CLIMATE NORTH STAR

A MAXIMUM SPEED GLOBAL CLIMATE RESCUE PLAN

We are unwilling "to be plunged into the abyss of despair."

Martin Luther King Jr.
"Letter from Birmingham Jail"
(paraphrase)

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CONTRIBUTORS

David Merrill
Project Director
Climate North Star

Mark Chavez
Climate justice organizer

Dr. Dominick A. DellaSala
Chief Scientist
Wild Heritage,
a project of the Earth
Island Institute

Steve Nelson
Independent energy researcher

Jeremy Drake
Certified Associate &
Instructor
Zero Waste USA

Dr. Scott Denning
Professor of Atmospheric Science
Colorado State University

Dr. Marshall McDaniel
Associate Professor, Agronomy
Iowa State University

EXECUTIVE SUMMARY

As the nation and world experience climate impacts of increasing frequency and ferocity one question has become central and urgent. How quickly can we execute a maximum speed global climate rescue plan? And what would be the impact on global temperature and other key metrics of such a maximum speed transformation? Climate North Star is a proposal that answers these questions in a scientifically grounded way.

Climate North Star demonstrates what a global cessation of fossil fuel burning and transformed forest and agricultural practices, all pursued at maximum speed, could yield in terms of reduced:

- Carbon emissions
- Global average temperature
- Atmospheric CO_2 levels
- Sea level rise

The 1.5 degrees Celsius Paris Agreement temperature target is the most pervasive metric in the public climate conversation. Therefore, we think that global average temperature, currently at 1.2 degrees Celsius above pre-industrial levels, should be the primary metric to track progress in that conversation.

The Climate North Star goal is to reduce global temperature to as close to 0.5 degrees Celsius above pre-industrial levels as rapidly as possible and no later than 2100.

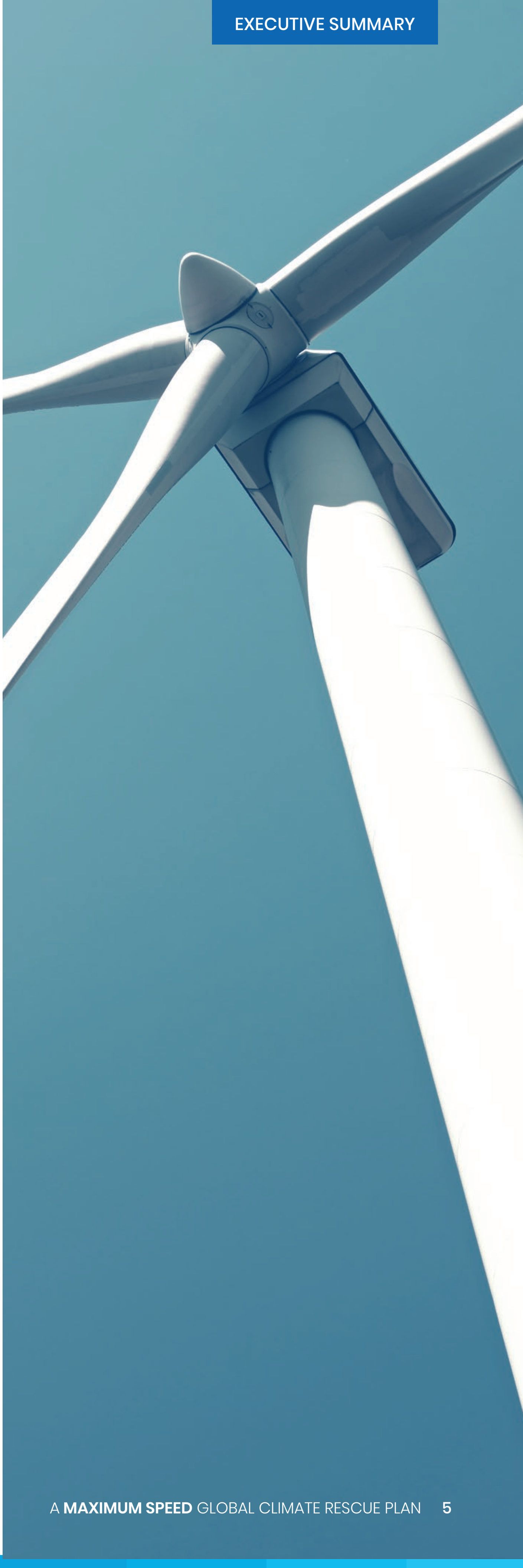
Climate North Star was inspired by a landmark paper published by James Hansen, PhD and colleagues in 2017, entitled “Young People’s Burden: Requirement of Negative Emissions.” That paper’s finding was that the safe long-term global warming temperature is 0.5 degrees Celsius above pre-industrial levels, last observed on Earth in 1985. This temperature, called the Holocene Maximum, is what allowed cities to be built on coastlines around the world. A “safe” temperature in this report is one that would prevent multi-meter sea level rise, which would flood coastal cities, and could lead to the collapse of society, an impact aptly referred to by some as the “world-killer.”

Isn’t 1.5 degrees Celsius a safe long-term temperature? No, it is not. The 1.5 C target is the product of political--not scientific--deliberation. Some climate scientists have defended a 1.5 degrees C warming goal because a 1.5 C rise would yield less devastating impacts than a 2 C rise. This is hardly a momentous revelation. And it is critical to understand that a long temperature of 1.5 degrees C global warming would be catastrophic. After the summer of 2023 that should surprise no one. Even our current 1.2 degrees C above pre-industrial levels is clearly too high as a long-term global average temperature.

KEY FINDINGS

Implementing the maximum Climate North Star recommendations we project would:

- Cause global average temperature to peak at 1.3 degrees Celsius above pre-industrial levels by 2030.
- Yield a 1 degree Celsius or lower global average temperature by 2100.
- Limit atmospheric CO_2 concentrations to 428 ppm by 2030 falling to 372 ppm by 2100.
- Limit 2100 sea level rise to 5 inches below the most aggressive IPCC scenarios, returning in a few centuries to pre-industrial conditions.



Reaching the Climate North Star temperature goal entails the following:

- Achieving global all-sector 100% renewable energy by 2035.
- Transforming global forestry practices at maximum speed to reduce the release of, and sequester, carbon in Earth's forests and store it long term. *(Unless indicated otherwise, we use carbon as the unit of measurement, not CO_2. To convert the carbon figures to CO_2 multiply the carbon figure by 3.67. To convert the CO_2 figures to carbon divide by 3.67)*
- Transforming global agricultural practices at maximum speed to reduce the release of, and sequester, carbon in agricultural soils around the planet.
- Although not quantified in this paper, Climate North Star advocates reductions in personal consumption and waste generation by wealthy countries and individuals. This would function as a carbon reduction accelerator, especially in the years before reaching the 2035 target of global 100% renewable energy.

WHY THE 'ALMOST IMPOSSIBLE' CLIMATE NORTH STAR GOAL IS NEEDED

Undoubtedly achieving a global 100% renewable energy system by 2035 will appear almost impossible to many. 'Almost impossible' we believe is the sweet spot of ambition and feasibility. If it doesn't seem almost impossible then clearly we need to increase ambition. Any plan to effectively address global warming at this late hour would, of course, seem almost impossible. The most distressing thought is not how daunting the task we face is; a far worse thought would be not reaching the 2035 goal and realizing the climate emergency has moved beyond human capacity to impact. Therefore, the scientifically-informed moral commitment must be to execute the global climate rescue as rapidly as possible.

CLIMATE NORTH STAR IS AN EMERGENCY-LEVEL RESPONSE TO THE CLIMATE THREAT

Passage of the Inflation Reduction Act, despite many strong provisions, in no way represents a maximum speed climate rescue in the United States, much less the entire planet, especially as the U.S. continues to approve new fossil fuel projects.

The recommendations in Climate North Star make sense only if we are executing a comprehensive climate emergency response. There are things one would do in an emergency that would never be considered under normal circumstances. Certainly threatening the livability of Earth qualifies as an emergency.

It is a situation that cries out for federal government leadership not only to achieve a maximum speed carbon transition here but around the world as well. The most obvious historical parallel is the U.S. World War II industrial mobilization, supported by both business interests and labor. This maximum speed transformation was carefully planned and executed under federal leadership in order to achieve maximal industrial production while supporting workers and preventing an economic collapse. It was wildly successful.

CLIMATE NORTH STAR THROUGH A CLIMATE JUSTICE LENS

This report, and many being released at this critical time, are stuck in an awkward position. They seek to address the climate crisis at a scale necessary to avoid immense human suffering and other dire consequences of continued inaction for all living beings. All the while, it hopes to achieve these ends in a way consistent with the recent influx of calls for Climate Justice.

It is important to note that the concept of Climate Justice isn't some new tagline we can just apply to a more people-centric approach to mainstream environmentalism. It's the result of decades of organizing within environmental justice communities – continuing centuries of resistance to slavery, genocide, and colonization – that have already endured immense amounts of suffering at the hands of globalized, extractive economies.

The terminology of that movement, including Climate Justice and Just Transition, has increasingly been co-opted by mainstream environmentalists, politicians, and corporations to make their work appear more aligned with the needs and desires of the social movements that demand we do better as a society. Their actions, however, continue to show they're committed to maintaining a status quo that picks and chooses communities as collateral damage.

As objective, scientifically-based approaches to addressing the climate crisis, the ideas laid out in this report have not thoroughly considered the real-time impacts of implementing this plan on people, and in particular, the communities most impacted by the societal and industrial practices of extraction that got us here in the first place.

To be clear, there are contradictions between what is being proposed in this report and what the Climate Justice movement is advocating for and fighting against. To name a couple of main points to consider:

- Since the Climate Justice movement is about systemic change, any proposal that does not actively extricate power, capital, and resources from the dominant extractive system in the pursuit of building entirely new (or reinforcing old) ways of being that ensure the needs of people and the planet are put before the economy, it likely isn't aligned with the movement.
- Climate Justice also demands leadership of and accountability to the communities most impacted by the climate crisis and the world-view of extraction (of fossil fuels, but also labor and wealth) that brought us to this precipice; and also regarding proposed plans to solve the problems we face. As mere messengers – since we are not the only ones who will put this proposal into practice – we can't guarantee how this work will manifest after it's put out into the world.

For all these reasons, we hope this is the beginning of a conversation with the Climate Justice movement to see if there is any way that we can ensure what is being proposed here can be in alignment with the work you are doing.

