Which Technologies Are Useful in a Transition Away From Fossil Fuels

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What are the Problems? Why act Quickly?

Fossil-fuel and biofuel air pollution cause ~7.4 million air pollution deaths/yr worldwide, costing ~$30 trillion/year

Global warming will cost ~$30 trillion/year by 2050.

Fossil fuels will become scarce, increasing energy prices and economic, political, and social instability

Drastic problems require immediate solutions

Wind, Water, Solar (WWS) Solution

Electrify or Provide Direct Heat For All Sectors and Provide the Electricity and Heat with 100% WWS

ELECTRICITY/HEAT	TRANSPORTATION	BUILDINGS	INDUSTRY
Wind	Battery-electric	Heat pumps	Arc furnaces
Solar PV/CSP	H_2 fuel cell	Induction cooktops	Induction furnaces
Geothermal		LED lights	Resistance furnaces
Hydro		Insulation	Dielectric heaters
Tidal/Wave			Electron beam heaters
Solar/Geo Heat			Heat pumps

Types of Storage for a 100% WWS System

ELECTRICITY STORAGE	HOT/COLD STORAGE	HYDROGEN STORAGE
CSP with storage	Water tank	Non-grid hydrogen
Pumped hydro storage	Ice	
Existing hydroelectric	Underground	
Batteries	Borehole	
Flywheels	Water Pit	
Compressed air	Aquifer	
Gravitational Storage	Building materials	
Grid hydrogen/fuel cells	Firebricks	

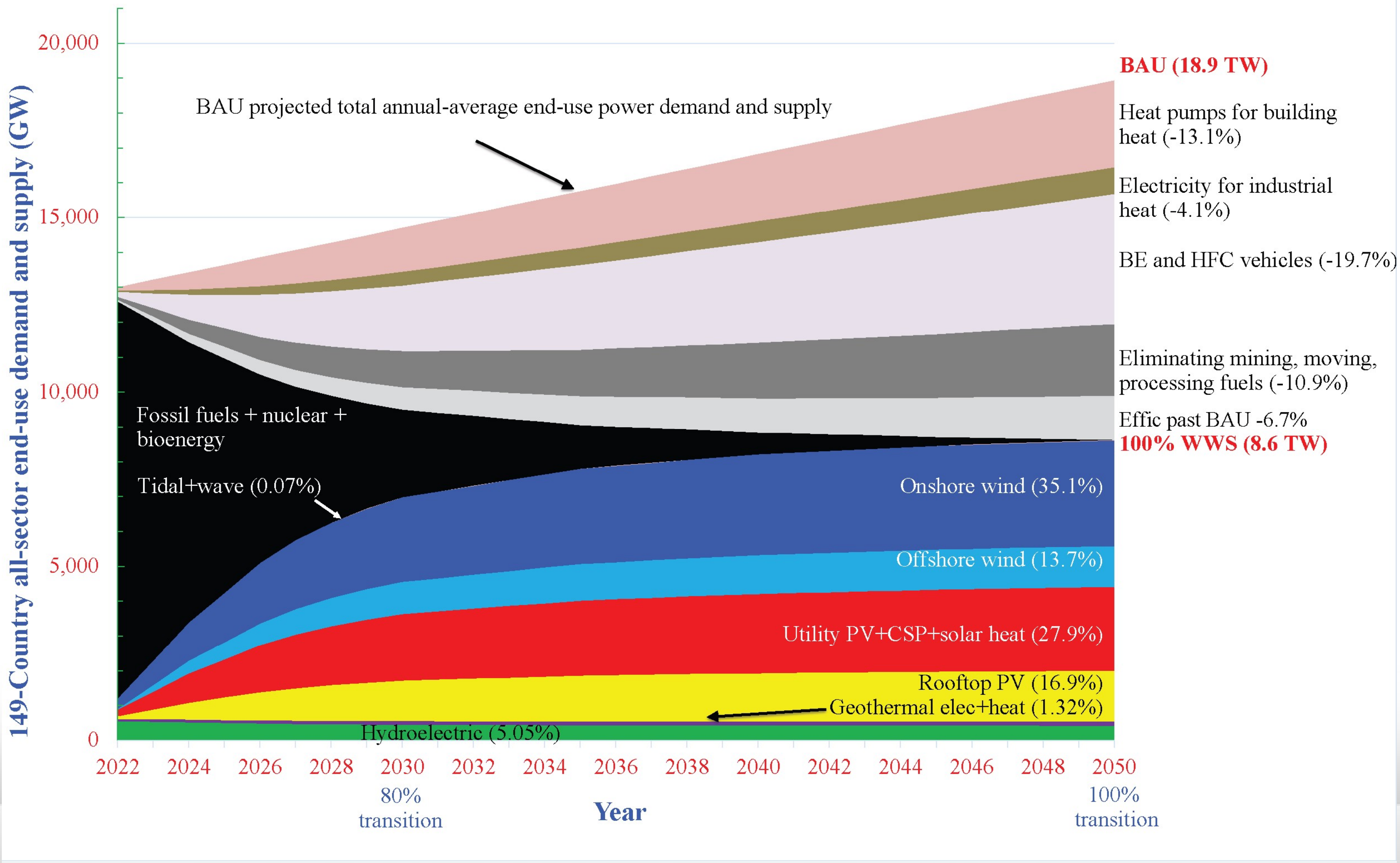
Can the World Transition to 100%, Clean, Renewable Energy for all Purposes?

