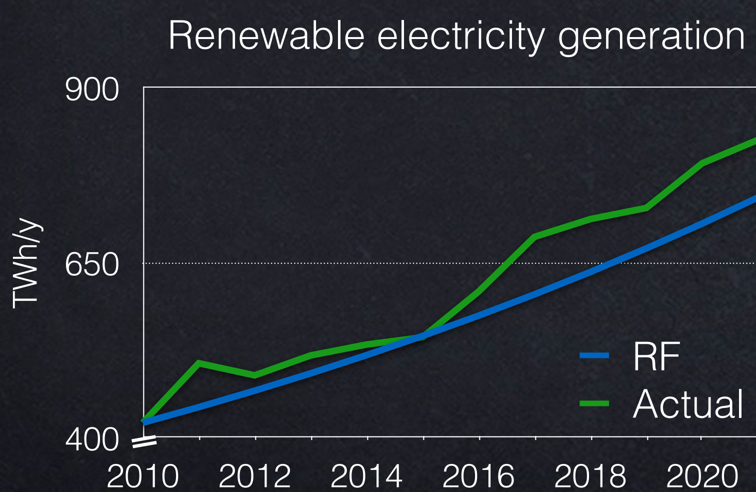
so…world economy: ≥5η?

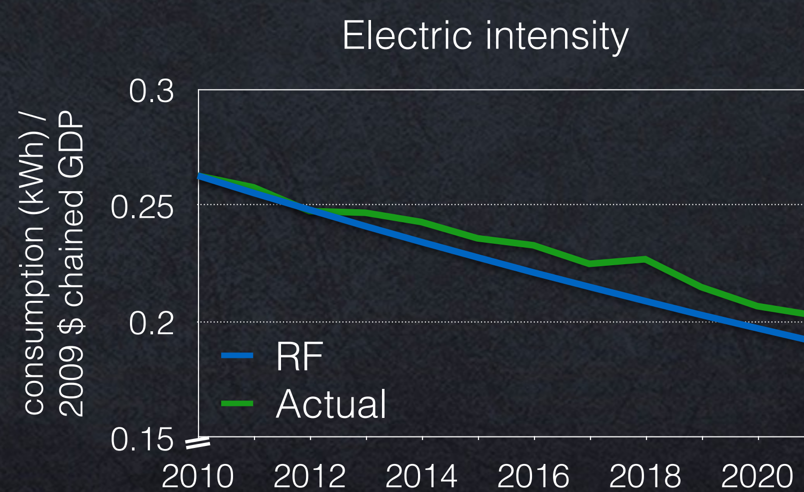
「Reinventing Fire」における年の目標に向けた2010〜21年の米国の進展

実績値（エネルギー情報局）は天候調整されていない。一定の指数関数的成長率に基づいて「Reinventing Fire」 の進展を示す。

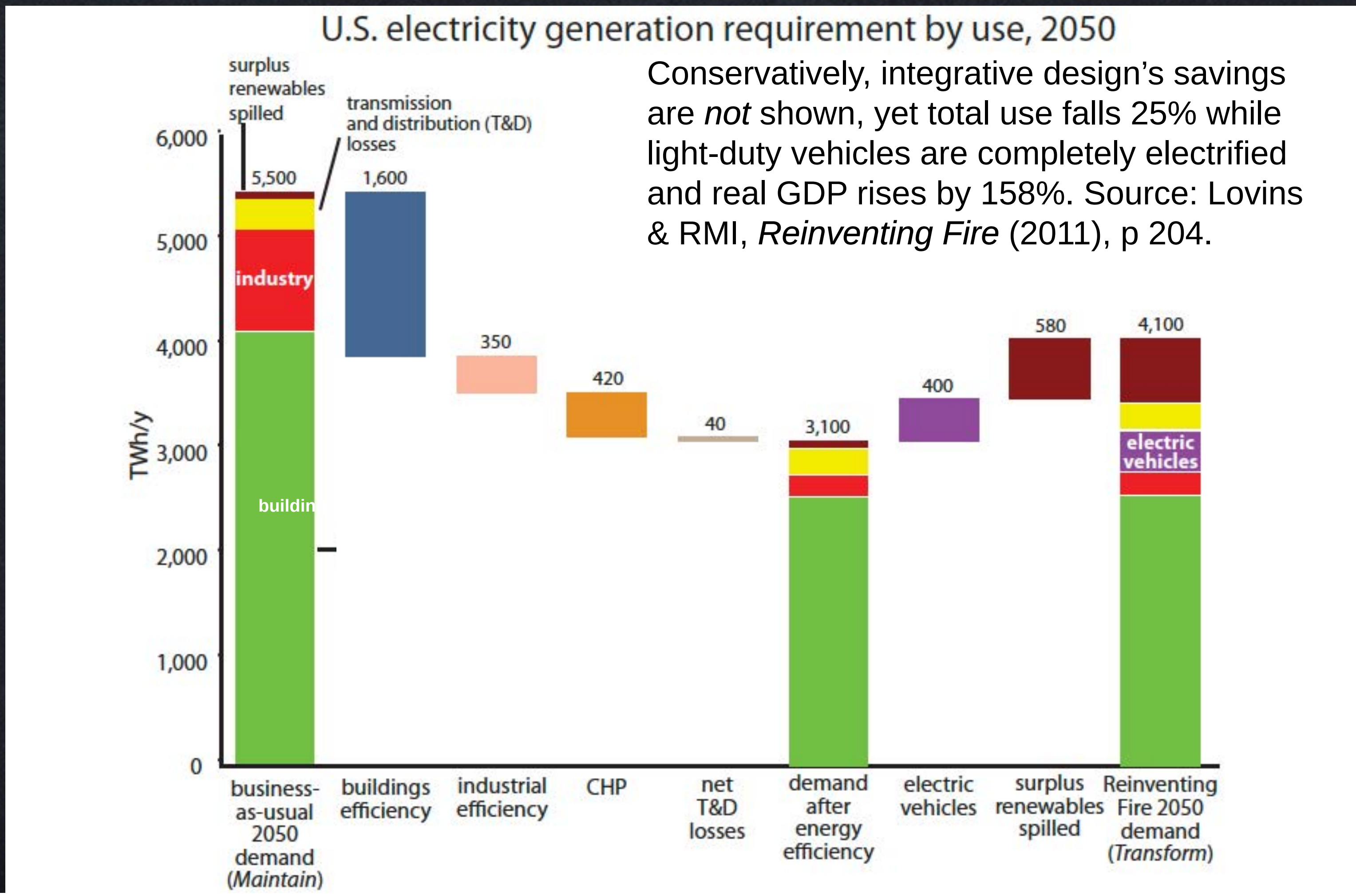








U.S. Electric Productivity Can Quadruple in 2010–50—~10x Cheaper Than Today's Retail Electricity Prices

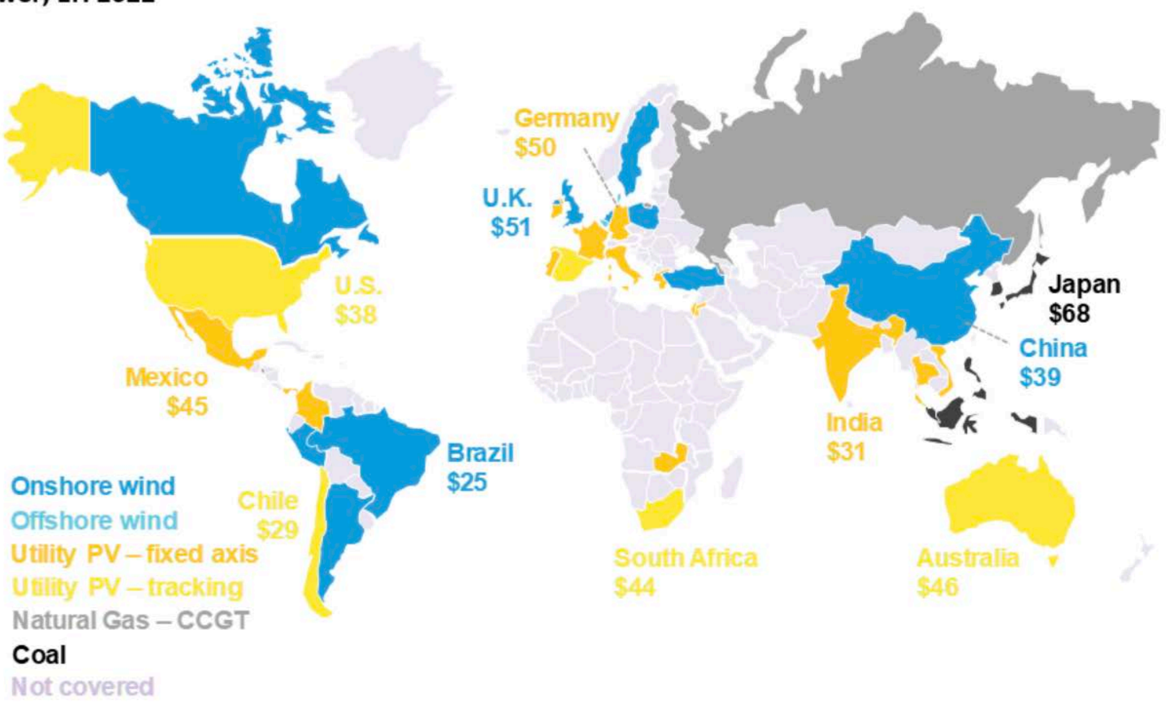


Conservatively, integrative design's savings are *not* shown, yet total use falls 25% while light-duty vehicles are completely electrified and real GDP rises by 158%. Source: Lovins & RMI, *Reinventing Fire* (2011), p 204.

By mid-2022, sun &/or wind were the cheapest source of new bulk electricity in countries with >⅔ of world population, >90% of electricity generation

(BNEF, 30 Jun 2022, https://about.bnef.com/blog/cost-of-new-renewables-temporarily-rises-as-inflation-starts-to-bite/)

Figure 2: Markets where new-build solar and/or wind are cheaper than new-build coal- and gas-fired power, 1H 2022



Source: BloombergNEF. Note: The map shows the technology with the lowest LCOE for new-build plants in each country where BNEF has data. The dollar numbers denote the per-MWh benchmark levelized cost of the cheapest technology. All LCOEs are in nominal terms. Calculations exclude subsidies, tax-credit or grid connection costs. CCGT is combined-cycle gas turbine.