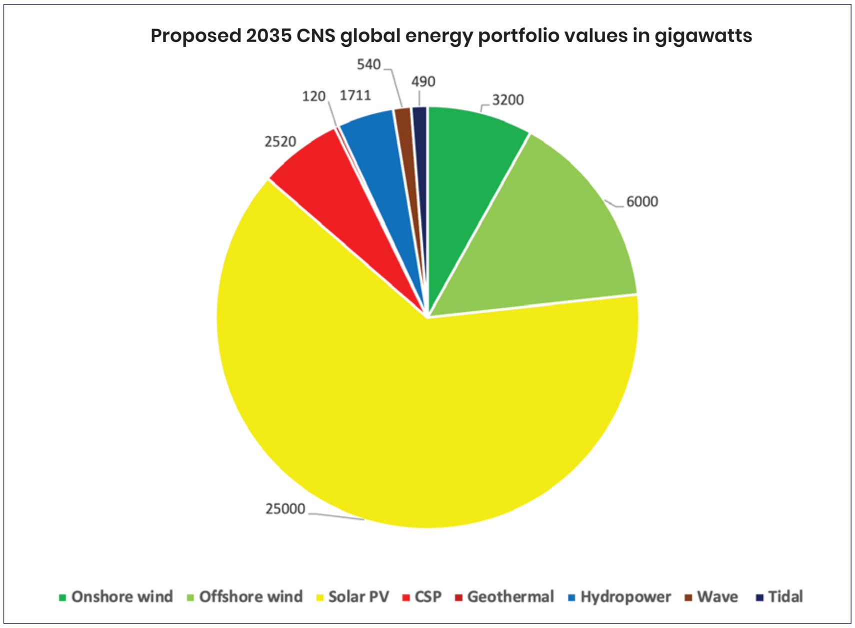
> *I am inserting this section into the paper you're reading so that every single person working to advance the Climate North Star (CNS) proposal cannot look back and say "I didn't know any better." A section on the importance of Climate Justice is included to give those less familiar with the concept an opportunity to deepen their understanding and because we believe at this point that incorporating a Climate Justice approach in everything we do is the best way to reduce harm – not just in the future – but for those already living through climate chaos and the extractive economy that needs to end.*

The Climate North Star Vision Rests on Four Pillars

PILLAR 01

TRANSITION TO GLOBAL ALL-SECTOR 100% RENEWABLE ENERGY BY 2035

Proposed 2035 Climate North Star Global Energy Portfolio



Climate North Star is undergirded by a scientifically informed moral imperative to carry out a maximum speed global climate rescue plan.

The faster we decarbonize the less destruction, suffering, death and risk of triggering increasingly catastrophic impacts.

Mark Jacobson, director of Stanford University's Atmosphere/Energy program and some of the world's leading wholesale energy transition researchers have concluded that achieving global 100% renewable energy for all purposes by 2035 is technically and economically feasible. The estimated global capital investment would be US$ 62 trillion. Over a 12 year period from 2023-2035 this would be approximately US$ 5 trillion per year out of an approximately US$ 100 trillion global GDP. The investment would be paid back in under six years from energy savings and under one year if social and environmental costs are included. (Energy&Environ. Sci., 2022, 15, 3343)

As climate impacts increase and intensify there is a growing sense that catastrophic global warming is everywhere now, perhaps captured most succinctly by July 2023 being the hottest month ever recorded on planet Earth.

Fortunately, our planet is blessed with an embarrassment of riches of renewable energy. The total annual solar radiation over the Earth's surface is greater than 5800 times the total global energy consumption by humans of 580 exajoules.

The fraction for 'solar PV' in our proposed 2035 portfolio is enormous; this would be a mixture of utility solar PV/non-agricultural, utility solar PV located on brownfields, floating utility solar PV, rooftop solar PV and parking lot solar PV.

High PV solar potential countries have a seasonality index below 2 and PV Output exceeds 3.5 kWh/kWpeak installed. Research shows that 86% of the global population lives in countries where these standards are met.

Additional resources proposed for the 2035 global energy portfolio are concentrated solar power, onshore and offshore wind, hydropower, geothermal power, and wave/tidal power.

PILLAR 02

IMPLEMENT GLOBAL CLIMATE-RESPONSIBLE FORESTRY PRACTICES AS RAPIDLY AS POSSIBLE

Forests are the most effective terrestrial carbon sinks on the planet and hold great promise for boosting the carbon transition but urgent steps must be taken now, the first of which is preserving unlogged forests, especially old growth and mature trees. Significantly, Climate North Star proposes natural carbon reservoirs and not the hugely problematic artificial carbon sinks that some IPCC scenarios rely upon for carbon reduction projections.

Climate North Star forestry recommendations

PROTECT THE STOCKS

In primary (unlogged) forests, especially mature-old growth forests and trees (most important) by ending deforestation and forest degradation. To maximize mitigation potential, deforestation and forest degradation would need to end now in the U.S., Canada and all other developed countries, and by 2030 globally, and forests protected for biodiversity and carbon at least tripled with half Earth protected by 2050.

PROFORESTATION

Allow degraded forests time to reacquire stocks by reaching maturity.

AFFORESTATION

Planting trees (preferably natives) on suitable fallowed fields.

REFORESTATION

(preferably natives) on cutover lands where needed.

The four pathways are all important in aggregate, however, protecting primary and older forests needs to be the top priority implemented in lock-step with getting off fossil fuels.

Protecting primary forests is the only effective carbon capture and storage approach that will work at scale immediately.

PILLAR 03

IMPLEMENT GLOBAL REGENERATIVE ORGANIC AGRICULTURE PRACTICES AS RAPIDLY AS POSSIBLE

Native Americans farmed in some parts of North America for 3,000-4,000 years prior to Euro-colonization. There is good evidence that many soils in the Midwest U.S. are now on average 46% of their capacity.

Global potential for sequestering carbon in agricultural soils is about 24 gigatons total, which is equivalent to approximately 2.5 years of energy related carbon emissions.

Climate change itself will have relatively minor effects on soil organic carbon in agricultural soils compared to changes in management practices, including the following:

5 PRINCIPLES OF SOIL HEALTH

Adapted from USDA Natural Resource Conservation Service

SOIL ARMOR	MINIMIZE DISTURBANCE	PLANT DIVERSITY	CONTINUAL PLANT/ROOT (PERENNIALITY)	LIVESTOCK INTEGRATION
Cover crops	Reduced tillage	Cover crop mixtures	Cover crops	Grazing cover crops
Residue	Lower compaction	Crop rotations	Perennial crops	Seed pastures in rotation
Reduced tillage	(controlled traffic)	Intercropping	Relay cropping	Adding manure
CRP (Conservation Reserve Program) or prairie strips	CRP or prairie Strips	CRP or prairie strips	CRP or prairie strips	

> *A "Regenerative Organic Agriculture" standard is possible, but will have to include scientific consensus and international government involvement. Standardization and third-party verification is also needed.*

PILLAR 04

REDUCE PERSONAL CONSUMPTION & WASTE

Wealth is a key driver of climate change and reducing waste is a key climate solution. Due to the complexities of measuring personal consumption and waste management activities across the globe, this section is not quantified and therefore will not be part of the calculations to determine the Climate North Star impacts on carbon emissions, atmospheric CO2 levels, global temperature and sea level rise described in the synthesis section of this paper.

But consider this: the Intergovernmental Panel on Climate Change (IPCC) has identified wealth as a key driver of energy demand[1]. And this: the U.S. Environmental Protection Agency has suggested consumption accounts for 50% of U.S. greenhouse gas emissions[2]. For those reasons, this section is designed to illuminate the connection between huge disparities in wealth, personal consumption, and waste generation in order to inspire a more frugal and consumption-conscious lifestyle.

A review of available global per capita energy use and waste data tracks with global wealth disparity largely on a nation-by-nation basis. On the one hand, Figure 1 shows the global average per capita amount of energy used in gigajoules per year (gj/a) for the residents of the world's wealthiest and poorest nations[3]. On the other hand, Figure 2 shows the same per capita breakdown for waste generation[4]. In both cases, the wealthy reign and American exceptionalism is on display: Per capita energy use in the U.S. is four times the global average and waste generation is three times the global average.

Figure 1. Comparing Per Capita Energy Use – 2017/2018

Average amount of energy used per capita in gigajoules per year (gj/a)

Per Capita Grouping	gj/a
United States	325
Wealthy Nations	210
Global average	80
Poor Nations	20

source: eia.gov

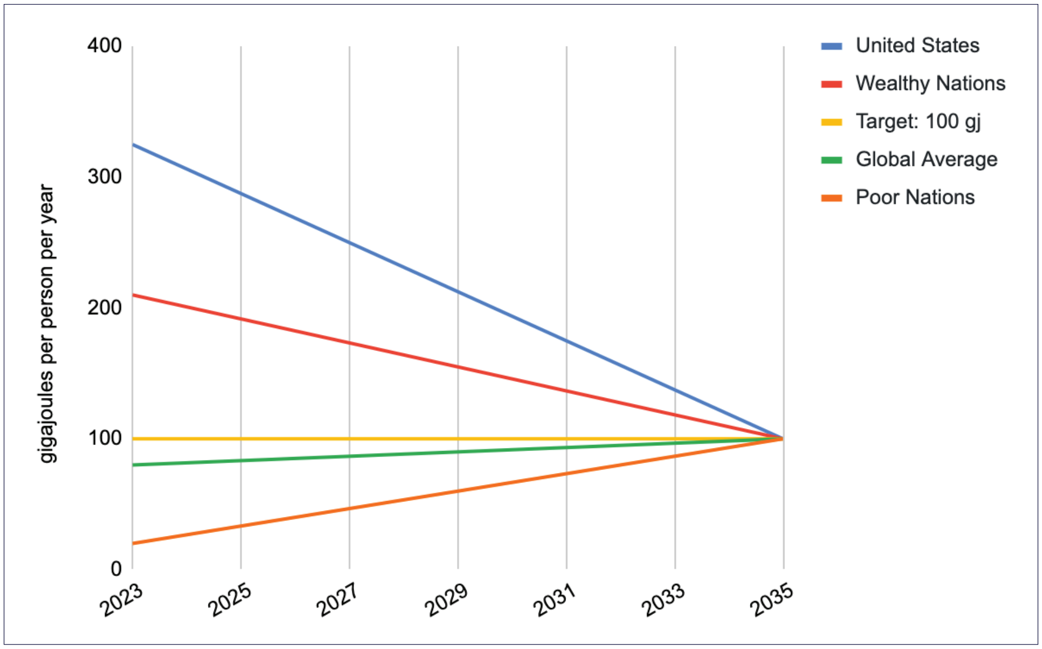
Figure 2. Comparing Per Capita Waste Generation

Per Capita Grouping	lbs/day
United States	4.9
Wealthy Nations	3.5
Global average	1.6
Poor Nations	0.9

source: worldbank.org

1. https://www.ipcc.ch/sr15/
2. U.S. EPA. (2009). Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices. https://archive.epa.gov/greenbuilding/web/pdf/ghg_land_and_materials_management.pdf
3. EIA data for energy consumption in wealthy countries (United States, Canada, United Kingdom, Italy, Germany, Japan, New Zealand, Australia, Luxembourg, Belgium, Austria, Switzerland, France, Denmark, the Netherlands, Finland, Sweden, Norway, Spain, Portugal, Israel, Ireland, and Iceland) and poor countries (Democratic Republic of Congo, Mozambique, Uganda, Tajikistan, Yemen, Haiti, Ethiopia, Tanzania, Kyrgyzstan, Uzbekistan, Zambia, Pakistan, Myanmar, Cambodia, Bangladesh, Cote d'Ivoire, Kenya, Nicaragua, India, Nigeria, Ghana, Vietnam, and Honduras) accessed via https://en.wikipedia.org/wiki/List_of_countries_by_energy_consumption_per_capita
4. World Bank. (2018). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. http://hdl.handle.net/10986/30317

We propose a roughly fair global per capita energy use target would be 100 gj/a. While we do not suggest a global per capita waste generation target, waste generation data suggest that wealthy nations could curb consumption and adopt Zero Waste policies, programs, and practices that would reduce waste and cut related emissions.