Roadmaps for 149 Countries

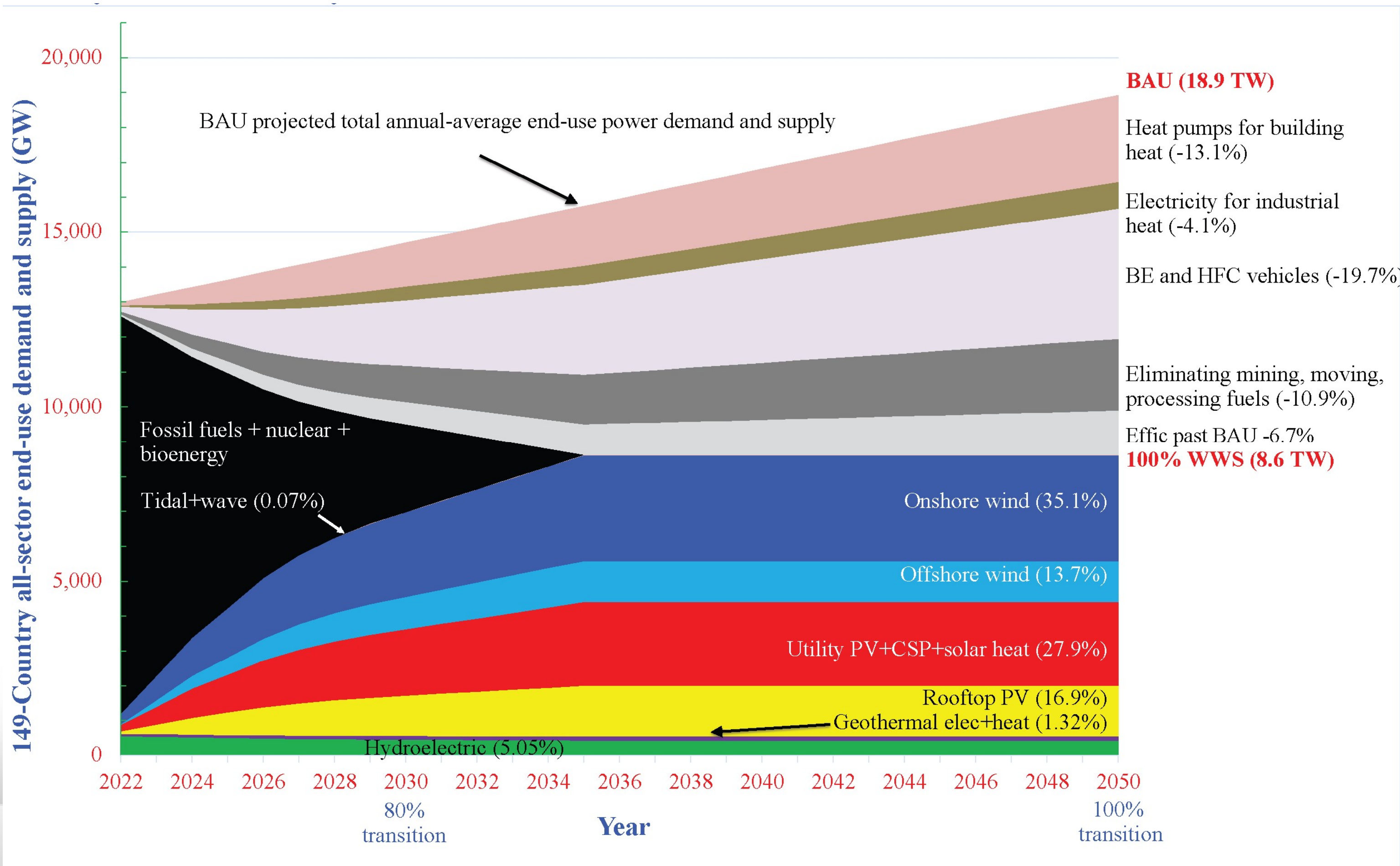
All-Sector End-Use Power Demand BAU v WWS