As of 2021:

Benchmark empirical prices included:

- *Onshore wind:* Brazil $17/MWh; Canada, Chile, India, UK, Spain, US, Mexico $26–30/MWh
- *PV:* India, UAE, Chile, Brazil, China, Australia, Spain $23–29/MWh

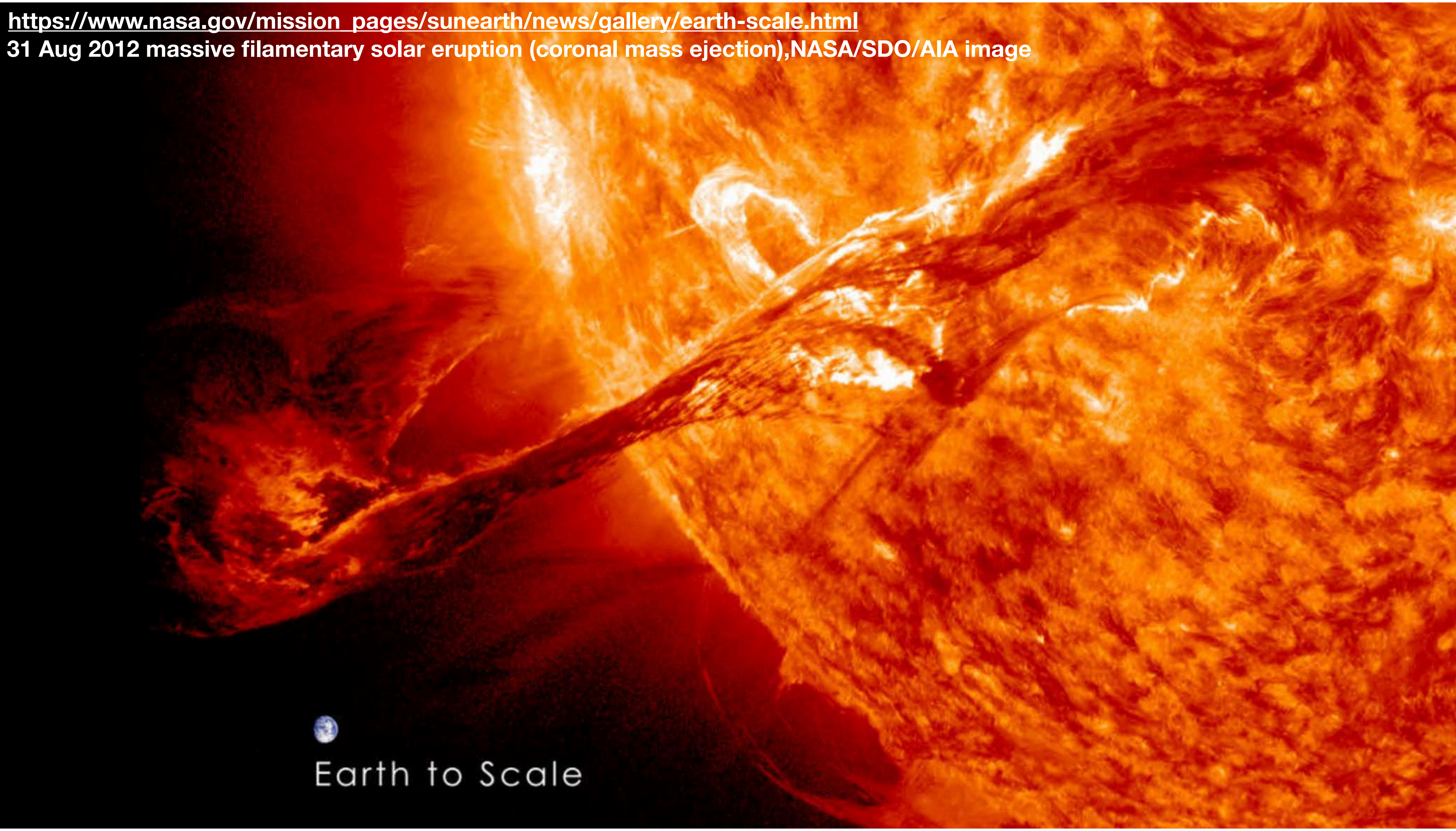
New solar and onshore wind can compete with *existing coal and gas plants' operating costs alone* in countries with nearly half the world's population and 48% of electricity generation, including China, India, France, and Spain (PV) and Sweden, UK, and Brazil (wind); by end 2021 these lists should include Chile, Italy, Germany, and Netherlands.

"Variable renewables and back-up are the cheapest new-build option to meet a flat load."

Battery storage (incl recharging) costs $138/MWh for 4-h or $204/MWh for 1-hour; 4-h –83% 2012–21.

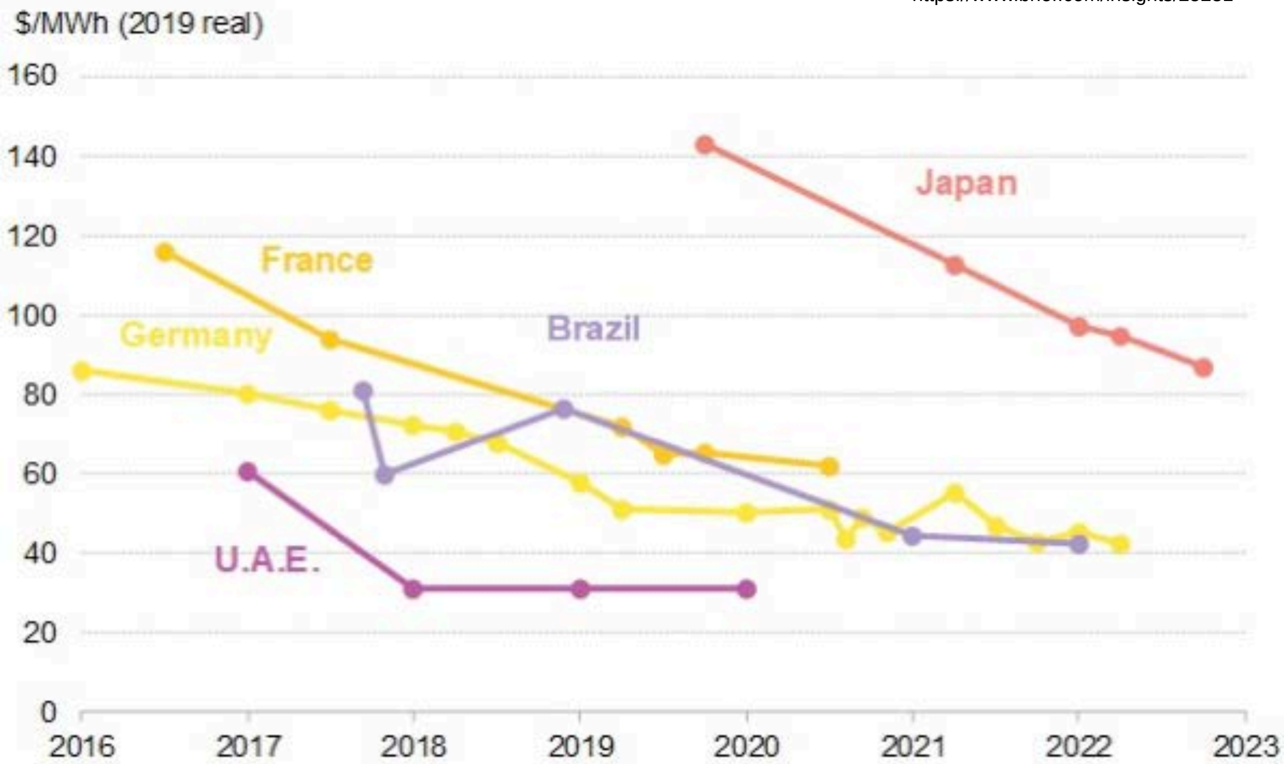
Estimated learning curves are 28.8% for PV modules, 12% for onshore wind projects (13.6% for turbines), ~18% for lithium battery packs (to ≥2030), 0 for coal and CCGT.

https://www.nasa.gov/mission_pages/sunearth/news/gallery/earth-scale.html
31 Aug 2012 massive filamentary solar eruption (coronal mass ejection),NASA/SDO/AIA image



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



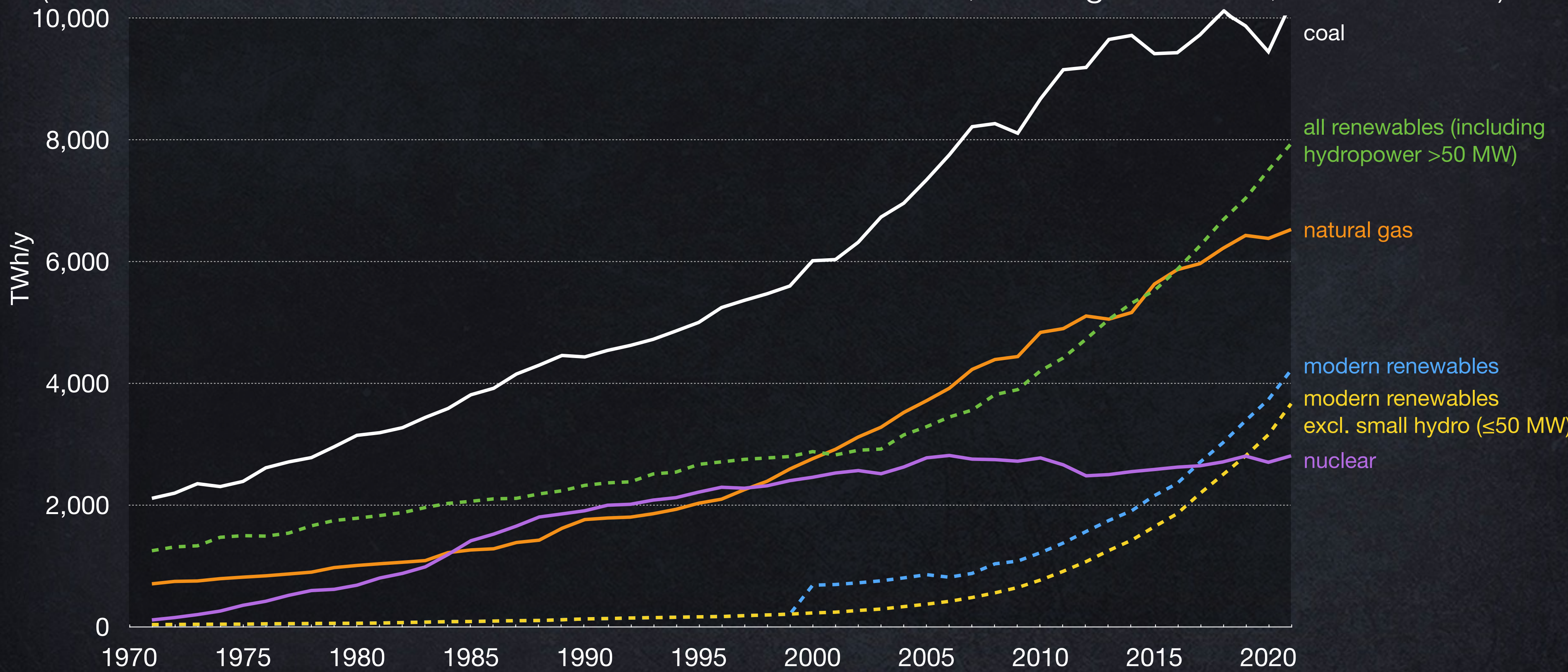
Source: BloombergNEF

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.