Reducing personal levels of consumption and waste is not a substitute for engaging in political action to address system wide challenges, which we desperately need right now. However, while most elected officials would consider addressing wealth disparity to be politically unfeasible, Zero Waste policies, programs, and infrastructure have gained traction across the globe for their support of local economies, environmental justice, and resource conservation while helping reduce consumption-related emissions.

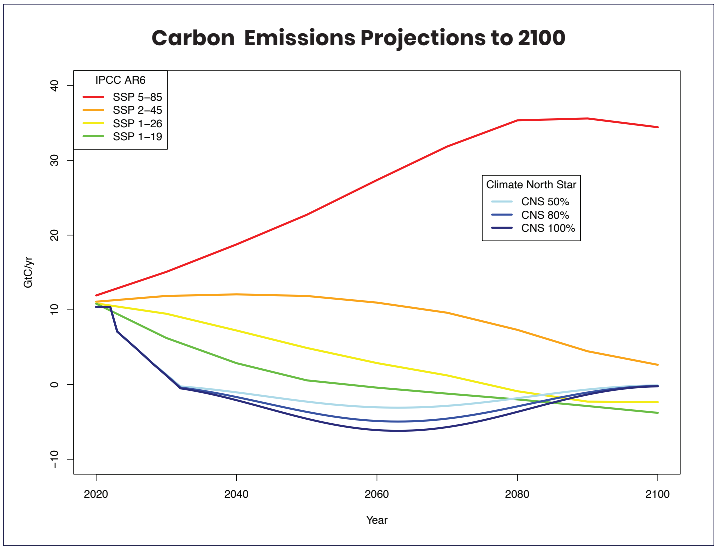
CLIMATE NORTH STAR

SYNTHESIS IMPACTS

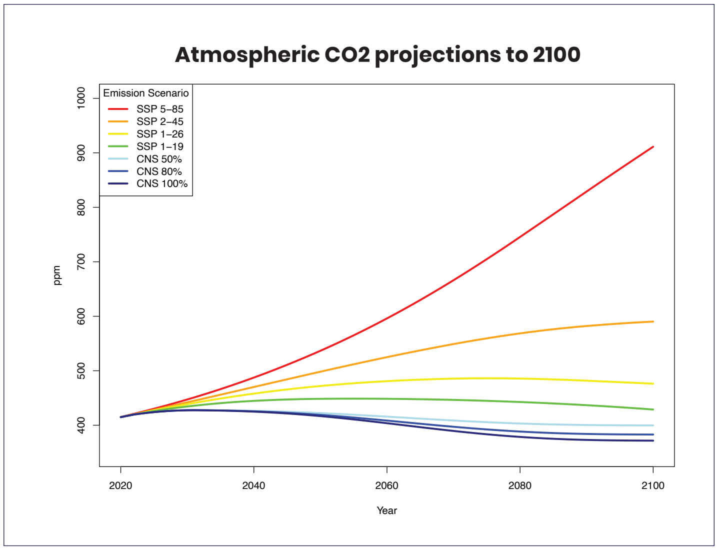
Climate North Star projects impacts on global carbon emissions, atmospheric CO² levels, global temperature and sea level rise from implementing the recommended fossil fuel emissions reductions and changes in forestry and agricultural practices.

There are three different Climate North Star scenarios projected for each of these metrics differentiated by percentage implementation of transformed forest and agricultural practices (50%/80%100%). The fossil fuel phase-out schedule is the same for all three scenarios.

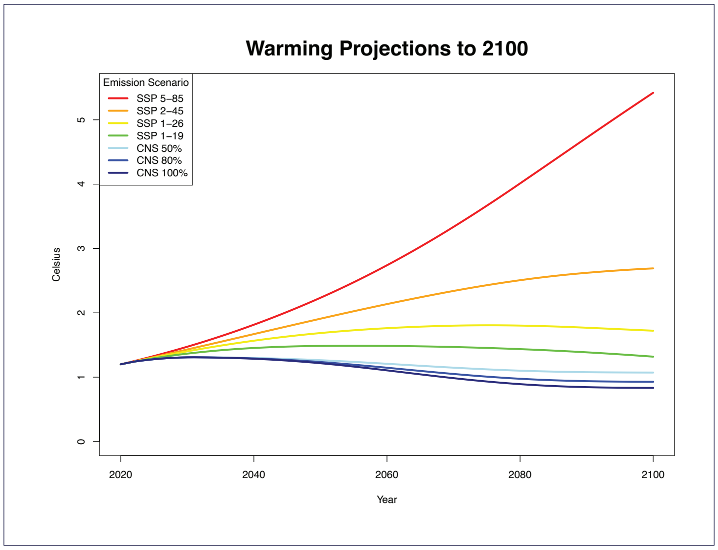
We call for emissions from fossil fuel combustion to fall to zero in 2035 in conjunction with land-use transformation. This impacts total carbon emissions at three different levels depending on the degree of land-use changes.



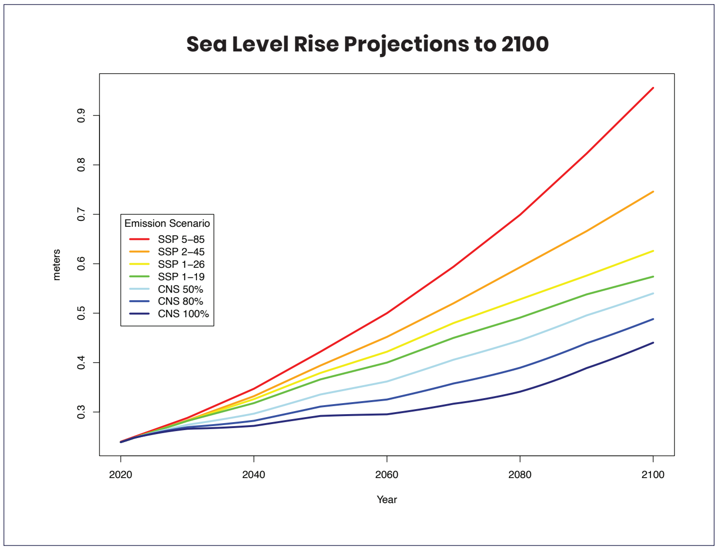
Atmospheric CO_2 levels peak at 428 ppm in 2030 in all three CNS scenarios and drops to as low as 372 ppm in 2100 under the CNS 100% scenario.



Global temperature in all three CNS scenarios peaks around 2031 at 1.3 Celsius and falls to 1.0, 0.9, or 0.8 C by 2100 depending on the degree of land use changes.

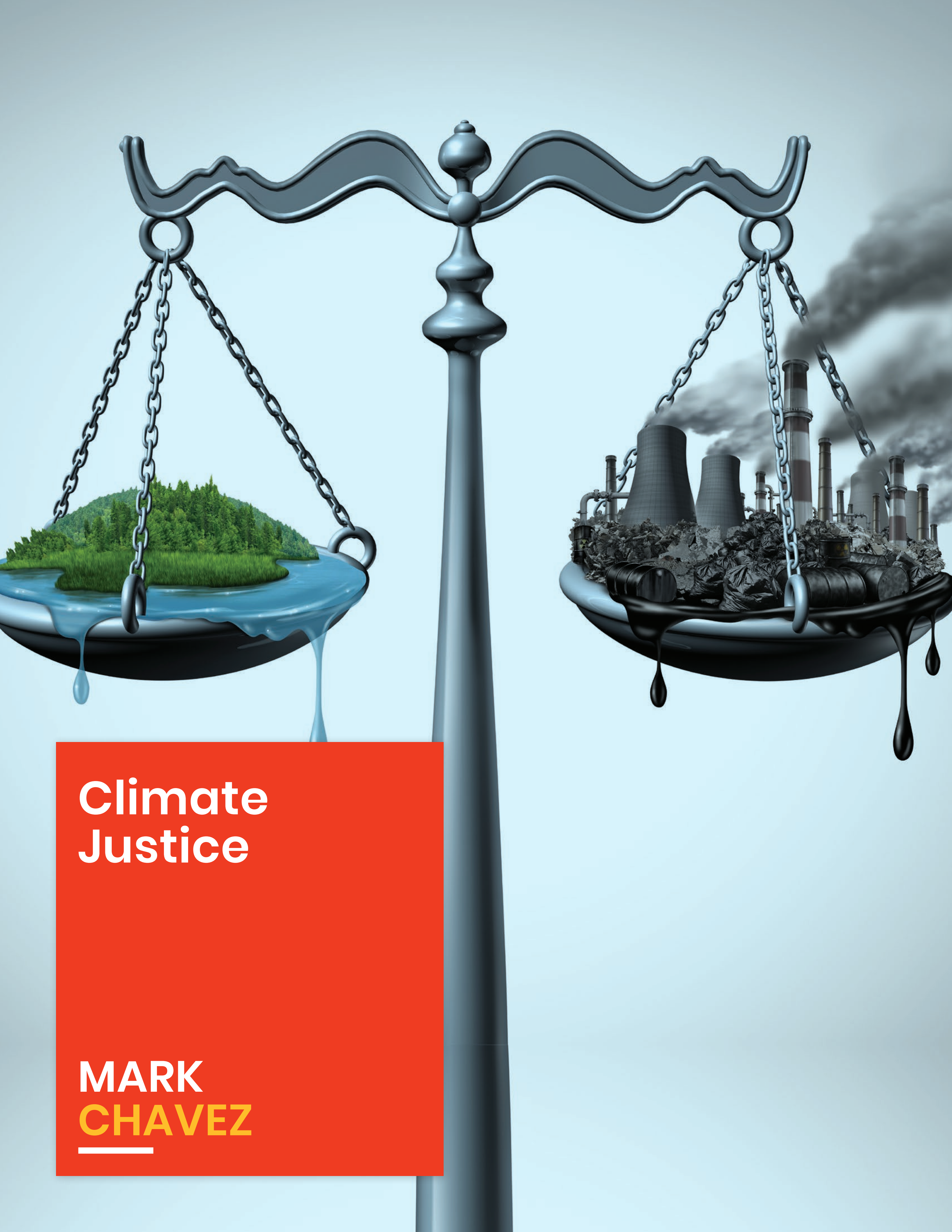


CNS 100% 2100 sea level rise is 5 inches less than the most aggressive IPCC scenario of 22 inches (here graphed in meters)



CLIMATE
NORTH STAR

FULL REPORT



Climate Justice

MARK
CHAVEZ

> ***I've been reluctant to write this section ever since I was asked to. Even as I sit here, rewriting this intro, after landing on what I feel is an adequate piece. After sharing it with some people to look over.***

I've been hesitant because I worry that having this section on Climate Justice in a paper about a fast-tracked decarbonization plan to address the climate crisis will be seen as a seal of approval. The mandate everyone was hoping for from frontline communities to those who wish to advance this agenda: because you skimmed through the now obligatory section on Climate Justice on your way to the important, juicy stuff. You trudged through this head nod to the frontlines: because mainstream environmentalism has had enough equity, diversity, and inclusion (EDI) training at this point to know how important it is to pay lip service to EDI in order to keep us angry Brown folks at bay.