Year and Fuel Type	149 Countries
2020 End-use demand	12.6 TW
2050 Demand with current fuels (BAU)	18.9 TW
2050 Demand with WWS	8.6 TW
2050 Demand reduction with WWS 19.7% efficiency of BE, HFC v. ICE 4.1% efficiency of electric industry 13.1% efficiency of heat pumps 10.9% eliminating fuel mining 6.6% efficiency beyond BAU	54.4%

Timeline for Transitioning 149 Countries 80% by 2030; 100% by 2050



Timeline for Transitioning 149 Countries 80% by 2030; 100% by 2035



Capital Costs Resulting in a Stable Electric Grids Upon Electrification of all Energy With 100% WWS

World (149 Countries): $58.2 trillion

U.S.: $5.7 trillion

China: $14.6 trillion

Europe: $5.06 trillion

2050 149-Country BAU vs WWS Annual Energy Cost

BAU fuel energy cost	$16.5 trillion/yr
BAU fuel health cost	$33.8 trillion/yr
BAU fuel climate cost	$30.9 trillion/yr
BAU total social cost	$81.2 trillion/yr
WWS total social cost	$6.7 trillion/yr

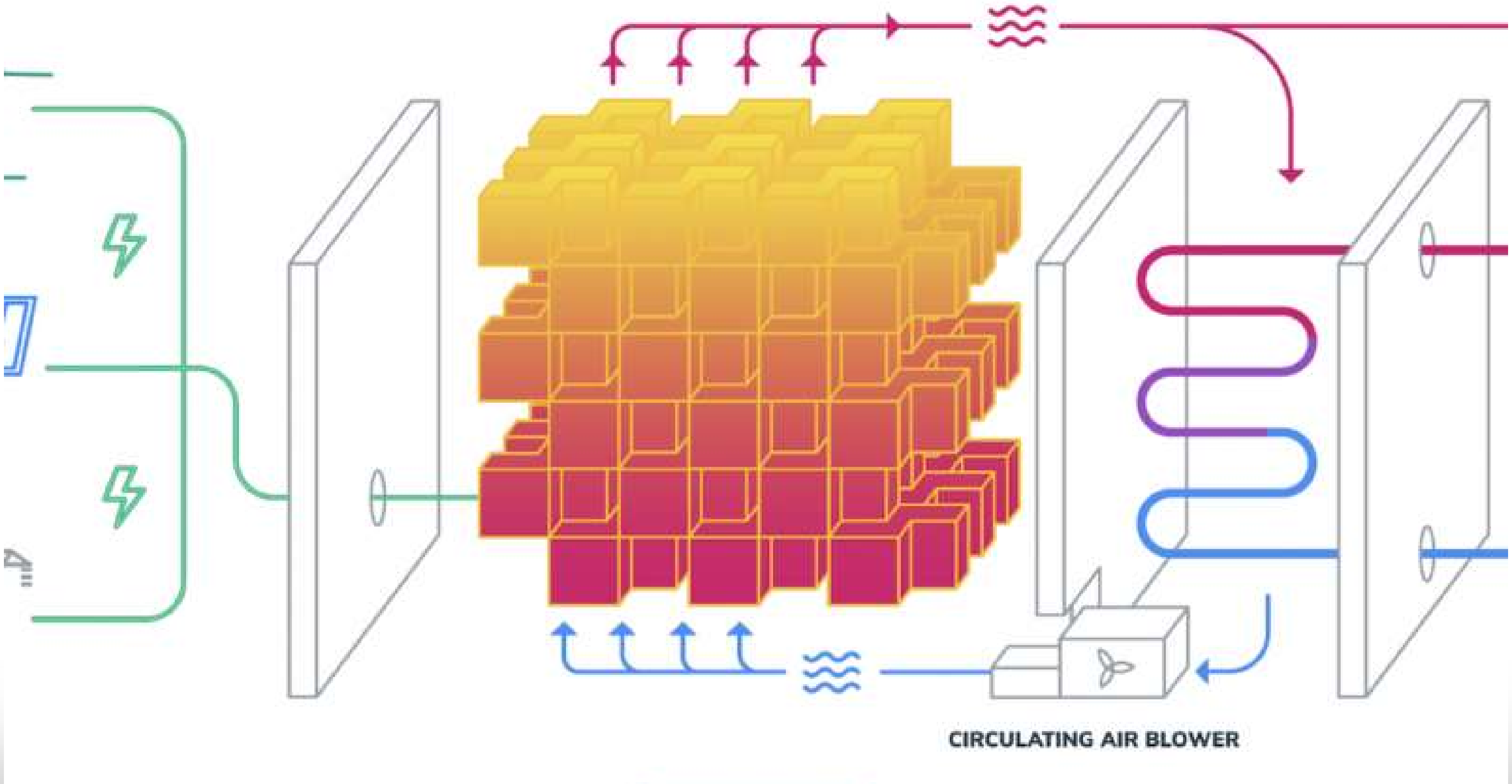
WWS reduces energy cost 60% and economic (social) cost 92%