Worldwide electricity generation by source, 1971–2021

(These curves are separate, not stacked) (2021 total = 28,466 gross TWh, BP)

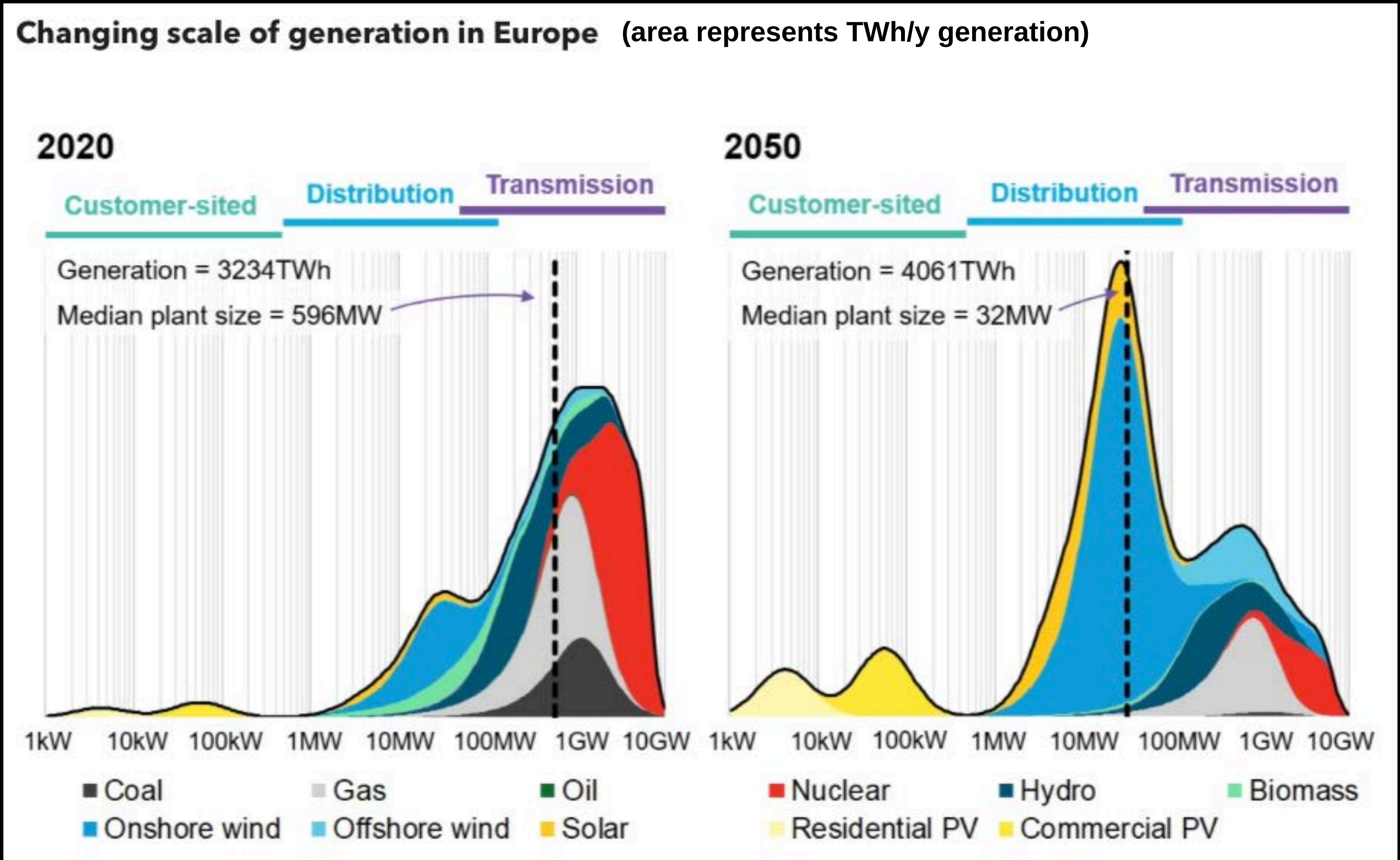
(IEA in Nov 2021 forecasted 2026 renewables at 11.3 PWh, the largest source, w/37% share)



Updated 17 Feb 2023 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. 1971–2021 data reconciled from same BP *Statistical Review of Energy* (2022 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 (720 TWh in 2021) is not shown.

BNEF forecasts the average European power plant will shrink 95%, 2020–50

M. Kenefick, 11 Feb 2021, https://www.bnef.com/shorts/10203

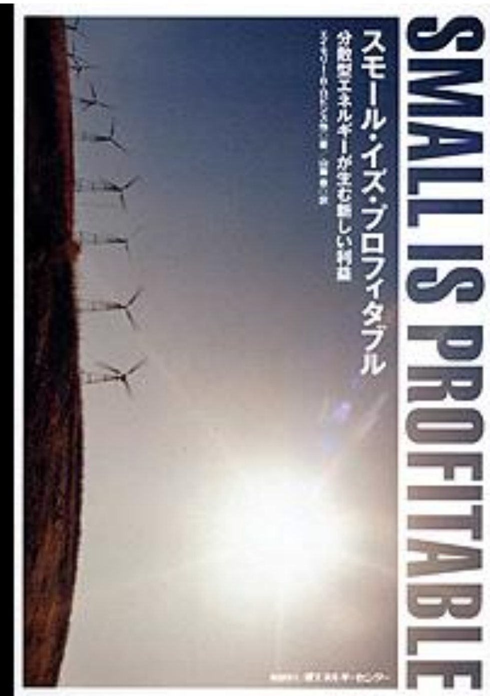


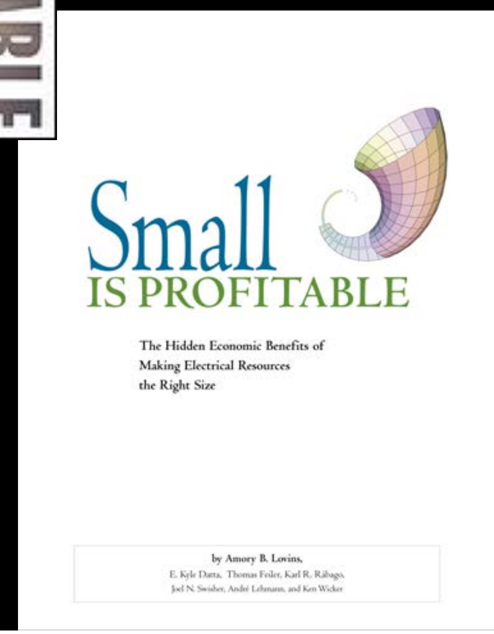
What's the right size for the job?

Free PDF at www.smallisprofitable.org, + Japanese
422 pages, 782 citations, data-rich, still definitive
One of *The Economist*'s 2002 top 3 business/ecs books
Uniquely detailed, systematic, comprehensive
Mashup of financial economics & electrical engineering
Includes public policy and business strategy

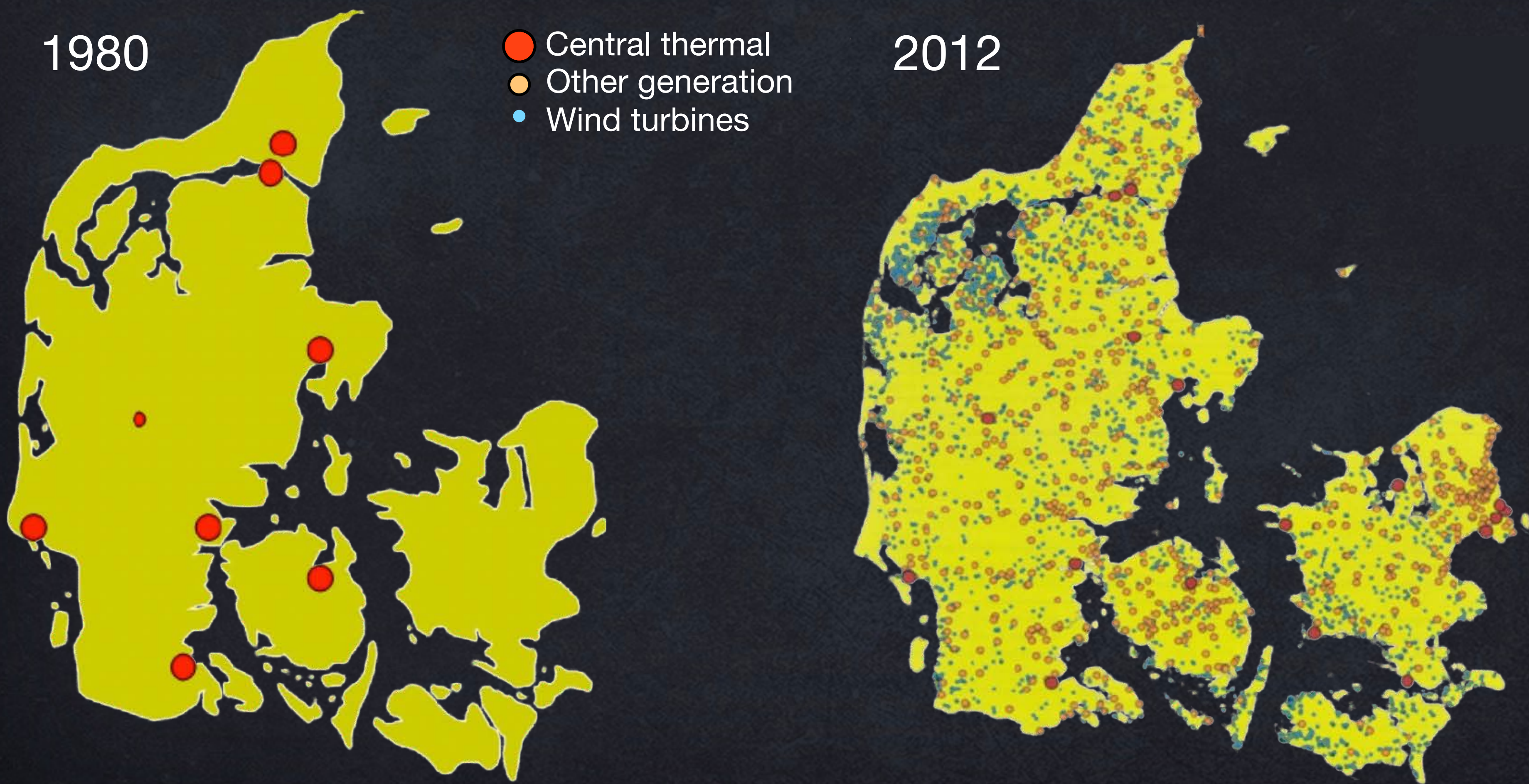
Documents 207 "distributed benefits" that make right-sizing of electrical systems *typically increase value by about an order of magnitude*, excluding any social and environmental advantages, by improving system planning, utility construction and operation (especially of the grid), and service quality

Actual value is highly site-specific but generally major
Applies widely beyond electricity, e.g. to water systems
Could and should be equally applied to efficient use!