This worry isn't unfounded. In a broader sense, this obsession with EDI is at best a way to ease white guilt, and at worst an act of racial capitalism. While more specifically, and in no uncertain terms, the Environmental and Climate Justice movements have long faced co-optation. The terminology created by these communities has long been taken and used by mainstream environmental groups who have profited to the tune of hundreds of millions a year. The most recognizable groups on the forefront of "saving the world", the ones with vest-adorned worker bees in the street, asking you to contribute to the fight, while they already absorb 99% of philanthropic dollars going towards addressing the climate crisis and conserving the natural environment. The same groups who have created program areas that replicate their traditional top-down approach and lack of community accountability, but call them Climate Justice, and Just Transition, and Just Recovery. Like corporate real-estate developers squeezing the lifeblood out of cities in the pursuit of profit while creating culturally devoid, gentrified wastelands. These flagrant attempts to label the ineffectual strategies and tactics of mainstream, white dominated work isn't just annoying. It's harmful. It's a racist and classist act that continues the "dominant" culture's extractive behaviors. It's a continuation of Papal Bulls – issued by popes in the 1400s giving Christian Nations permission to "claim" non-Christian lands as their own. It's a manifest destiny over grassroots movements – Americans fulfilling their essential duty. It's 21st century pilgrims riding the wave of American Exceptionalism that is going to save the world and its needy people, by any means necessary, whether they like it or not.

If you haven't realized it yet, I'm not here to give y'all a thumbs up. I'm here to challenge you. I'm here to call attention to repeated mistakes on the part of mainstream environmentalism, that have been repeated so much that at this point it only feels appropriate to refer to it instead as a well tuned system doing exactly what it was designed to do. Issues that perpetually draw attention away from the critical work being done to create alternative economic structures, work led by communities most impacted; work that digs deeper than the surface and addresses root causes of problems rather than focusing on mere symptoms.

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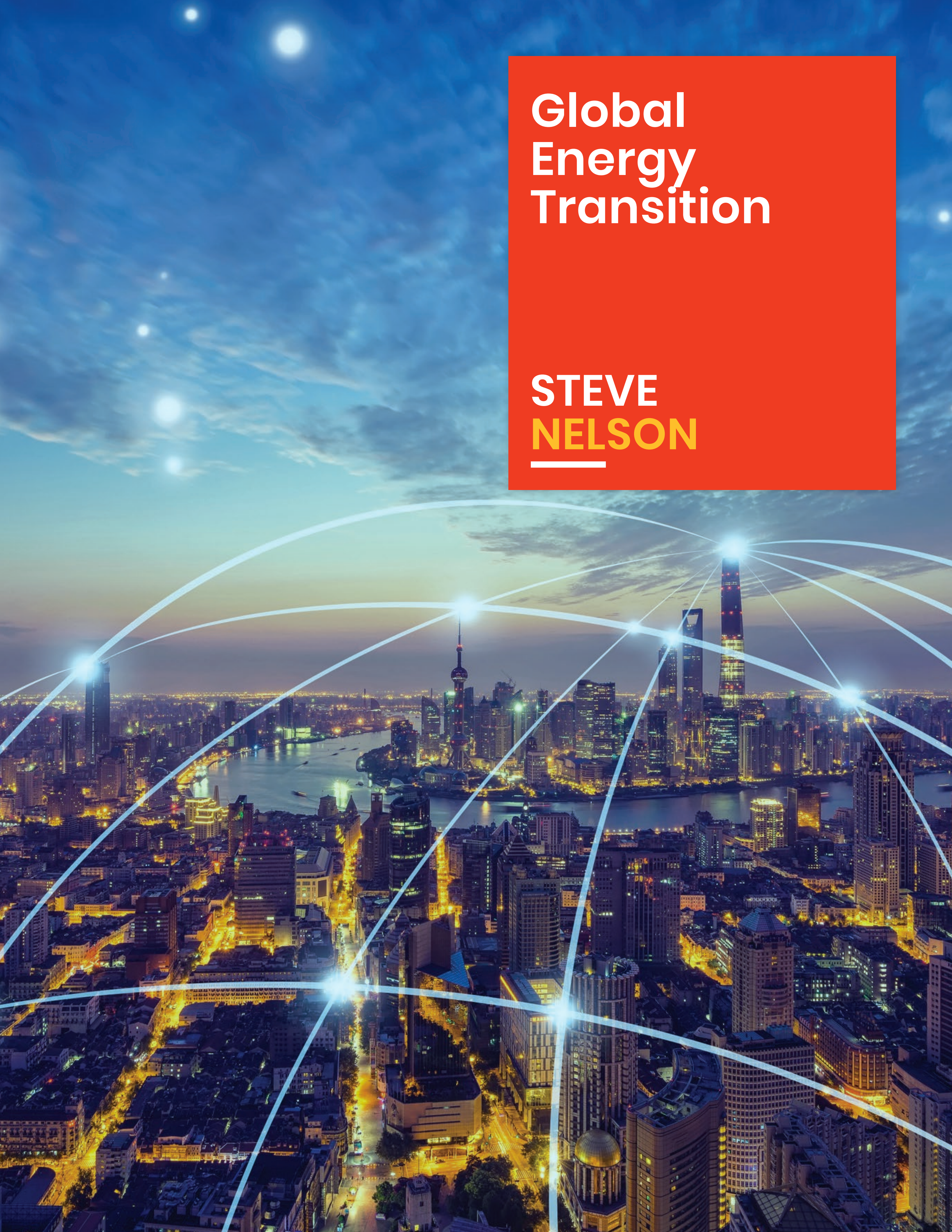
Global Energy Transition

STEVE NELSON

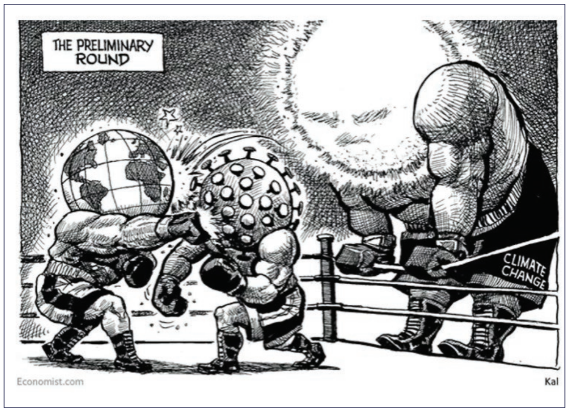


A MAXIMUM SPEED TRANSITION TO GLOBAL ALL-SECTOR 100% RENEWABLE ENERGY BY 2035

How quickly, quantitatively, could fossil fuel generation be replaced with renewable generation plus storage, an upgraded grid, demand-side management and efficiency measures. This section of the paper lays out the multi-layered response to this question. The driving imperative is the need to rapidly decarbonize our energy infrastructure to surmount the laissez-faire 'can't do for some reason' entrenchment that characterizes humanity's insufficient response to our greatest challenge and threat to our existence.

The first truth: we need enormous amounts of renewable energy generation, storage, manufacturing capability and creative financing, and we need it in a very short time frame. Suffice to say we will need to build our grid to 2.5 times current capacity to electrify our entire energy system, we will need 13 TWh of storage (US) and 80 TWh (globally) to back up intermittent wind and solar resources, all in twelve years to implement the changes that Climate North Star recommends. To achieve this, we will need a vast palette of energy and storage options, each technology contributing to energy production in its appropriate niche and at its maximum production capacity. No technology should be overlooked based on cost; if COVID-19 served no other constructive purpose to humanity but to clear away illusions that a global catastrophe's lasting impacts on life, liberty and the pursuit of happiness can be ignored or minimized, then we should look forward with different eyes to the impending and immediate challenge, chaos and suffering that climate change promises. The costs of climate change will dwarf those of the technologies that we seek to marshal in the effort to avert this cataclysm.

Source: The Economist



> *"For business and political leaders Covid-19 conveys two other lessons. First, their organizations can move more quickly than they ever thought possible. Second, those who played down the warnings of the plague have now received a taste of what it will be like if they continue to ignore scientists warnings about a far greater scourge to humanity: climate change."*
>
> --Michael Moritz, Financial Times

However, no technology should be embraced without a thorough review of its potential to address energy transformation in a substantial, efficient and just way. Additionally, these technologies cannot be built virtually; all will require material construction, and therefore resources. While every effort must be made to ensure that buildout of the green energy structure yields minimized environmental impact on an already stressed system, let us be clear that "minimized" is non-zero….meaning there will be impacts. And one of the first tasks will be to identify those impacts and choose wisely in a dance that maximizes carbon reduction while minimizing environmental degradation.

The second truth: This transition will be a beneficial change. It will meaningfully address climate change, not by some slow and ineffectual piecemeal process, but by a bold movement forward that encourages innovation and education, provides jobs, business, taxes and investment opportunities, and focuses our national and international attention on a positive goal: creating a more sustainable and just world for all.

The total global energy use is staggering, *but the available non-fossil energy resources are even more staggering*. There are many who say it is impossible, but implicit in that statement is commentary on the political will to act, not the technological power to address climate change. It is our duty to preserve a livable world for our children and generations to come who will look back on us. Will they look with respect and gratitude or horror and hatred?

A TERA-WHAT?

An understanding of the magnitude of the task is critical and requires grasping the size of the numbers in that process. The following examples will hopefully illuminate the quantities (in terms of watt-hours) necessary to achieve this task.

What is a watt?

A watt is a unit of power and is defined as the equivalent flow of electricity at a rate of one joule per second…that will suffice for physics, but not a layperson's gut feeling. A better real-world example: burning a wooden match produces approximately 0.3 watts; 3.5 matches yield around 1 watt of power. One watt is sufficient power to illuminate 2.5 incandescent mini-Christmas bulbs.

What is a watt-hour?