Jacobson et al. (2024)

World Average Levelized Cost of Electricity in 2023 (IRENA, 2024)

Fossil fuels	$100 / MWh
Utility PV	$44 / MWh (56% lower)
Onshore wind	$33 / MWh (67% lower)
Offshore wind	$75 / MWh (25% lower)
Geothermal	$71 / MWh (29% lower)
Hydro	$57 / MWh (43% lower)

Firebricks



Bricks that store heat up to 2,000 Celsius for 90% of industry

Impacts of Firebricks on Cost of WWS System

Bricks that store low- to high-temperature heat for 90% of industry

Heat (resistive) from 100% renewable wind-water-solar (WWS) electricity

Air blown through channels in the bricks allows industry to run 24/7 on WWS

One tenth the cost per kWh-storage as batteries & eliminates need for furnaces

Tests across 149 countries with firebricks replacing other heating: Reduces world capital cost to transition by $1.27 tril. (from $58.24 to $56.97 tril.) and LCOE by1.8%.

AOTA Vs WWS: 4 Cases Across 149 Countries

BAU: Business-As-Usual

BAU-CC-BAU: CC attached to fossil and bioenergy stationary sources; SDACC offsetting mobile and distributed CO_2 sources, and using BAU sources to supply the electricity for CC and SDACC

BAU-CC-WWS: Same as BAU-CC-BAU, but using WWS sources to supply the electricity for CC and SDACC

WWS: Replace all non-WWS BAU energy with WWS

Impacts of CC and SDACC on Cost + Emissions

2050 BAU energy demand 6.74% lower than 2020 due to energy efficiency improvements

9.8% of remaining 2050 BAU demand comes from WWS; 2.3% comes from nuclear. Such sources are assumed to emit no CO_2.