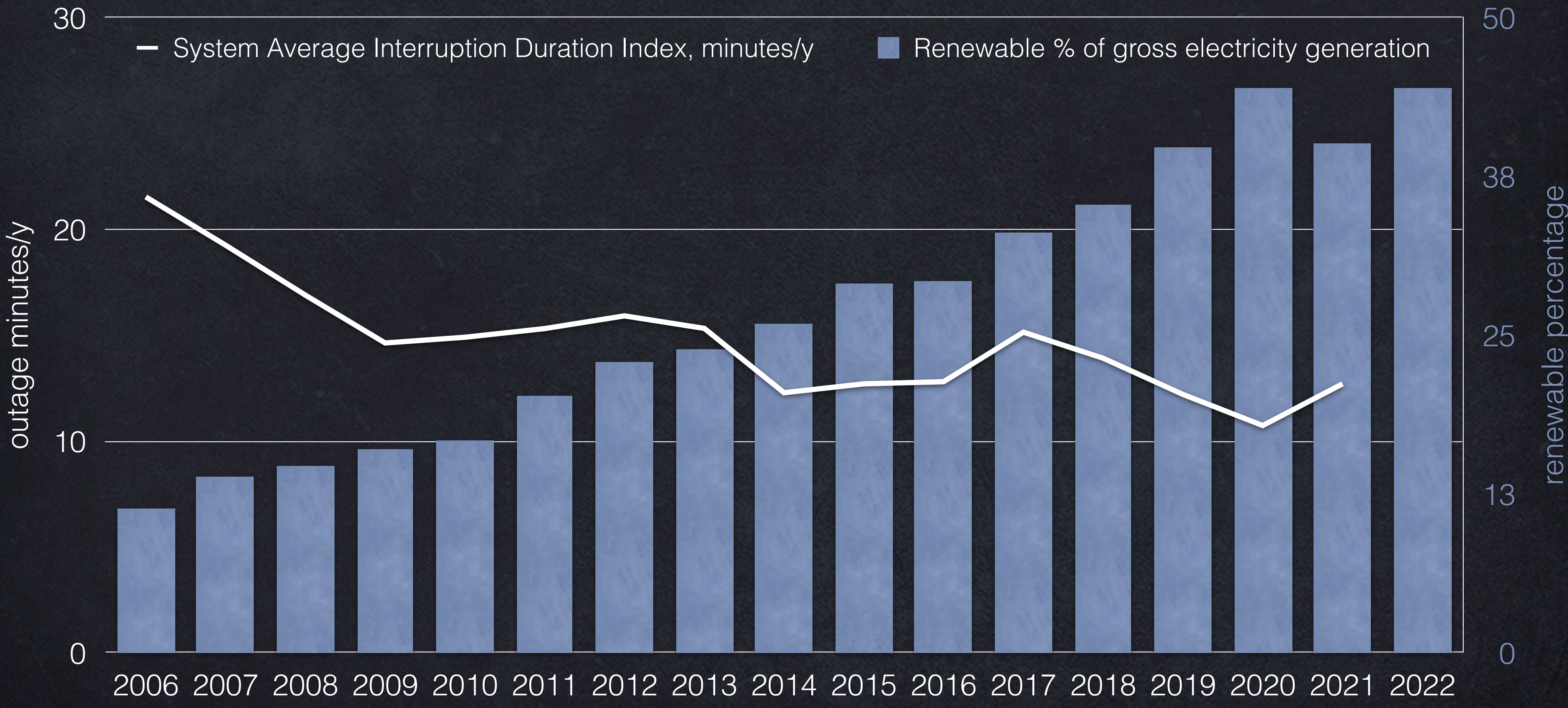


Transitioning to distributed renewables in Denmark



Source: Risø

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

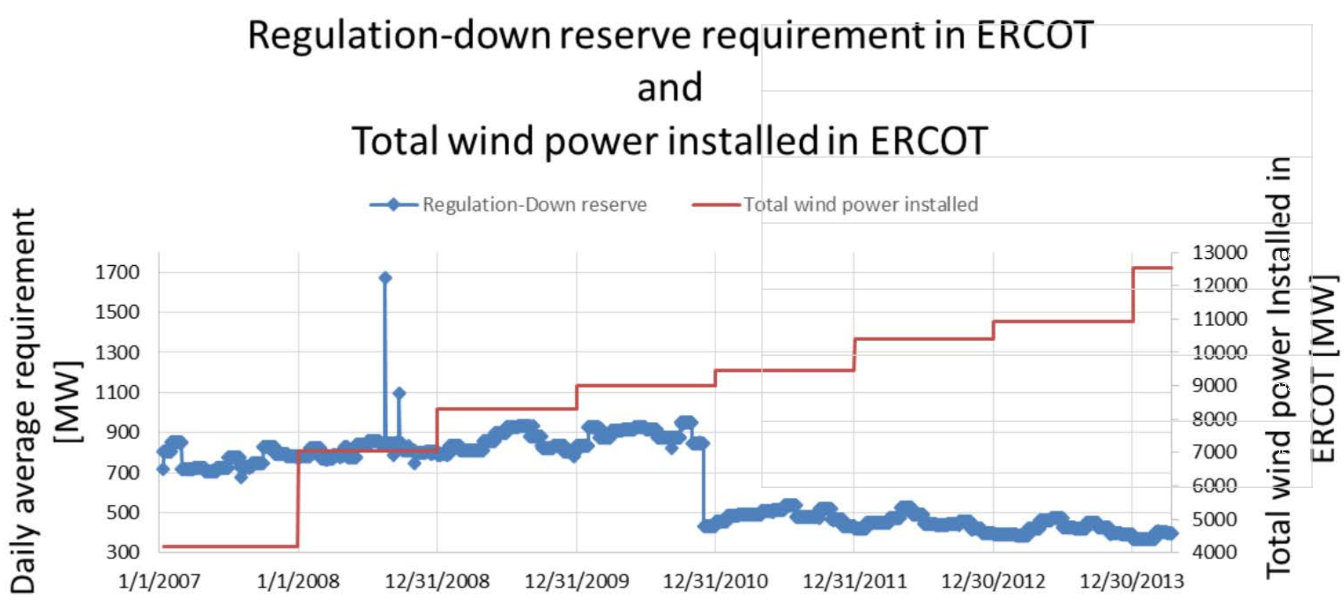


SAIDI data: Bundesnetzagentur, https://www.bundesnetzagentur.de/EN/Areas/Energy/Companies/SecurityOfSupply/QualityOfSupply/start.html

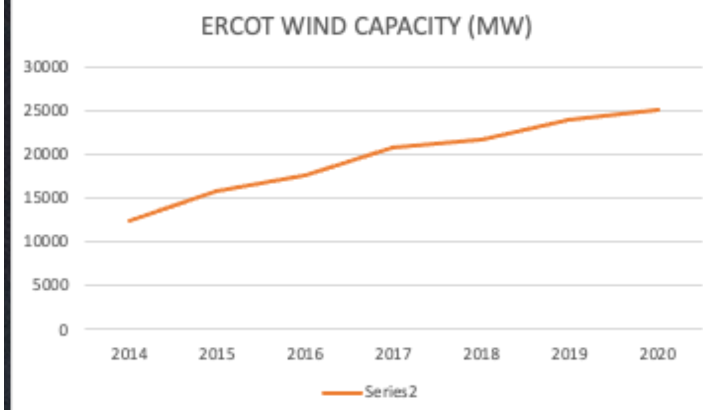
Renewable share data (gross generation): AG Energiebilanzen Bruttostromerzeugung in Deutschland ab 1990 nach Energieträgern, Dec 2020. https://www.ag-energiebilanzen.de; in net terms, 2022 share was 49.6%.

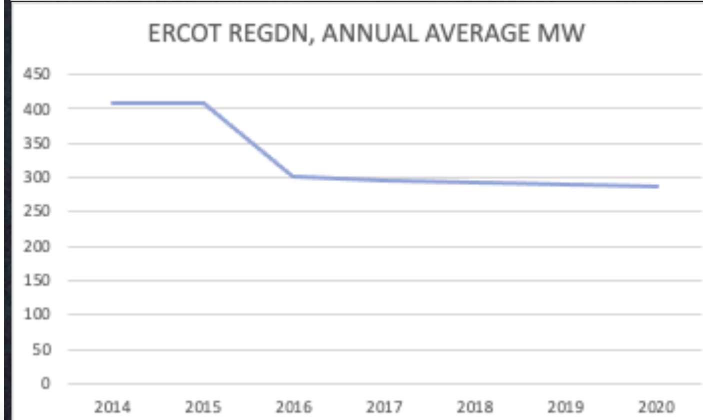
Texas grid's regulation-down procurements fell as windpower tripled and frequency stability (CPS1) improved by about one-sixth; then windpower doubled again while regulation-down fell by another 30%

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



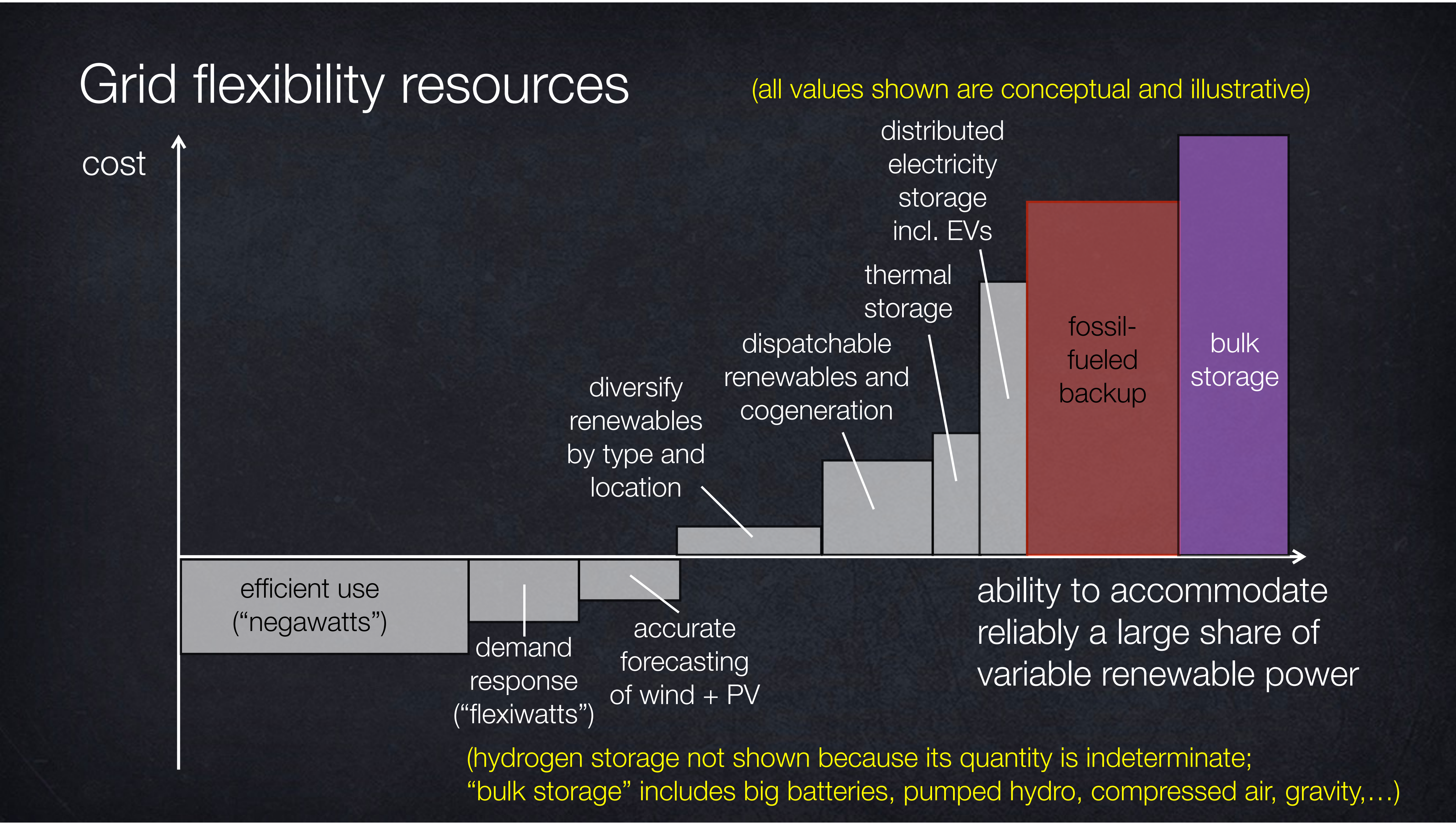
The Full Cost of Electricity (FCe-) Executive Summary: The Full Cost of Electricity, April 2018 | 28