An old incandescent light bulb rated at 100 watts illuminated for 1 hour uses 100 watt-hours of energy (100W x 1.0 hour). Ten 100W bulbs illuminated for 1 hour used 1000 watt-hours, or a kilowatt hour (kWh). The average US household uses around 24 kWh daily, or the equivalent of ten 100 watt bulbs turned on all day.

Kilowatt, Megawatt, Gigawatt and Terawatt?

A Tesla Model S at highway speeds uses 1 kilowatt hour (kWh) of energy to travel 5.1 km (3.1 mi.)* At a speed of 75mph, the Model S will use approximately 24.2 kWh of energy in 1 hour of driving.** In 41.3 hours, the "S" will travel 3100 miles, the equivalent of a road-trip from San Francisco to Portland Maine, and will use 1000kWh, or 1 megawatt-hour (MWh) of energy. 1000MWh, or a gigawatt-hour (GWh) of energy will drive the "S" 3,100,000 miles, which is a longer road-trip of 6.5 round-trips to the Moon and back. 1000GWh, or a terawatt-hour (TWh) will push the "S" 3,100,000,000 miles, which is the equivalent of 17 round-trips to the Sun and back.

In 2019, the US used 9,580 TWh of end-use energy. This amount of energy will push the Model S to 30 trillion miles, well beyond the nearest star, Proxima Centauri, at 25 trillion miles. World energy consumption is at least five times this amount.

* insideevs.com/news/347918/tesla-model-s-long-range-epa-rating

** (1 hour in the "S" = average daily household. For comparison, a gallon of gasoline supplies about 34 kWh of energy, but only around 25% of that is used to drive the car...the rest is lost as heat and mechanical inefficiencies. To travel 75 miles in a gasoline car getting 25 mpg requires 3 gallons or ~100kWh of energy)

The total energy use globally in 2021 was 172,000 TWh, which is 172,000,000,000,000 kilowatt-hours (kWh). For comparison, the average US household in 2021 used 10,632 kWh (eia.gov); the average global household used around 3,500 kWh (2010, World Energy Council). 172,000 TWh would power 16.2 billion American households, and nearly 50 billion global households. A joint declaration by the Global 100% RE Strategy Group (2021) which is backed by research from Mark Jacobson et.al., states that the entire global energy demand can be met with renewable energy, primarily wind and solar, supported and integrated by "storage, sector coupling, demand response management, large- and small-scale grid integration", with the transformation of the electrical sector feasibly by 2030, followed by the entire global energy sector by 2035.[1] Such a transition will create jobs, reduce mortality due to air pollution, and be an economic engine in the long term. Jacobson et.al. outline a roadmap for the transition for 145 countries in their paper "Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries"[2]. Increasingly, the roadblocks to this transition are political vision and will, and decreasingly technical feasibility, economics and job issues.

In this section, we review the resource availability after filters of technological readiness, feasibility, geography, and other metrics are applied. Based on this review and the application of conservative estimates for actual use of each resource, it is abundantly clear: the replacement of fossil fuels by renewable resources is possible. Energy storage, essential to addressing the challenge of ensuring dispatchable power in the face of intermittency and possible long-term loss of resource (storms, calm winds, smoke from forest fires, extreme cold and heat), as well as leveling the electrical load/ demand curve typical of all users, is addressed later in this section.

CURRENT GLOBAL ENERGY PORTFOLIO

Global energy use values calculated for 2021 ranges from 165,451 TWh (Statista.com) through 167,781TWh (ourworldindata.org) to 172,000TWh (Statistical review of World Energy 2021). We did not try to elucidate the reasons for the variation; instead, we assumed a total use of 170,000 TWh of primary energy for 2021 globally. The breakdown of these values is in table 1, and include consumption by source.

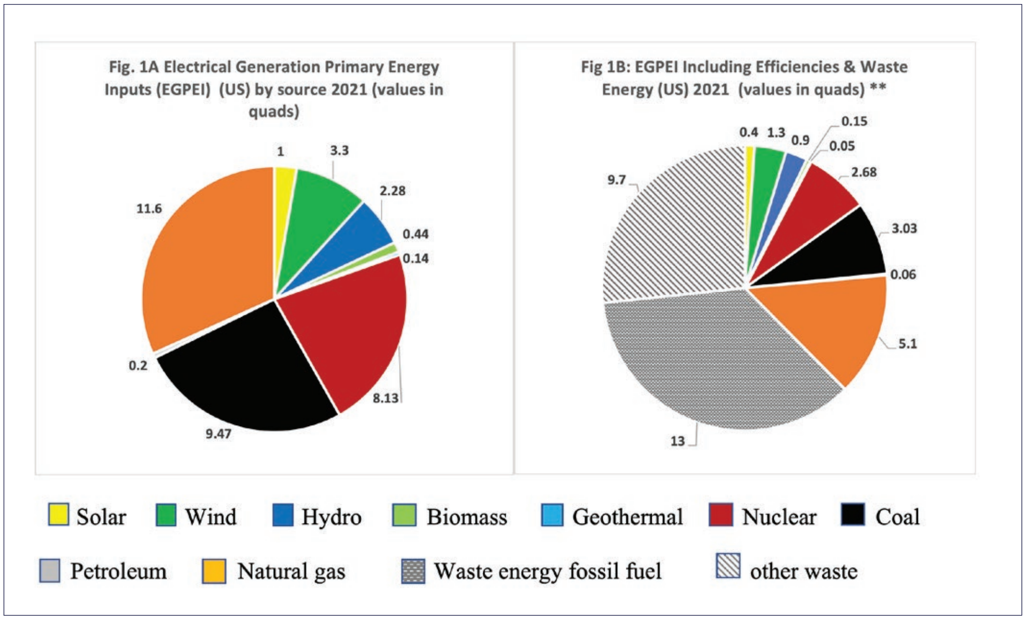
Table 1: Global energy data (three sources): primary energy by source
(Statista lists the global energy use 2021 as 595.15 exajoules which = 165,451 TWh)

Source:	%	TWh[3]	quads	TWh[4]	Other	TWh[4]	TWh ('18)[5]
Oil	31.2	53664	183	51170			52820
Coal	27.2	46784	159	44473			43924
Nat gas	24.7	42484	145	40375			38304
Hydro	6.9	11868	41	11183			10564
Nuclear	4.3	7396	25	7031			6672
Other	5.7	9804	34	13549			7506
					Solar	2702	
					Wind	4872	
					Mod biofuel	1140	
					Other renew	2373	
					(unspecified)	2462	
Total	100	172000	587	167781*			159850

Current global primary energy use

Energy use is best described in terms of primary energy used rather than the quantity of end-use energy. For example, a natural gas home furnace that is 80% efficient might have an output of 80,000 btus of actual heat energy pumped into a living space; however, because the furnace is only 80% efficient, 100,000 btus of primary heat energy are required to be used (combusted) in order to create the 80,000 btus of heat (end-use); the remaining 20,000 btus of energy are exhausted up the flue. Similarly, an internal combustion engine that is 35% efficient may consume 200,000 btus of primary energy in gasoline, but only 70,000 btus is available to do actual work of moving the car (end-use); the remaining 130,000 btus is lost as heat, typically through friction and cooling by the radiator. The useful (end-use) energy is important to quantify, as this is what is actually used; however, when discussing an energy transition, it is critical to quantify the primary energy that will be replaced. Since fossil combustion is typically 25-45% efficient, we need only replace the useful energy, not the waste energy.

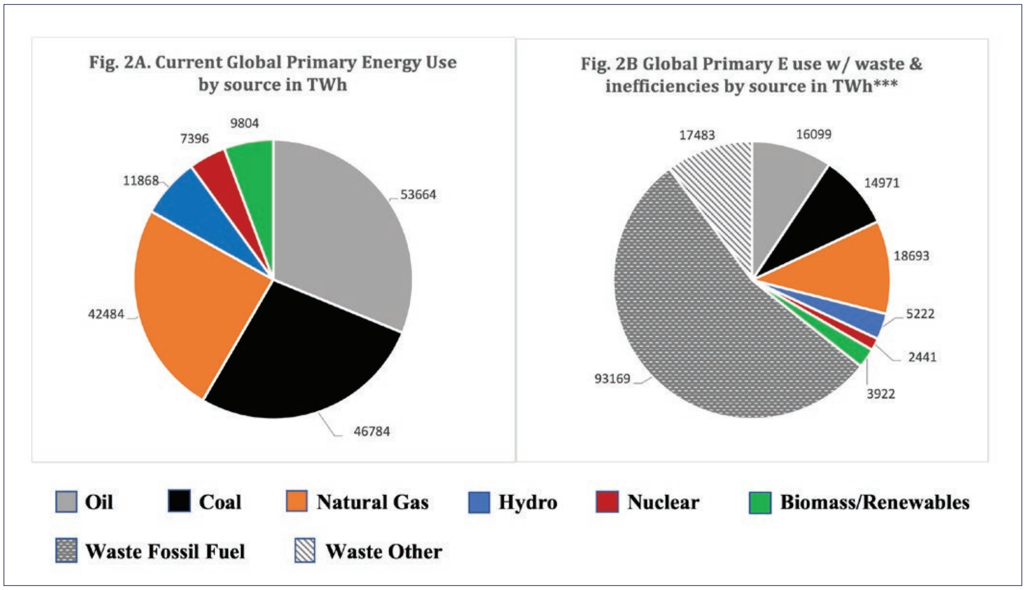
Figures 1A and 1B illustrate the quantitative difference in primary energy inputs (1A) and the amounts of waste associated with that primary energy (1B) for the US electrical generating sector in 2021. Note the colored portion of 1B is the actual end-use. *(US electrical generation is used here for example only because it was the most easily quantified for straightforward illustration).*



Source: Sankey diagrams, Lawrence Livermore National Laboratories; https://flowcharts.llnl.gov/sites/flowcharts/files/2022-04/Energy_2021_United-States_0.png

Figures 2A and 2B compare global primary energy use with the same data broken down into waste and usable energy. Calculations for these values can be found at the end of this section. These numbers are a first pass at dealing with the enormous challenge of an energy transition, and do not include many variables which will affect their values going forward. Efficiencies used in calculations are averages, and will necessarily change as more efficient technologies and equipment evolve in transportation, heating, lighting, and industrial processes.

(One important note: all processes have accompanying inefficiencies; no process can be 100% efficient. A future world of primarily renewables will still suffer energy losses. However, the transition to carbon-free energy must include concerted efforts at energy conservation as well as continued advancements in energy efficiency in order to minimize these losses. Our grids will require upgrading/modernizing; electrical demand will need to be shaped through demand-side management; buildings will require upgrades in efficiency and insulation/venting; innovations in energy storage and other components will address the intermittency of renewable energy).