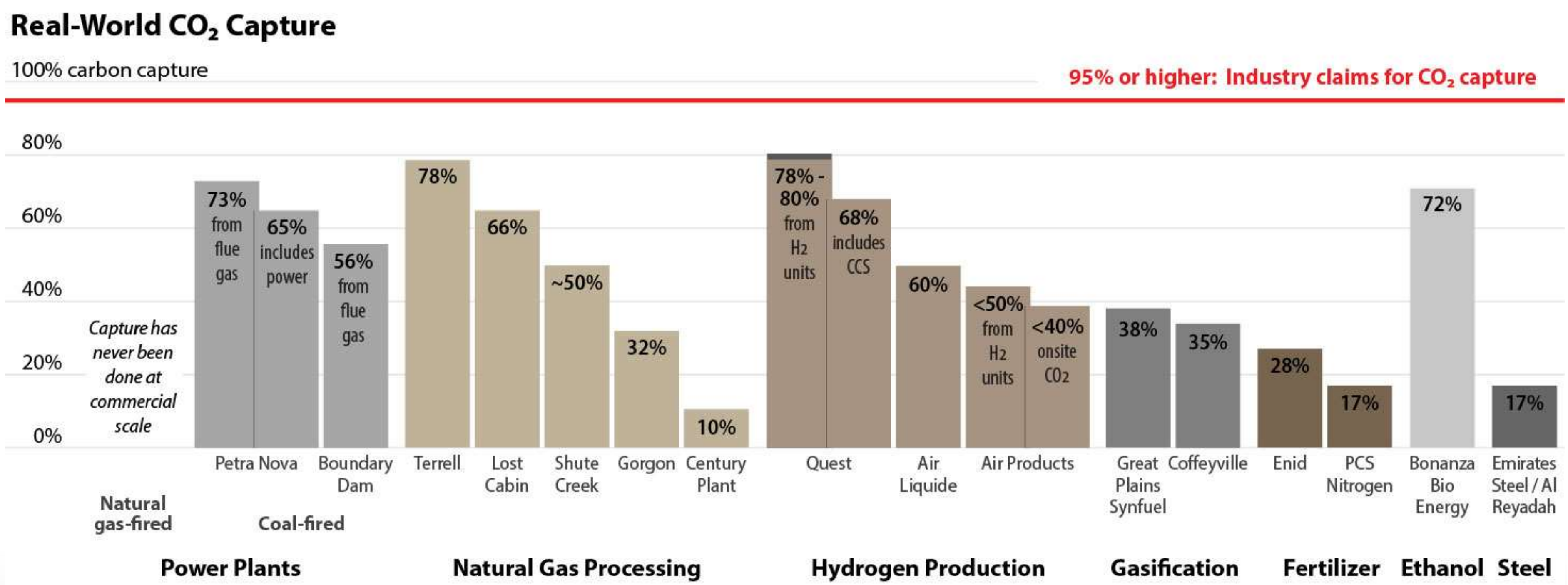
85% of remaining BAU CO_2e emissions are CO_2

80% efficiency of CC and SDACC equipment (IEEFA: 10-80%)

25% more energy needed with CC and SDACC (IPCC: 13-44%)

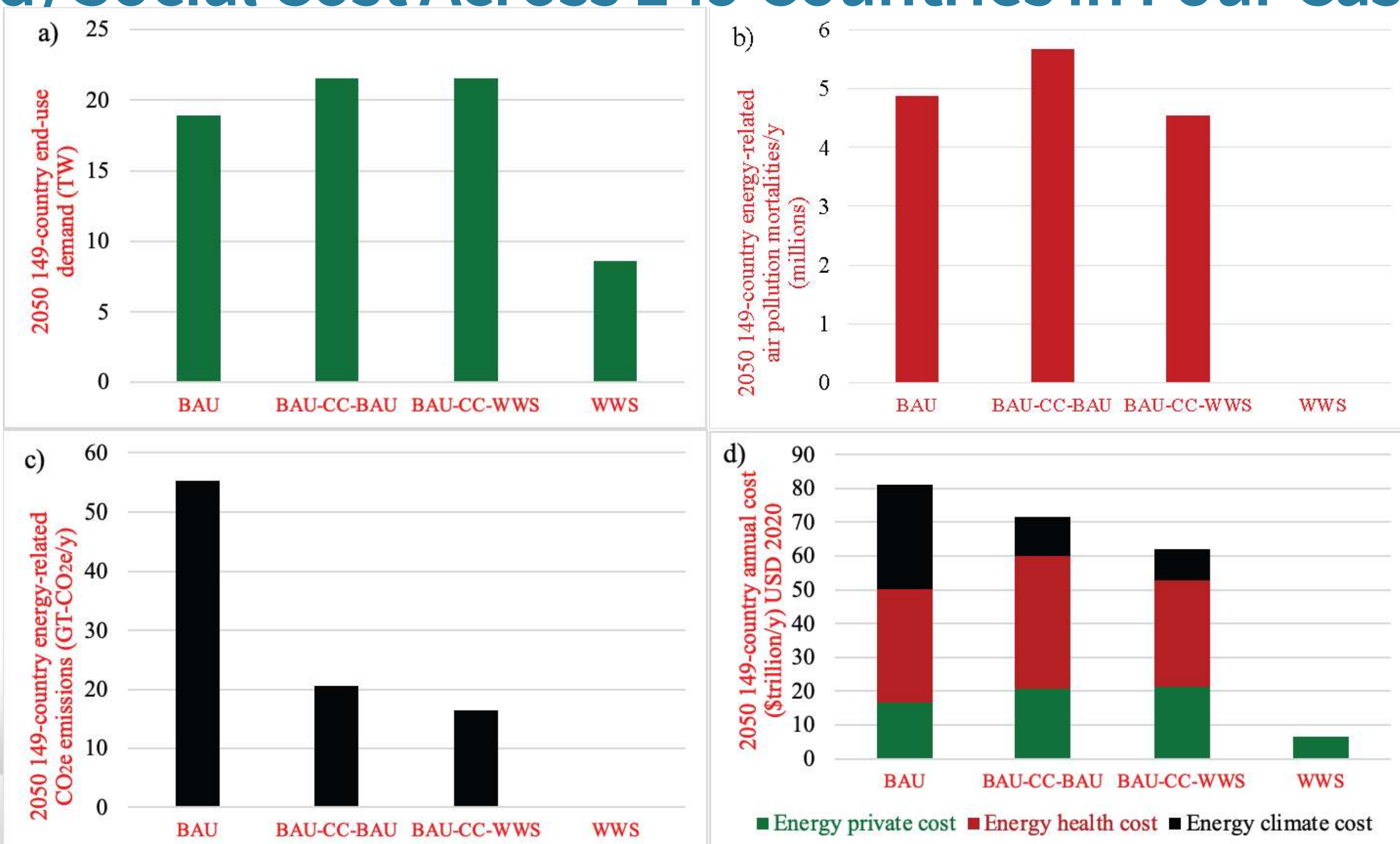
Assumes all CO_2 stored although 82% today used for EOR, which releases 30-40% back to air during EOR operations & 20-80% due to burning extra oil