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


Grid flexibility resources
(all values shown are conceptual and illustrative)
cost
efficient use (“negawatts”)
demand response (“flexiwatts”)
accurate forecasting of wind + PV
diversify renewables by type and location
dispatchable renewables and cogeneration
thermal storage
distributed electricity storage incl. EVs
fossil-fueled backup
bulk storage
ability to accommodate reliably a large share of variable renewable power
(hydrogen storage not shown because its quantity is indeterminate;
“bulk storage” includes big batteries, 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% 2nd-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

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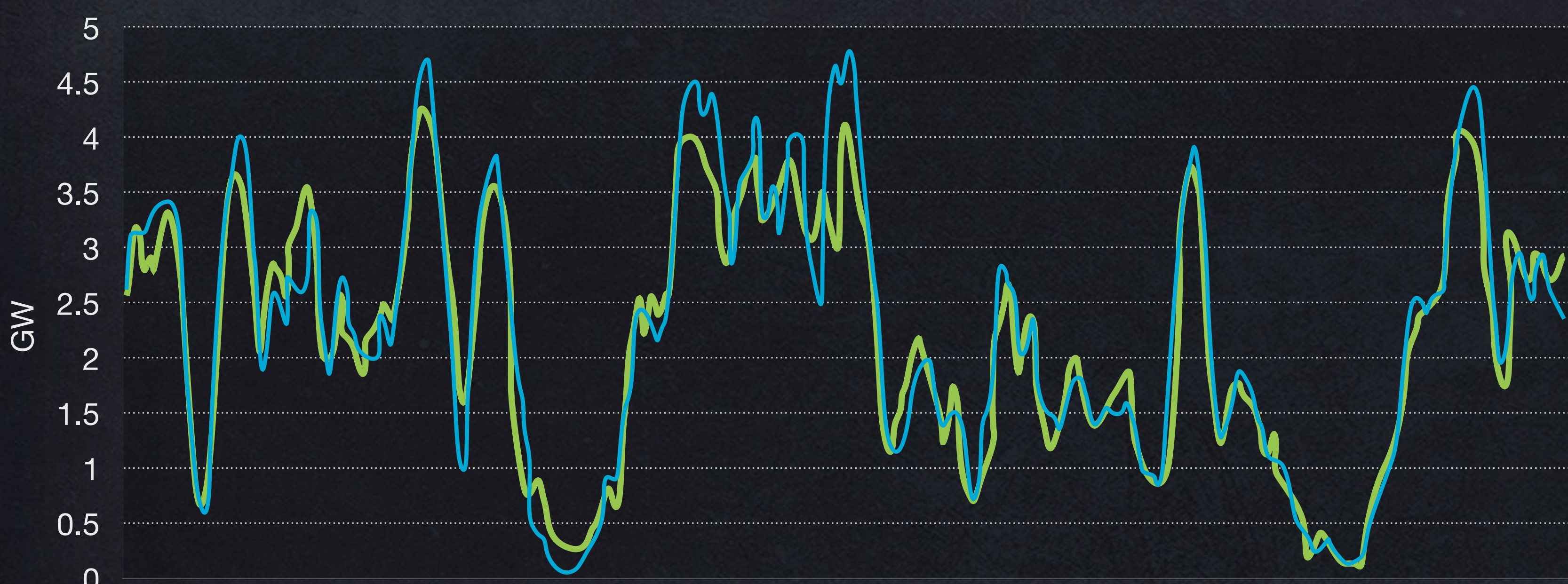
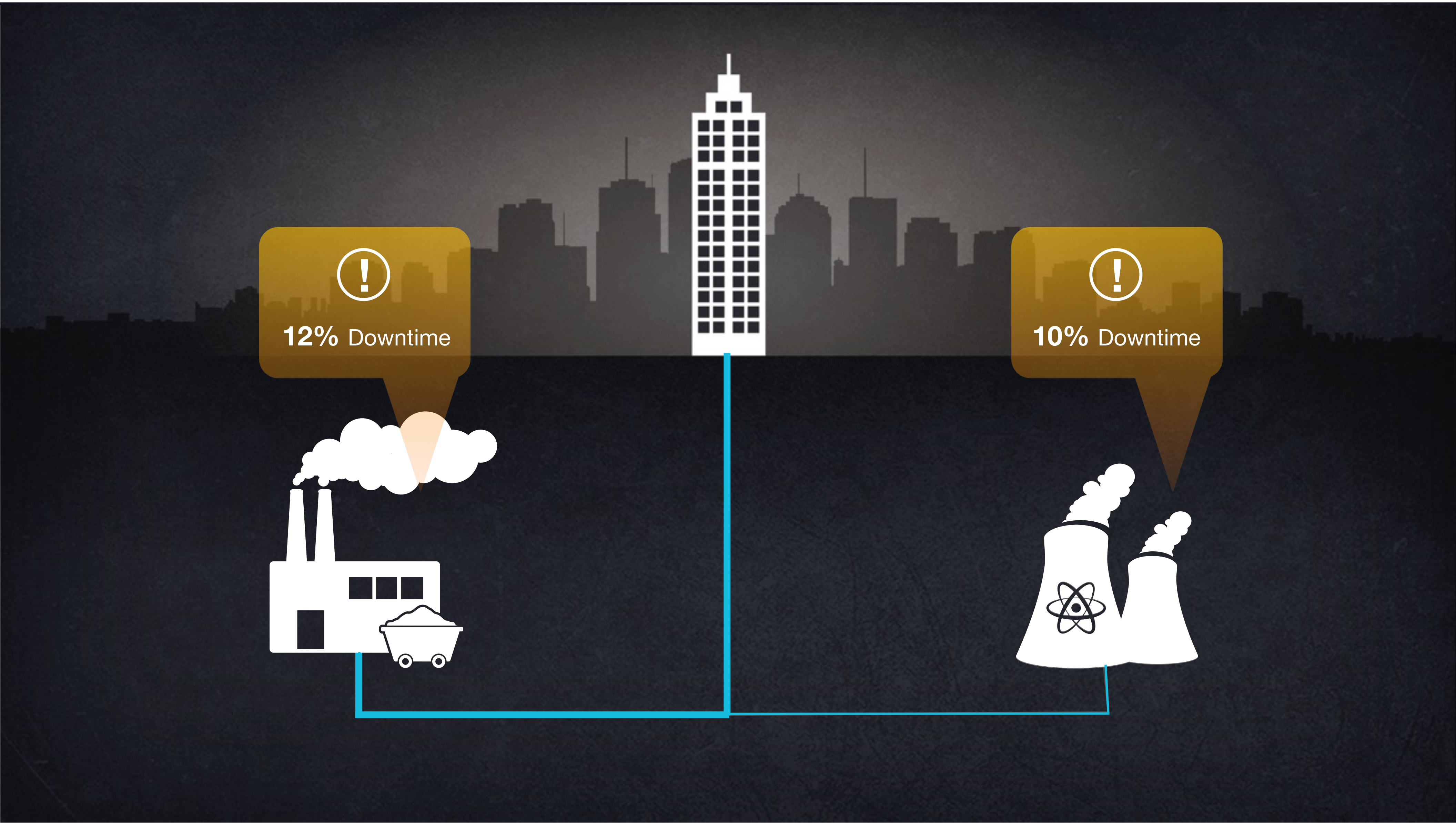
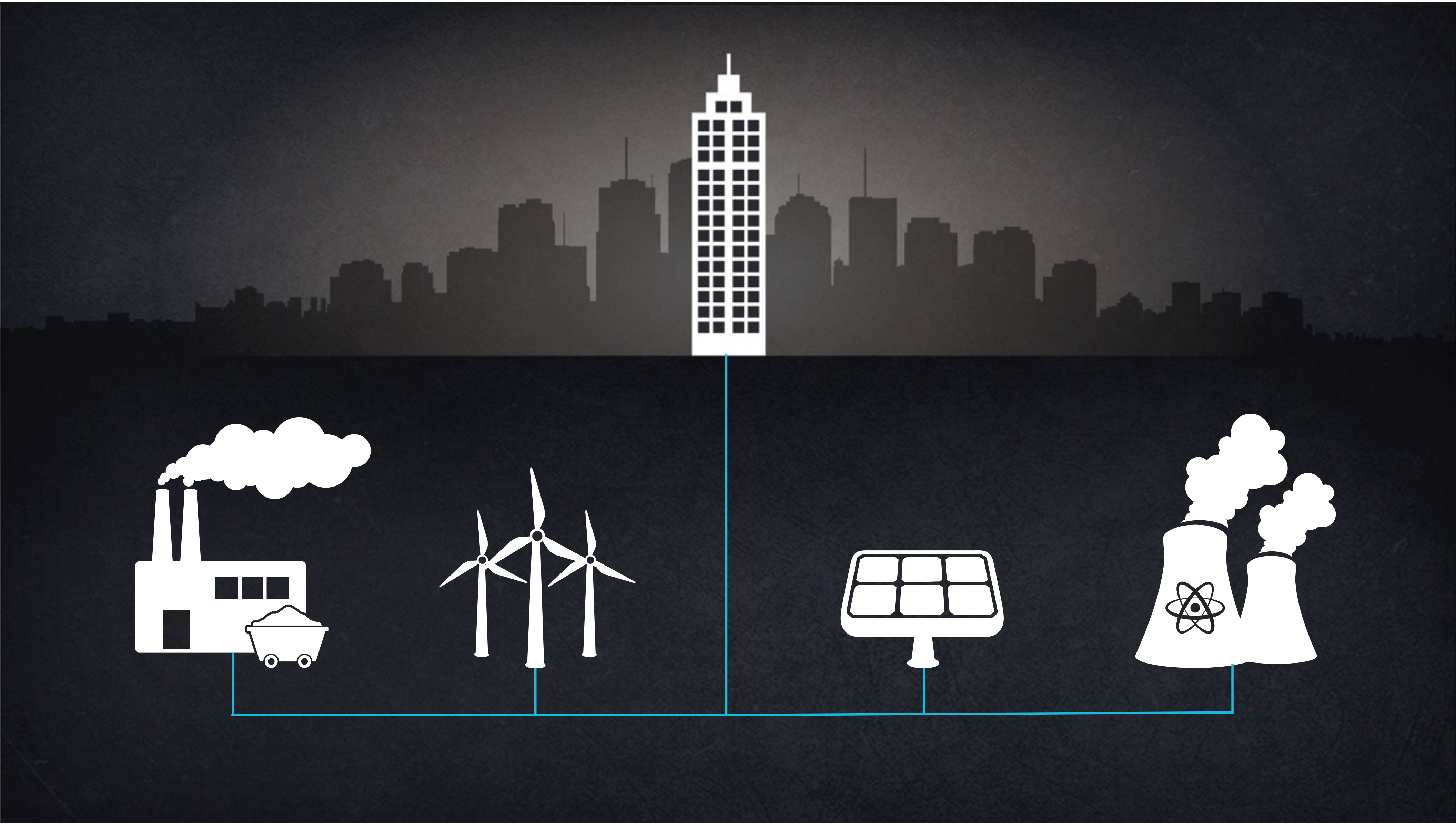
Variable Renewables Can Be Forecasted At Least as Accurately as Electricity Demand