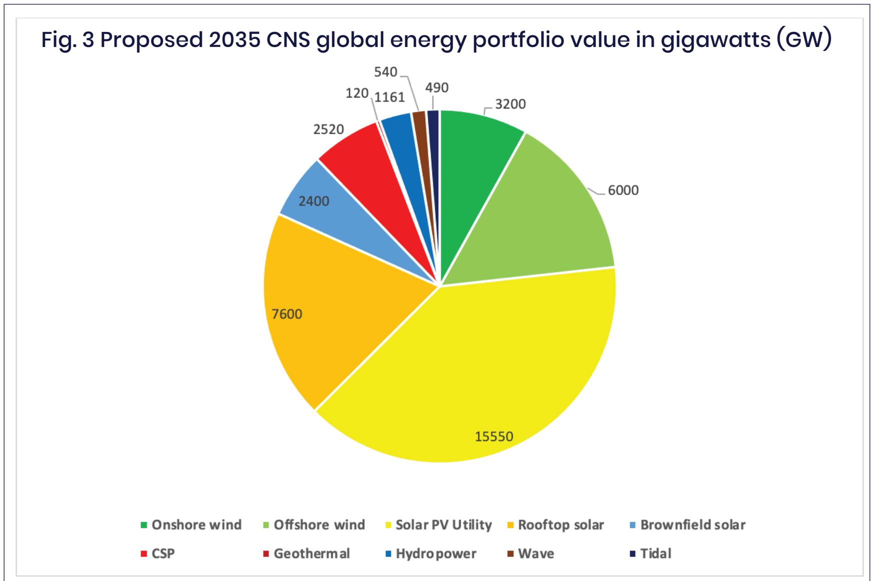


Source: see table 1 and *** at end of paper

Potential global resources for renewable energy

Our planet is rich in renewable resources: the total annual solar radiation over the Earth's surface is greater than 5800 times the total global energy consumption by humans of 580 EJ[3]. Harvesting this resource and others is technologically feasible and would be vastly cheaper than the costs and impacts of continued fossil fuel use. The objective of this section is to examine the potential resource availability within the context of a global renewable energy portfolio (see Figure 3). The proposal for 'solar PV' is enormous; however, this section will be composed of a mixture of utility solar PV/non-agricultural, utility solar PV located on brownfields, floating utility solar PV, rooftop solar PV and parking lot solar PV.

Proposed Climate North Star Global Energy Portfolio



Source: author's own calculations based on the following data.

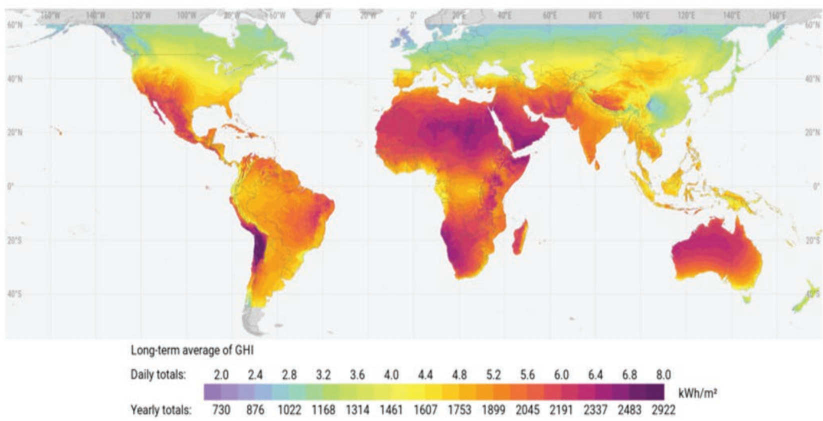
Source: author's own calculations based on the following data.

Following is a discussion of the various resources and estimates for total and technologically feasible resource values in the Climate North Star global energy portfolio.

Solar PV

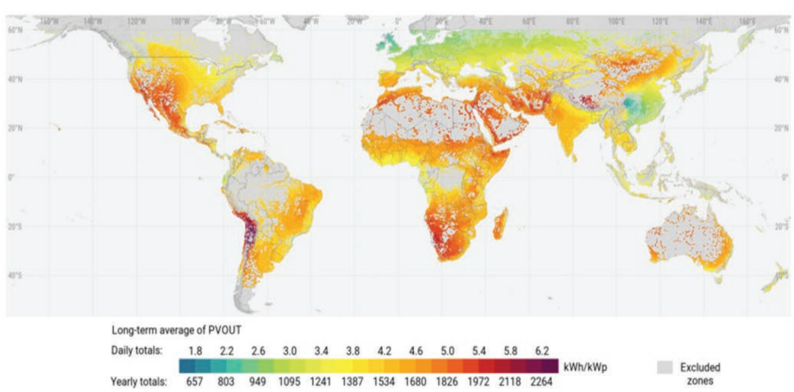
Finding an estimate for total global potential for installed PV capacity, filtering out all but the most feasible both technologically and economically, has been an elusive task. In a study titled "Global Photovoltaic Power Potential by Country", performed by Solargis and published by the World Bank as ESMAP[4], the authors assess global PV potential at 3 levels: Level 0 is the theoretical potential without regard to technical design or operation (see figure 4 below); Level 1 is the practical PV potential, which takes into account theoretical potential, air temperatures which affect system performance, shading and soils, topographical and land-use constraints (see figure 5 below). Level 2 filters for "soft constraints", such as unfavorable regulations by countries or regional authorities; level 2 illustration can be found in source material.

Figure 4: Level 0 PV potential



Global Horizontal Irradiation (GHI): Long-term yearly average of daily and yearly totals
Source: (ESMAP 2020 Global Photovoltaic Power Potential by Country, Washington, DC: World Bank)

Figure 5: Practical PV potential at Level 1



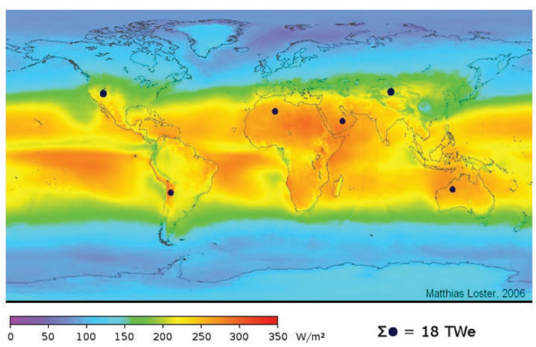
Practical photovoltaic power potential (PVOUT) at Level 1: Long-term yearly average of daily and yearly totals
Source: (ESMAP 2020 Global Photovoltaic Power Potential by Country, Washington, DC: World Bank)

The metric used is PVOUT (PV power output, which is the ratio of power generated over the long term per unit of installed capacity…kWh produced/kW peak capacity). Higher values are favorable.

The study continues to refine potential incorporating a seasonality index, which is the ratio between highest and lowest monthly totals. High potential countries tend to have low seasonality indexes (<2) and vice versa. The most favorable conditions for economically feasible PV installations are high PVOUT and low seasonality. Note the clustering of countries with high PVOUT and low seasonality index. The study finds that 86% of the global population lives in countries wherein the seasonality index is below 2 and PVOUT exceeds 3.5 kWh/kWpeak installed.

Figure 6 below illustrates the area of installed PV (black dots, 100km radii) required to supply global energy demand for a year. The figure is only an illustration, but certainly implies that there is an enormous potential to be tapped.

Figure 6: Illustration of required surface area of PV installations (black dots, radii =100km) required to supply all of the global energy needs for a year: **Σ black dots ≅170,000**



Source: (Solar Energy Potential and Utilization, www.e-education.psu.edu/earth104/node/950)

Based on these estimates, there exists an enormous global potential for solar PV.

Rooftop Solar

In 2018, rooftop solar accounted for 40% of global installed PV capacity and 25% of all renewable capacity additions in that year. Although little information exists on the global potential for rooftop solar, a new study, attempting to quantify this potential at high spatiotemporal resolution, finds there exists the potential for 27,000 TWh/year that are technically feasible with costs ranging between $40-280/MWh. (These can be compared to sample global levelized electricity prices calculated by Lazard, which suggest a cost of $36 per MWh for utility-level solar, $40 for onshore wind, $112 for coal, and $164 for nuclear power in 2020.)[5] The study further finds a total potential for 10,000 TWh/year below $100/MWh. This potential is predominantly located in Asia (47%), North America (20%) and Europe (13%)[6]. Assuming only this highest quality rooftop potential is utilized, and assuming a capacity factor c.f.) of 15%, 10,000 TWh could be produced from 7,600 GW of installed capacity.

Brownfield Solar

The National Renewable Energy Laboratory estimates there are 15 million acres of brownfields in the US; a study by the Solar Energy Technologies Office estimates the potential to generate up to 2TW of power via utility-scale solar PV installations on these sites[7]. Estimating the brownfield-to-solar PV capacity globally is hampered by lack of data; challenges with definitions, cost considerations, and the fact that a large portion of the global economy is still agrarian…brownfields tend to be associated with industrial activity. However, given that 63 economies are considered industrialized, that environmental regulation is likely minimal globally, and that 20% of the global population lives in industrial economies[8], the likelihood that there are many brownfields across the planet is high. Following a very crude analysis: there are 8 billion people on Earth, 20% of whom live in industrialized countries (1.6 billion), and 330 million people in the US. If we assume that brownfields occur in industrialized countries approximately proportional to the population, and using the US as a base case, there could be: (2 TW/0.33 billion people US) x 1.6 billion people globally = 9.7 TW capacity potential. Assuming 25% of this potential is realized we recommend 2400 GW of installed capacity in the Climate North Star portfolio.

Concentrated Solar Power (CSP)

The study "Global Potential of Concentrating Solar Power," Franz Trieb 2009, cites the potential for 2,946,000 TWh per year globally utilizing suitable land. If only 2% of this potential were developed, approximately 58,920 TWh could be supplied. Assuming a 40% capacity factor with storage, the potential exists for 16,800 GW of installed capacity. Jacobson et.al. call for 420 GW of CSP in their proposal, with a higher capacity factor (0.77)[9]. Given the abundance of CSP potential, we use only 15% of the 16,800 GW potential as a conservative figure, adding 2520 GW of power to the portfolio.

Offshore wind

A study of global offshore wind potential by the Energy Sector Management Assistance Program (ESMAP), a partnership between the World Bank and 24 partners, estimating the potential generating capacity that is feasible using current technology and considering only wind speed and water depth, found a potential of 71,000 GW of technically extractable resource. However, "this is intended as an initial, high-level estimate and does not look at other technical, environmental, social, or economic constraints. Once these other constraints are considered, the realistic practical potential is only a small fraction of the total technical potential but, given the vast global offshore wind resource, even this small fraction is still a significant and abundant energy resource."[10] Eurek et.al. "estimate the total global wind generation potential of 315 PWh (quadrillion watt/hour) for offshore wind with 67% classified as mid-to-high quality."[11] Using the lower end of capacity factors for offshore wind (40-50%)[12], the potential exists for nearly 60,000 GW of installed capacity[13]. Utilizing 10% of this capacity would provide 6000 GW of power to the Climate North Star portfolio.