Real-World CO_2 Capture Efficiency: 10-80%, Not 95%



Schlissel, D., and A. Juhn (2023), IEEFA

a) Energy Demand; b) Air Pollution Deaths; c) CO_2e; d) Social Cost Across 149 Countries in Four Cases



Conclusion With Respect to CC/SDACC

Climate policies that propose the use of CC and/or SDACC to reduce energy-related CO_2, will instead increase air pollution, CO_2e emissions, energy needs, and private energy costs substantially relative to policies requiring 100% WWS. Social costs will be 9.3 to 10.7 times those with 100% WWS.

The conclusions apply to any level of carbon removal above zero.

CC and SDACC may, in the limit, cause millions of unnecessary air pollution deaths each year and substantial climate damage in the short and long term.

As such, policies promoting CC and SDACC should be abandoned.

Nuclear Planning-to-Operation Times

	Construction Time (Years)	Plan-to-Operation Time (Years)	Cost $/W
Olkiluoto 3 (Finland)	18	23	8
Hinkley Point (UK)	11-13	21-23	19
Vogtle 3 and 4 (US)	10-11	17-18	16
Flamanville (France)	17	20	16
Haiyang 1 and 2 (China)	9	13-14	
Taishan 1 and 2 (China)	10-11	12-13	
Shidao Bay (China)	10	17	
Barakah 1-4 (UAE)	9	12-15	

Issues With New Nuclear as Part of the Solution

Takes 12-23 y between plan & operation v 0.5-5 y for new solar/wind

Capital cost 10-20 x and cost per unit energy 3-8 x those of wind/solar

Produces 9-37 times more CO_2e & pollution per unit energy than wind

IPCC 2014: P. 517. "Robust evidence, high agreement" that increased use of nuclear leads to more

(a) Weapons proliferation risk
(b) Meltdown risk
(c) Waste risk for 200,000+ years
(d) Underground uranium mining lung cancer risk

Book on 100% WWS ("'No Miracles Needed'")

https://web.stanford.edu/group/efmh/jacobson/WWSNoMN/NoMiracles.html

100% WWS Plans for Countries, States, Cities

web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html

Online Course on 100% WWS

https://stanford.io/windwatersolar

Infographic maps

https://sites.google.com/stanford.edu/wws-roadmaps/home

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