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



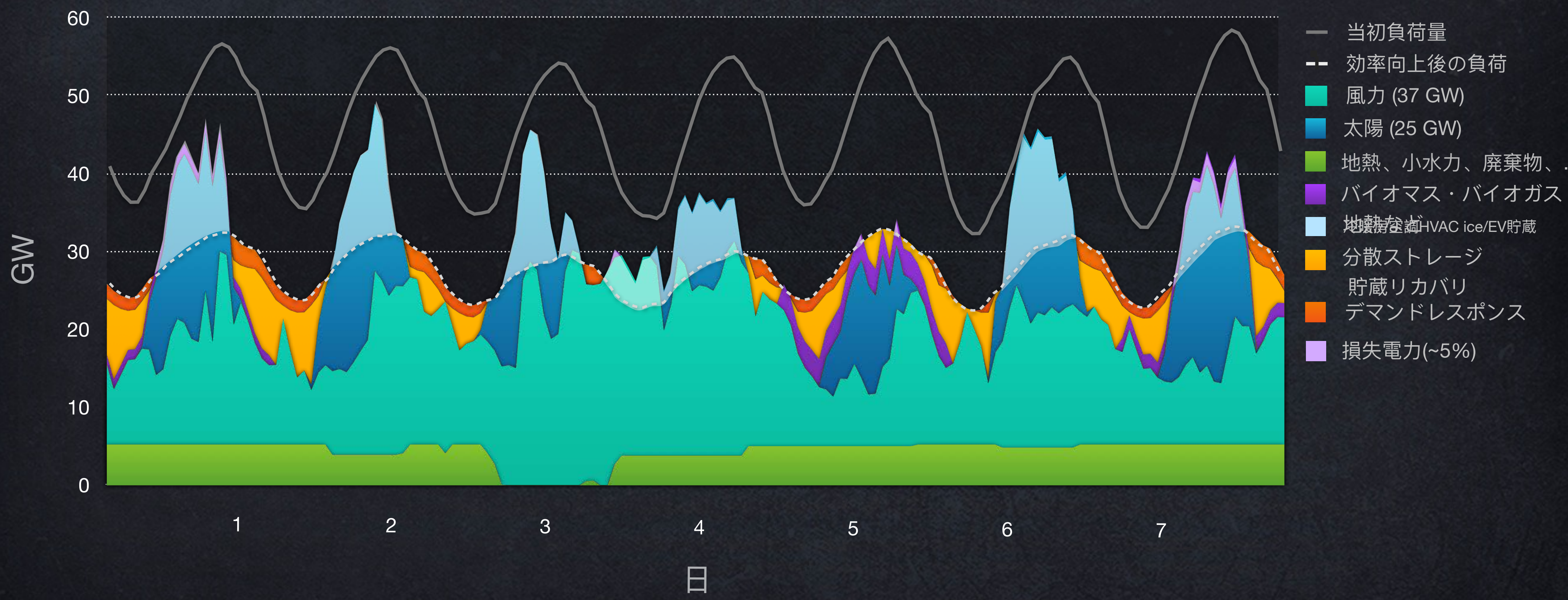
Source: Bernard Chabot, 10 April 2013, Fig. 7, www.renewablesinternational.net/wind-power-statistics-by-the-hour/150/505/61845/, data from French TSO RTE


12% Downtime
10% Downtime



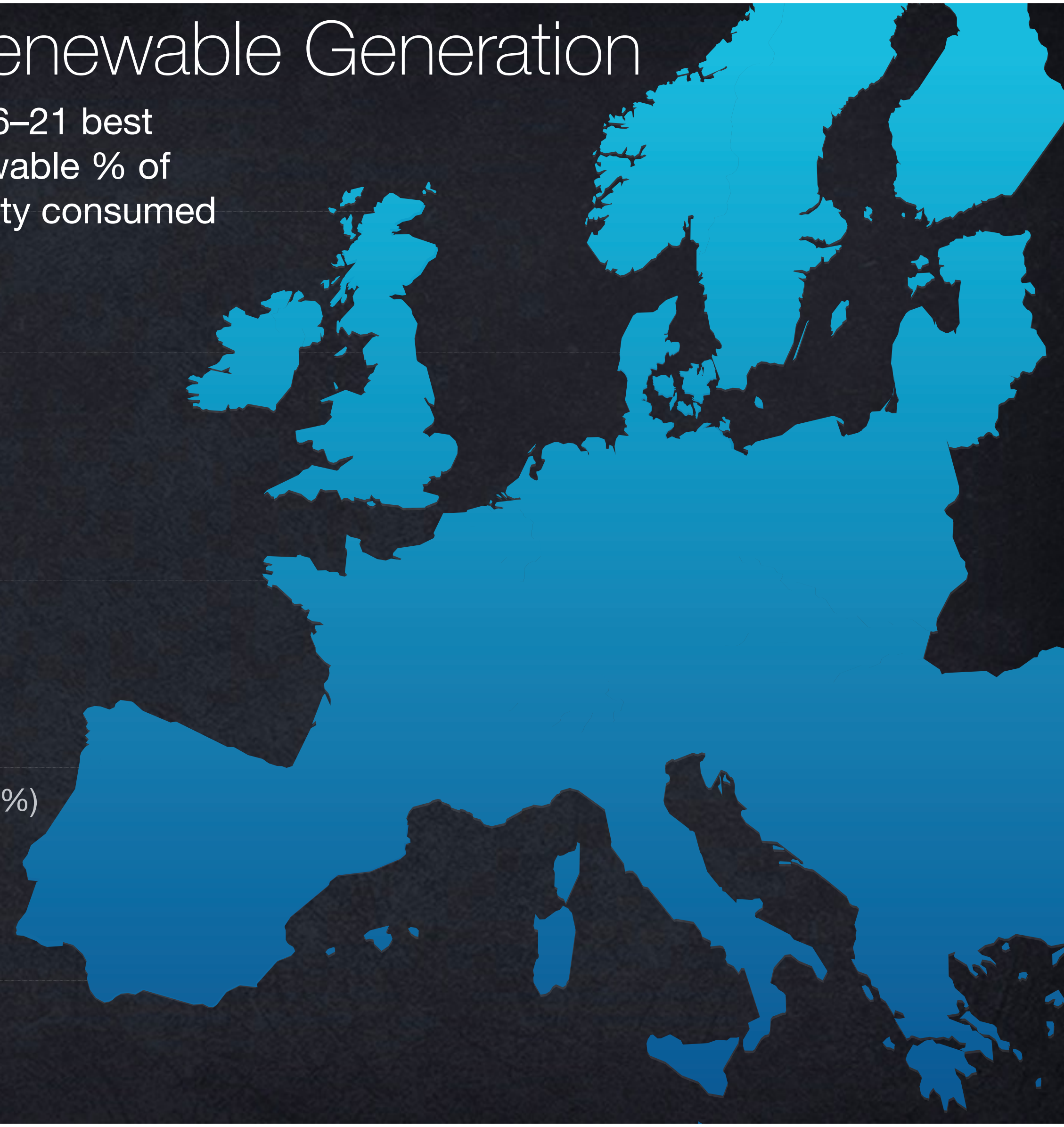
変動型再生可能エネルギーの計画的発電

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Ｉ週間
（RMI による時間ごとのシミュレーション）



Choreographing Variable Renewable Generation

Europe, 2016–21 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)

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)

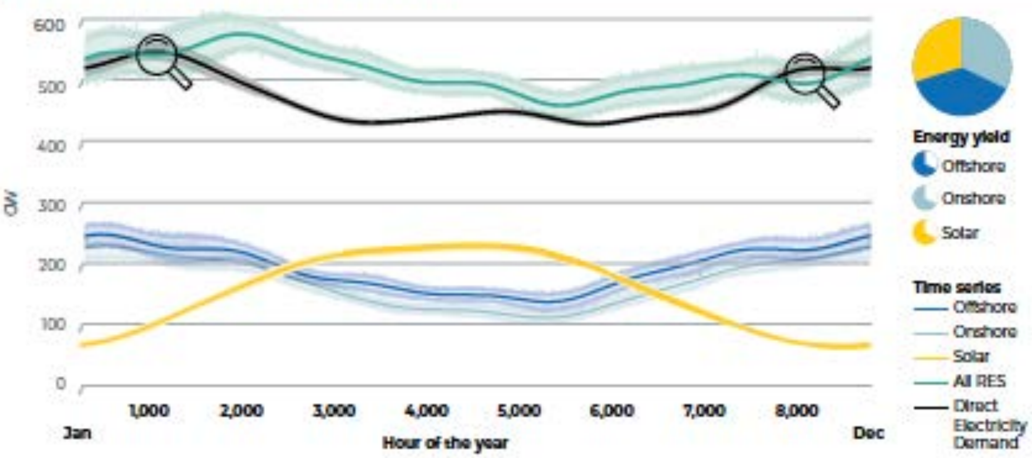
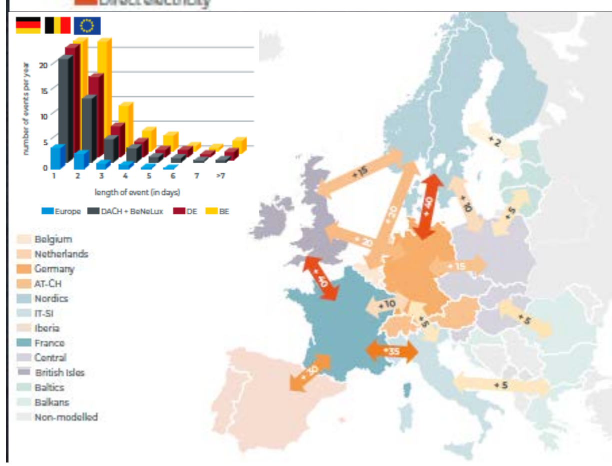
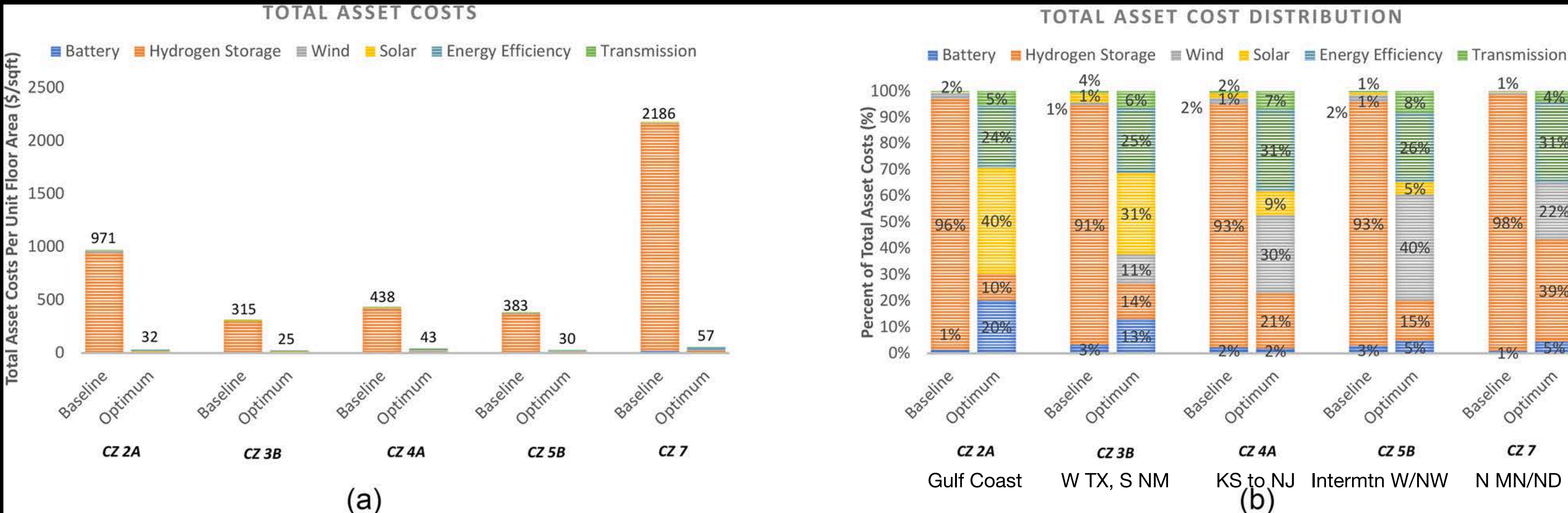