Onshore wind

Eurek et. al.[14] "estimate the total global wind generation potential of 560 PWh for terrestrial wind with 90% of the resource classified as low-to-mid quality." Using only the top 10% of terrestrial wind potential that is above low-to-mid quality yields a potential of at least 56,000 TWh. Utilizing an additional 10% of better low-to-mid quality might yield an additional 44,000TWh, for a total of 100,000 TWh. Using a conservative capacity factor of 35%, the potential exists for 32,000 GW of installed capacity.[15] Xi Lu et. al. estimate that " a network of land-based 2.5-megawatt (MW) turbines restricted to non-forested,

ice-free, non-urban areas operating at as little as 20% of their rated capacity could supply >40 times current worldwide consumption of electricity, >5 times total global use of energy in all forms."[16] (860,000 TWh). Jacobson and Archer estimated that the global wind power in 2000 was ~72 TW; using a capacity factor of 0.3, a network of onshore wind generators could theoretically produce 190,000 TWh. Although these are all raw potential estimates, they provide an upper limit to global onshore wind potential. We use the lowest of these estimates (from Eurek et. al.) of 32,000GW potential installed capacity (utilizing the top 10% of higher quality plus 10% of the low to mid quality), then assume only 10% of that is economically developable, providing 3200GW of proposed capacity.

Geothermal

The total global development of geothermal energy for power generation is currently around 15 GW capacity. The Geothermal Energy Association estimates that only 7% of global resources have been tapped; that value implies a total global resource estimate at 214 GW. The IPCC estimates the potential between 32GW and 2TW[17]. (Retrieved 27 August 2022.) Jacobson et.al. propose 97 GW of geothermal power stations and 109 GW of geothermal heat source in their paper[18]. We adopt a conservative potential of 200GW, with a realized 120 GW developed by 2035.

Hydropower

Hydropower is currently the largest source of renewable power, with a current global installed capacity of 1360 GW, with an annual output of 4327 TWh. (average capacity factor of 36%). Hydropower experienced a building boom from the 60s to the 80s. However, the rate of additions has slowed considerably and the persistence of severe droughts has reduced the average output of existing hydropower plants. Additionally, at this point nearly 40% of the hydroelectric generating stations are at least 40 years old….the average age of the global fleet is 32 years. Once hydro plants reach 40-60 years of age, they require major refurbishments and modernization to maintain performance and ensure safety.[19] Additionally, the environmental and social disruptions that accompany new dam/power plant construction come at a large cost that was not typically valued in past planning, but must be addressed in the future. Given all of these factors, the potential for expansion of the hydroelectric sector seems challenging; this power would be more easily supplied using aggressive solar buildout. We assume some retirement of existing power plants. Climate North Star calls for zero new hydropower. Jacobson et al estimate the potential for 1161 GW of available hydropower going forward; we use this value in estimating our portfolio.

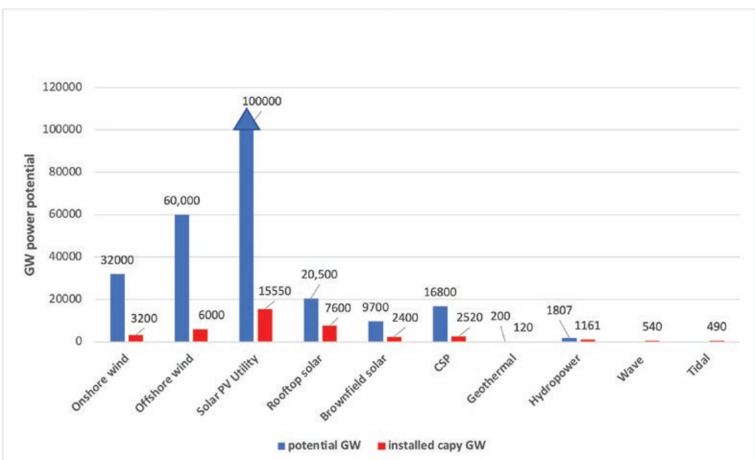
Wave and Tidal power

There is little data on wave and tidal power installations and potential; this method of generation is new, but the total power of Earth's waves and tides is likely quite large. We use Jacobson's numbers, assuming there will be future recognition and development of these resources as part of a global energy transition.[20]

Resource availability

Figure 7 below compares the magnitude of technologically feasible power potential for various renewable resources versus Climate North Star's proposed installed capacity; numbers based on the discussion in previous paragraphs. Note: the installed capacity for onshore and offshore wind, solar PV and CSP are modest fractions of the available resource.

Fig.7 Renewable resource potential vs. proposed installed capacity global



Source: author, based on above discussions

ENERGY STORAGE

Proposals for a carbon-free grid generally rely on a robust mix of solar and wind power replacing the bulk of fossil generation. Wind and solar generation costs are generally well below coal and about par with natural gas; the technologies are mature and benefit from new innovations that increase efficiency and reduce costs for both. The Levelized Cost of Energy (LCOE) for fossil generation is driven by the cost of fuel, whereas the LCOE for renewable generation is driven by the cost of the technology, which historically benefits from favorable learning rates (the relative price decline associated with each doubling of experience). However, the intermittent nature of the energy resource (e.g. wind and sun) challenges their dominance in dispatchability. Co-development with storage technologies can achieve dispatchability for these intermittent resources, but the devil is in the details. ("Storage" includes pumped hydro, battery, gravity systems, liquefied air energy storage, compressed air energy storage, power-to-hydrogen-to-power, flywheels, molten salts, phase change materials, capacitors, hydroelectric reservoirs and others).

First, the demand for storage is increasing as grid operators bring more intermittent generation online. Requirements for storage technologies include affordability, duration, efficiency, scalability and reliability. These challenges loom larger as the transportation sector's electrification grows in market share (and customers demand that the electricity is carbon-free), and efforts to reduce emissions from the residential, commercial and industrial sectors focus on electrifying heating and cooling, as well as high-temperature process heating. The required storage to meet these demands is a steep exponential curve.

Second, the amount of storage for a given region will depend on capacity factors for wind and solar generators, the degree to which they can complement each other locally, the potential for interconnection with other regional complementary generation, the costs for storage, the maturity of the technology, the scalability of each storage technology, etc.

Third, the economical development of storage will be impacted by the availability of other resources that can provide the same services, resources that may already exist and are cheaper. Existing hydropower, pumped hydropower, existing nuclear, and natural gas facilities that are new, efficient and considered costly stranded assets if decommissioned will impact cost/investment decisions regarding storage.

Fourth, "electricity" for most of us means power that comes at the flick of a switch and is most commonly quantified by familiar terms such as voltage, current, resistance and the power bill. "Electricity" for those who provide us with it is vastly more complex and must be quantified using terms such as frequency regulation, voltage control support, ramping, load following, reactive power control, energy arbitrage, dynamic power response, low voltage ride through, spinning contingency reserves, and others. These are complex dynamics that affect reliability, but must be considered and satisfied when designing and implementing storage systems in the grid.

Up until very recently, grid storage has been dominated by pumped hydro, with 23 GW of capacity, a mere 2% of total US generating capacity. New pumped hydro development is limited by geographic and regulatory constraints, as well as long construction time-frames. The immediate need for increased storage is driving rapid innovation and diversification of technologies with surprising speed and cost projections.

How much storage is needed?

For 100% WWS 2050 global energy demand of 8.9 TW Mark Jacobson et al calculated a global energy storage requirement of 5,473 TWh (of which 4,567 TWh already exists.) ("Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries†," Energy and Environmental Science, 2022, table S13, page 42 of Supplemental Information)

However, Jacobson projects 2035 global energy demand of 7.5 TW, which is 16% less than 2050 demand.

Here are the projected storage capacities needed for 2035, calculated by reducing the 2050 storage requirements for each portfolio element by 16% (except hydropower, all of which already exists):

Electricity Storage
PHS: 14 TWh
CSP: 7 TWh
Batteries: 71 TWhh
Hydropower: 4,567 TWh (already exists; no new hydro)

Cold/Heat Storage
CW-STES: 1 TWh
ICE: 1 TWh
HW-STES: 12 TWh
UTES-heat 657 TWh

See selected definitions here:

Concentrated solar power phase change materials (CSP-PCM)

CSP technologies use mirrors to reflect and concentrate sunlight onto a receiver. PCM refers to the use of phase change materials which are substances that change from a solid , liquid or gas to a different state to produce heat that can spin a turbine or power an engine. These technologies can be used to generate electricity or in a variety of industrial uses. The most common in usage today is molten salt.

Chilled water sensible heat thermal energy storage (CW-STES)

These are technologies that remove heat from an energy storage medium during periods of low cooling demand, or when surplus renewable energy is available, and then deliver air conditioning or process cooling during high demand periods.

Ice thermal energy (ICE).

Ice thermal energy storage is like a battery for a building's air-conditioning system. It uses standard cooling equipment, plus an energy storage tank to shift all or a portion of a building's cooling needs to off-peak, night-time hours. Ice is made during off-peak hours and stored inside energy storage tanks.

Hot water sensible heat thermal energy storage (HW-STES)

Sensible heat storage is shifting the temperature of a storage medium without phase change. It stores heat in a storage medium and releases it when necessary.

Heat underground thermal energy storage (UTES)

Underground thermal energy storage provides large-scale seasonal storage of cold and heat in natural underground sites.

Batteries

Battery technology offers one of the best options for grid-scale storage; batteries can offer high energy densities (though not all do); they can be efficient in terms of charge: discharge ratios; they offer decent discharge durations; they are scalable to MW range and, with Li-ion, soon to probable GW range; they are modular and easily manufactured in a plant; and offer long lifetime cycling capacity. Perhaps one of the greatest advantages of batteries lies in the multiplicity of chemistries that can be applied and tweaked to reach higher efficiencies, discharge durations, safety, energy density, recyclability, and ease in manufacturing.

A study of current battery R&D reveals a wide variety of chemistries and configurations. The holy grails of duration, number of lifetime cycles, cost, scalability, safety and recyclability of components offers the creative enticement for this effort; the need to decarbonize the energy sector of the globe is the moral imperative driving this effort. The R&D effort is growing and healthy. What technologies will emerge as the winners is not yet clear. Li-ion leads the way, as its costs have plummeted as a result of R&D and economies of scale; however, the rapidly growing demand for Li-ion will likely lead to supply chain bottlenecks and the resulting cost adjustments. In addition the packs must be replaced at around 10 years due to decreased capacity. Therefore, the drive to develop alternative battery chemistries beyond lithium is accelerating.

A brief synopsis of emerging battery technologies follows.