FIGURE 2: STRONG ELECTRIFICATION OF END USE (AS UNDER THE ELEC-PATHWAY) SAVES UP TO 1,800 TWH AT THE EUROPEAN LEVEL COMPARED TO THE MOL-PATHWAY. DIRECT ELECTRICITY DEMAND UNDER THE ELEC-PATHWAY INCREASES BY 70% COMPARED TO TODAY'S DEMAND. A TRIPLING OF TODAY'S RES EXPANSION RATE IS NEEDED TO MEET THIS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

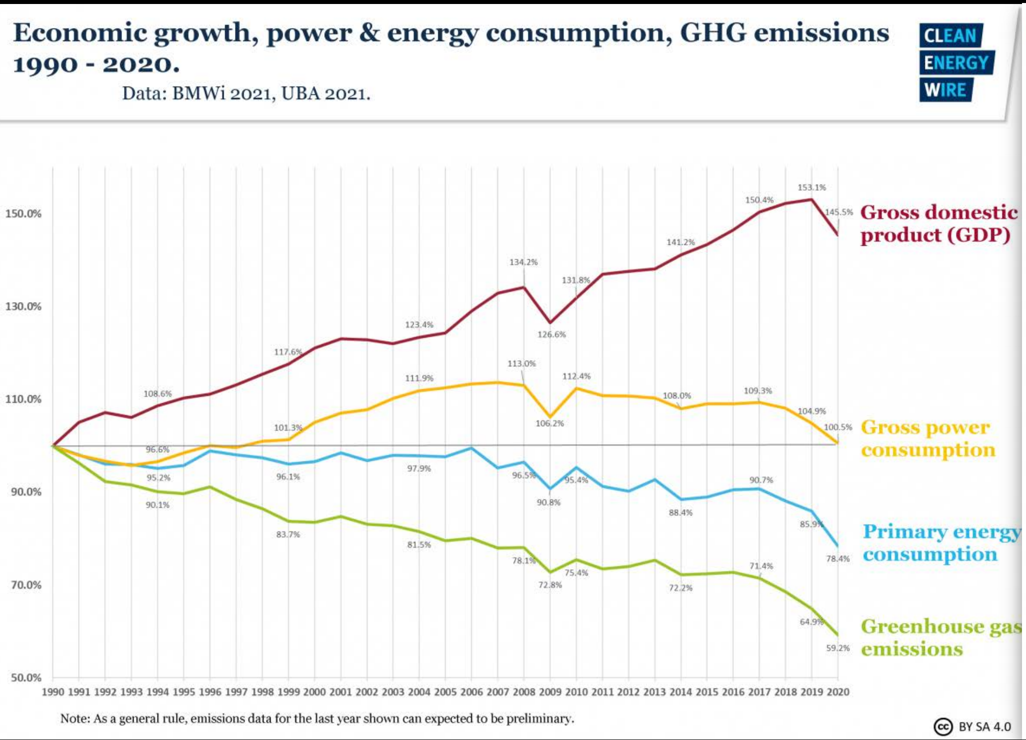
Energy-efficient buildings displace and outcompete electricity storage

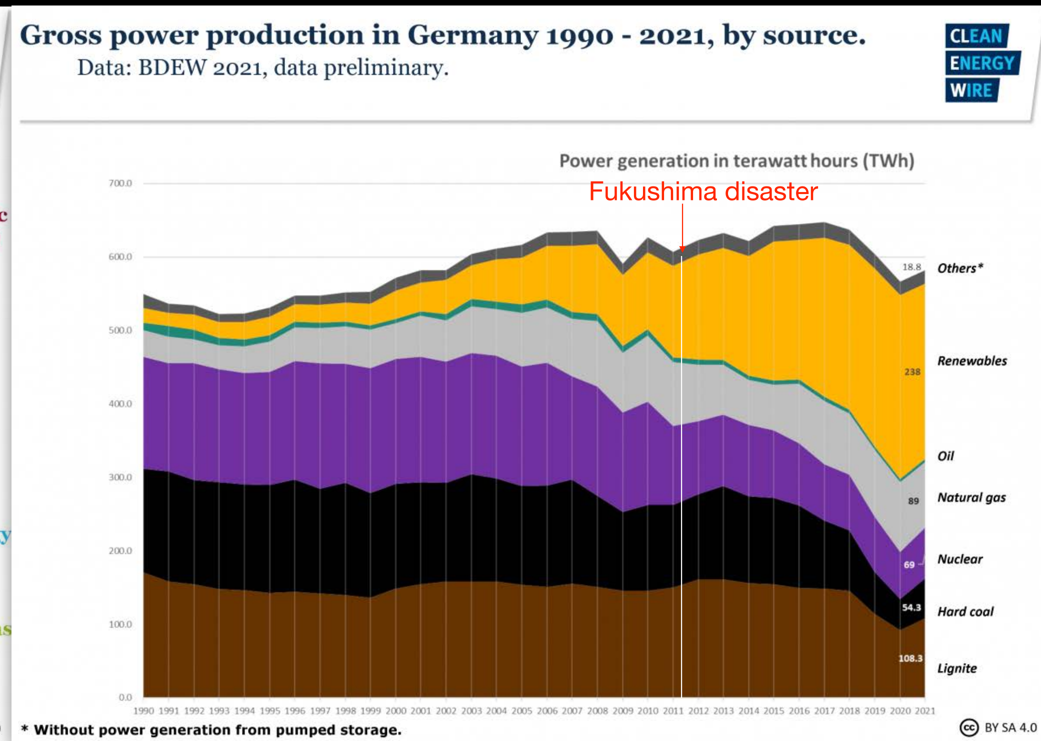


Retrofitting conventional building efficiency, plus extra renewables in an optimal mix, largely displaces H_2 long-term storage, *cutting investment by ≥1 order of magnitude*. This "can eliminate the need for long-duration energy storage for U.S. regions" defined by" the Gulf Coast, the desert Southwest,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

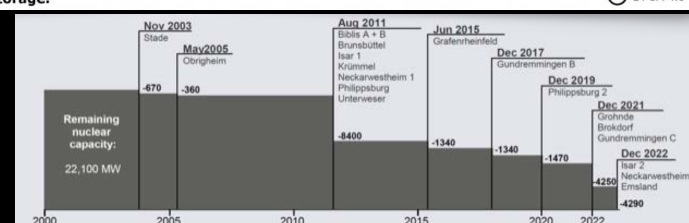
Germany’s nuclear phaseout came with huge coal and CO_2 reductions; Germany in 2021 began closing coal plants opened as recently as 2015





1990–2020: electricity/GDP –31%,
primary energy/GDP –46%,
GDP +46%, greenhouse gas emissions –41–43%,
GHG emissions/GDP –59%

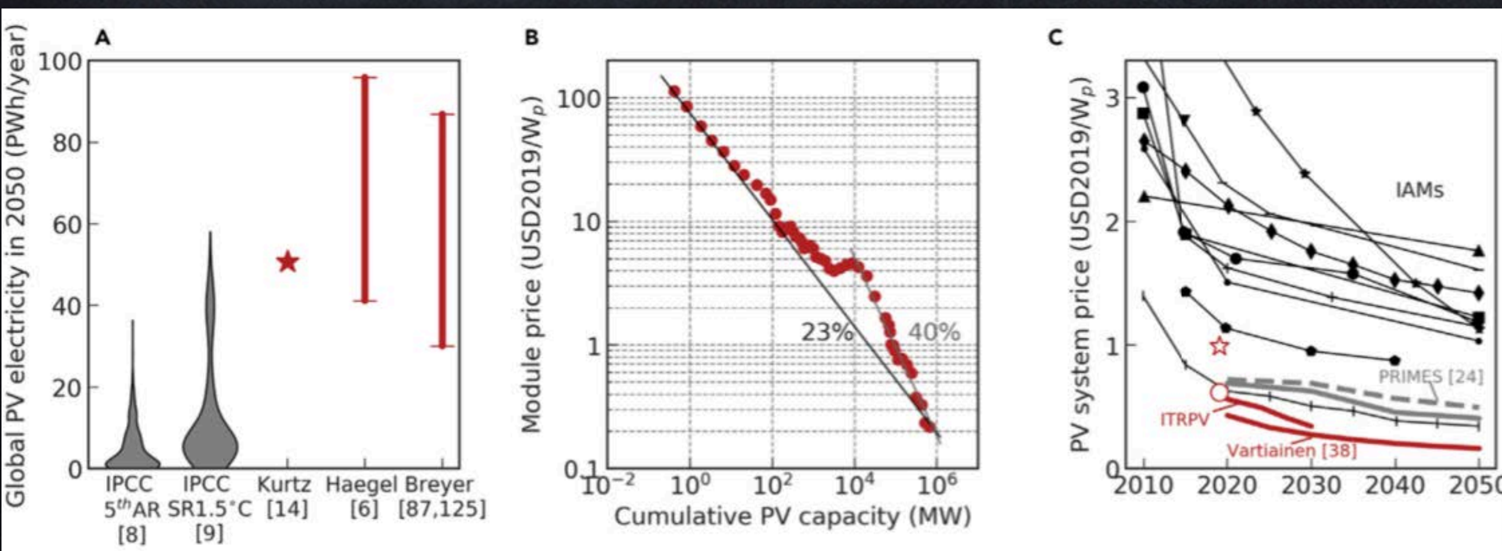
Retirement schedule of German nuclear power capacity, 2000–2022 →

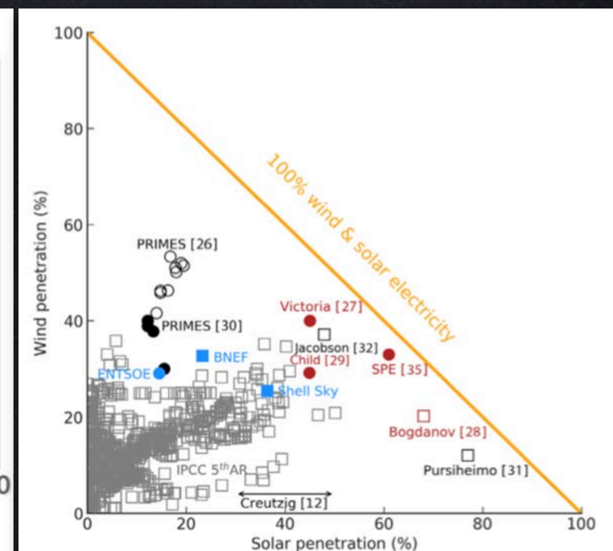


https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mix-charts, based on official federal Ministry & industry (BDEW) statistics

Permanent closure of the last three units was delayed from 31 Dec 2022 to 15 Apr 2023 as insurance against potential European shortages, due most of all to major shortfalls in French nuclear output.

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?

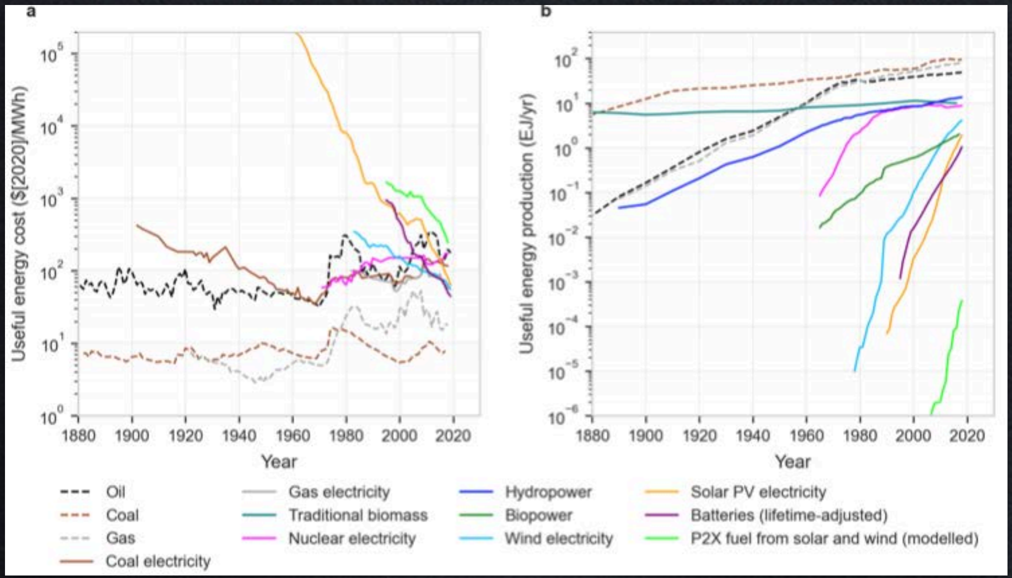
PV modules' experience curve is 23% starting in 1976, but **40%** starting in 2007. Why keep using that 1976 origin today? And why not apply learning *in* the model?

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.

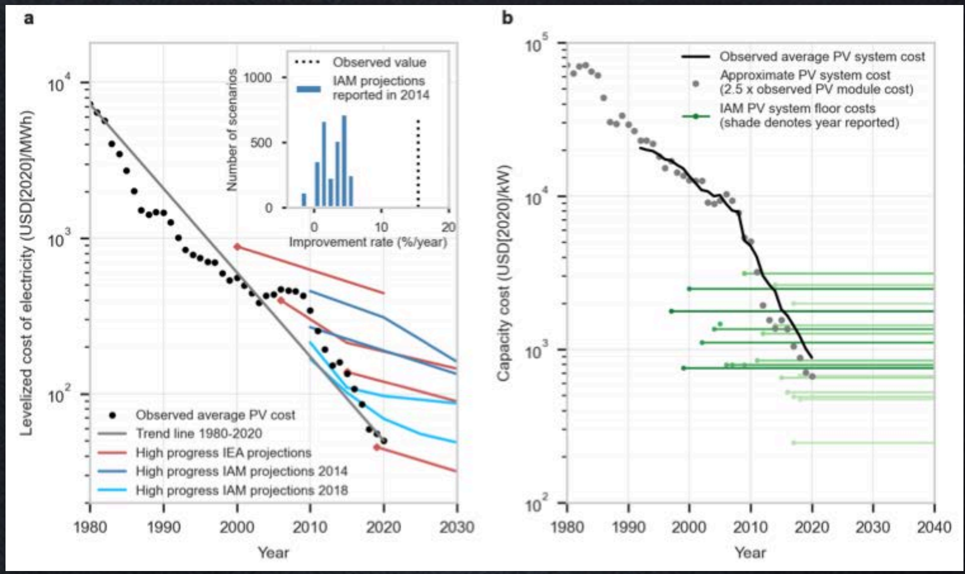
Figs. 2–3, M. Victoria *et al.*, "Solar photovoltaics is ready to power a sustainable future," *Joule* **5**:1041–1056 (19 May 2021), https://doi.org/10.1016/j.joule.2021.03.005.

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.



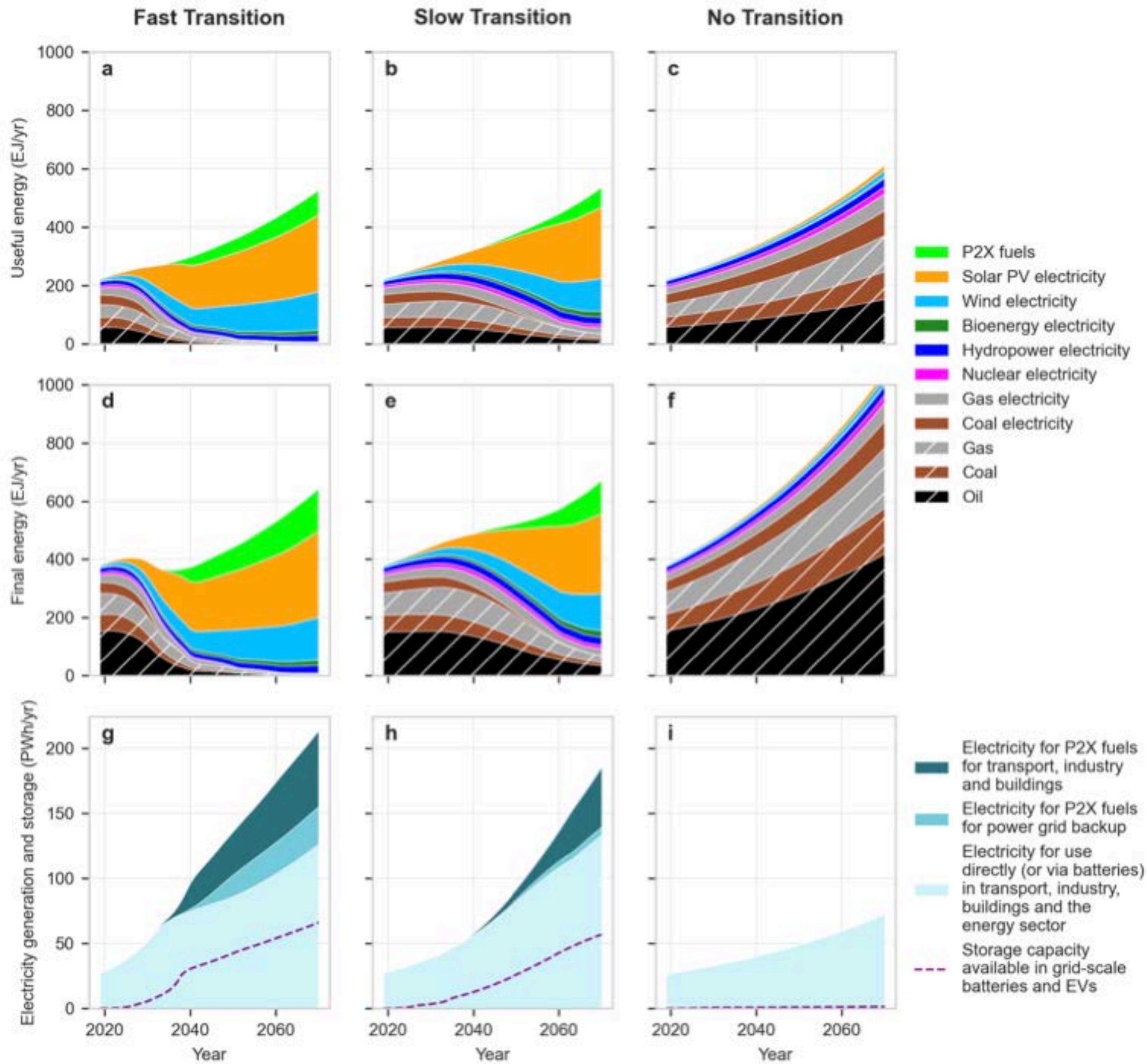
Histogram: 2,905 Integrated Assessment Models predicted PV costs in 2010–20 would fall by 2.6%/y mean, <6% max. *Actual: 15%/y*. Only the fastest-growth IAM and IEA projections are graphed (colored lines).

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.

Empirical prices imply cheap, fast, all-renewable futures



- Deliberately simple global scenarios for 2019–2070
- Grounded in empirical costs and historic behaviors
- Four sectors—transport, industry, buildings, and the energy sector's self-use—in a transparent laptop model
- "Useful" energy is final energy delivered as services, assumed to grow 2%/y (slightly above post-2010 av.)
- ***No* energy efficiency or demand response assumed**
- All 3 scenarios reliably provide the same energy services
- Grid balancing by **one month of full battery storage** (!)
- Long-term storage by power-to-*X* fuels (H_2, NH_3,…), which also serve heavy transport and industrial heat
- Minor renewables, liquid biofuels, cogen all omitted
- Fossil fuels with carbon capture and storage omitted because too slow and costly to matter or be needed
- Nuclear power tested—conservatively $15–27t costlier
- **Fast**: *off fossil fuels in two decades; little asset-stranding*
- **Slow**: rapid slowing of renewable growth, so fossil fuels still dominate until mid-century
- **No transition**: scales current proportions ("worst case")
- ***Fast** transition costs far <u>less</u> than **Slow** transition, at <u>any</u> reasonable discount rate (e.g. by $14t @ 1.4%/y real)*
- *Efficient use would save even more (but not analyzed)*
- "Transition costs" are illusory: *"A greener, healthier and safer global energy system is also likely to be cheaper."*

Fig. 4, 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.

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