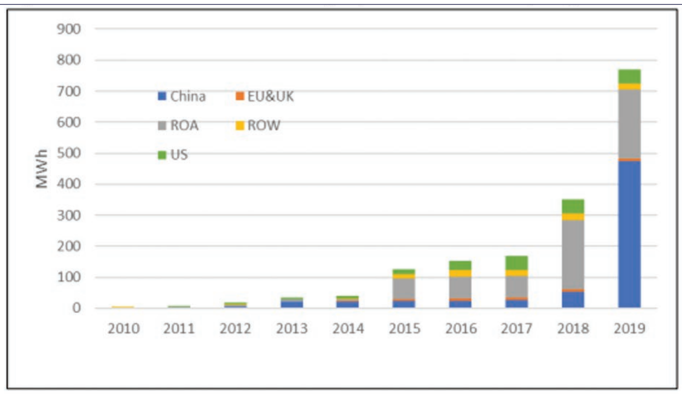
Zinc-air batteries

A Canadian company, Zinc8, has announced plans to build three pilot plants (a 100kW/1MWh (10hr), and a 100kW/1.5 MWh (15hr) in New York, a 40kW in Canada) for its proprietary zinc-air energy storage system. Zinc-air is safer than lithium, can store multiple days of energy, doesn't degrade, and is 5 times cheaper than Li-ion, according to Zinc8's CEO and former MoP Ron McDonald. It has a theoretical Round Trip Efficiency (RTE) of 65%. They project capital costs for an 8-hr storage system at $250/kWh, for a 32-hr system at $100/kWh, and for a 100-hr system at $60/kWh. Such a reduction is possible because scaling up only requires larger tanks of electrolyte, which is relatively inexpensive. LCOS for these systems is $100/MWh for 10 hours, and $180/MWh for 100 hours, a reflection of the scalability.[21]

Redox Flow batteries (RFB)

Redox flow batteries are poised to begin competing with Li-ion batteries in the long-term grid energy storage market. They have many advantages over Li-ion: they can offer longer discharge durations, they are not prone to overheating, are aqueous based (with an ion-exchange membrane), use relatively non-toxic materials, can be readily scaled with additional tanks of electrolyte, and the electrolyte can be recycled. In addition, they have longer cycle-lives (>25,000 vs Li-ion, <10,000). Challenges remain regarding power density, which will require continued innovation in ion-exchange membranes and choice of redox pairs, in an effort to drive costs down as well as to find materials that are inexpensive, environmentally benign and which do not contribute to inhumane mining conditions (as in the case of cobalt mining). Figure 8 illustrates the growth in RFB technology 2010 to 2019.

Figure 8: Global cumulative deployment of RFBs by region[22]



Source: Bloomberg New Energy Finance, "Storage Data Hub - Storage Assets," Bloomberg NEF, New York, 2020.

Zinc-ion batteries

The standard, non-rechargeable alkaline battery is based on zinc ion chemistry. Researchers at Stanford University are working to create a battery based on zinc, which is rechargeable. Since zinc-ion can work safely in an aqueous electrolyte (whereas Li cannot work in an aqueous electrolyte, and therefore must use organic solutions) it is a safer alternative. The current rechargeable prototype offers an energy density of 135 Wh/kg (compared with 81 Wh/kg for disposable Zn-alkaline and lithium's density of 100-265 Wh/kg).....promising, but plagued by loss of cycling stability: after 80 charge/discharge cycles, the battery retains only 68% of its charging capacity. The researchers have tweaked the chemistry, and now have a version that loses only 5% of its charging capacity after 50 cycles.[23] Zinc-ion offers supply-chain security, as they can be made mostly from materials sourced in North America.

Sodium sulfur (NaS) batteries

Pioneered by Ford Motor Co in the 60's, these batteries rely on sodium and sulfur to produce electricity; materials are abundant, available and relatively safe. One drawback is that sodium is highly reactive to water and oxygen, therefore requiring sealed batteries and other fire-related precautions. They also require fairly high operating temperatures (300-350°C), as both the Na and S must be in the liquid phase. These batteries offer longer discharge durations (6 hours), 85% RTE and lifetimes of 2000 cycles at 100% depth of discharge (DOD) or 4500 cycles at 80% DOD. Japan has installed several NaS batteries: a 34MW/245MWh battery in Aomori Prefecture, and a 50MW/300MWh battery in the Fukuoka Prefecture.[24] The largest sodium sulfur storage system in the world is a 108MW/648MWh behemoth in Abu Dhabi.[25]

Iron-saltwater flow battery

This battery uses iron and saltwater in a flow battery format to store electricity. Chief advantages are low-cost and low-impact materials that are abundant, long discharge durations, a RTE of 70% and lifetime of 20,000 cycles at 100% DOD without degradation. ESS of Portland OR offers a field proven, stand alone 75kW/500kWh containerized system, and is now introducing a modular system for large scale grid storage, starting at 3 MW and providing 6 to 16 hours of storage.[26]

Aqueous air batteries

Form Energy manufactures a battery charged by iron, water and air that can store 100 hours of electricity. The company has commercialized the battery with three electric utility projects moving forward: Minnesota based Great River Energy, Xcel Energy and Georgia Power. The battery will move into full-scale production at a recently announced factory to be built in West Virgina. The company says it expects its battery cost will be less than $20/kwh. Compare to $152/kwh for lithium-ion batteries.

Batteries currently lead the field for storage, in terms of cost, reliability, scalability, maturity, and momentum. Assuming a continued trajectory, batteries will have to provide the lion's-share of storage for the foreseeable future.

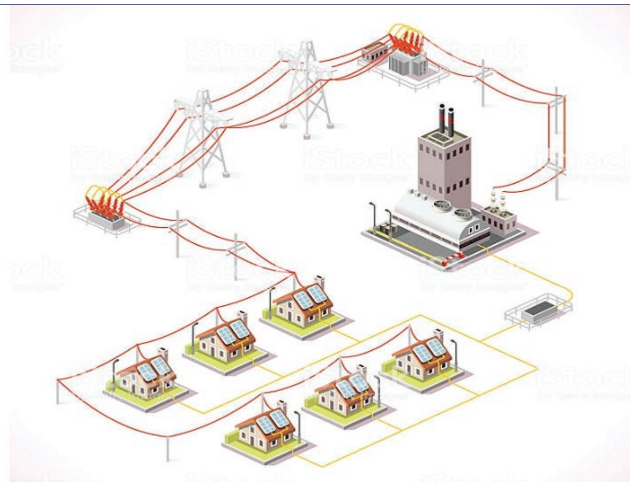
THE GRID: A BRIEF PRIMER

The US utility grid has been called "the world's largest machine and part of the greatest engineering achievements of the 20th century" (National Academy of Engineering 2003). Designed to provide quality electricity for all people and all electrical uses on demand, 24/7/365, the nation-wide structure, which includes electrical generation, transmission, distribution and end-use, staggers the imagination. We take this system for granted, expecting power literally at the flick of a switch. However, few users understand the enormity of the task that grid operators, controllers and engineers are responsible for at every moment. As the reduction and replacement of fossil fuel electrical generation has become imperative, it behooves activists and policy makers to understand the basics of grid operation and expectations in order to facilitate dialog with power companies, politicians and regulators throughout the transition.

The origins of the "grid" began on September 4th 1882 at the Pearl Street Station in Manhattan, where a direct current generator began supplying electricity to 85 customers, sufficient to power 400 electric lamps. Over time the success of that first operation grew into many local power plants supplying local customers. However, direct current suffers large energy losses over distance due to the physics of electrical current, and power plants and customers had to be in close proximity to one another. George Westinghouse's competing alternating current technology could more readily exploit the physics of transmission and succeeded in reducing the transmission losses by stepping voltages up (today: 150,000 to 750,000 volts) for long-distance transmission, then stepping the voltage down for use by customers (120 to 440 volts). Instead of many smaller localized power generating stations connected to smaller pools of customers, AC allowed for large, centralized generating stations taking advantage of economies of scale, and sending power via long distance power lines to a large pool of customers. Thus began the era of the large-scale electrical grid.

In simplest terms, the "grid" consists of a) all of the people and processes that require electricity to function (end-users), b) the wires, associated transformers, breakers, meters and other equipment that get that electricity to end-users, and c) the electrical generating plants. See Figure 9:

Fig 9. Typical grid illustration



Source: https://www.vecteezy.com/free-vector/power-grid

The US electrical grid is essentially a 19th century structure attempting to meet 21st century demands. It is relatively reliable overall, but is pushed to its limits regularly, often with catastrophic outages for large regions of customers. The estimated costs of power outages vary, and are difficult to calculate. They range from $25-70 B/yr (Congressional Research Service/Campbell 2012), $150 B/year (Department of Energy 2018), $18-33 B/yr (American Society of Civil Engineers 2017) and $104-164 B/yr (Electric Power Research Institute 2011). Annual maintenance costs are estimated at $75-100 B/yr (Brattle Group for Edison Electric). Costs to upgrade the grid to accommodate digital technology and smart metering (creating a fully functional smart grid) are estimated at $338-476 billion dollars (EPRI) but would yield benefits with a value of $1.3-2 trillion; upgrading to a smart grid is projected to yield emissions reductions of 58% below 2005 levels (EPRI 2011).

Grid terminology/concepts

There are a vast array of terms and definitions that are used to describe the dynamics and mechanics of grid operation: generating capacity, load, demand, supply, power, energy, capacity factor, baseload, intermediate load, peaking load, dispatchable power, power quality, firming capacity, to name a few.

Power: the amount of energy delivered per unit time by a system. In electrical applications, the unit of power is the watt (W). A small incandescent Christmas tree light bulb in a 100 watt bulb strand uses about a half a watt of power. A typical hair dryer on high heat requires 1500 watts of power. 1000 watts is a kilowatt (kW), 1,000,000 watts is a megawatt (MW), 1 billion watts is a gigawatt (GW) and 1 trillion watts is a terawatt (TW).

Energy: the capacity to do useful work. The units are typically calories, joules or in the case of electricity, kilowatt-hours. 1 kilowatt-hour (kWh) is the amount of energy that is provided by a 1 kilowatt generator during an hour's time.

A typical bicycle generator can provide 100 watts of power. If you pedal such a generator for 10 hours, you will produce 100wattsx10hours=1000 watt-hours=1kWh.

Electrical load: the portion of an electrical circuit or system wherein current is transformed into something useful, e.g., a motor, heat, light, refrigeration, etc. The load on the grid is the sum of all of the individual loads arising from electrical use by end-users (residential, industry, businesses, municipalities, transportation, etc.).

Electrical demand: the maximum amount of electricity needed to meet consumption levels at a given time on an electrical system.

Peak demand: the maximum demand on an electrical grid during a given season. Summer peak demand is usually driven by air conditioning loads, winter peak due to heating and lighting loads.

Generating capacity: the maximum power rating for an electrical generator. The above bicycle would have a "nameplate" capacity of 100 W. A typical residential solar panel has a capacity of 250 W. Large wind generators have nameplate capacities of 1 to 3 MW. The massive Three Gorges dam in China has a generating capacity of 22.5 billion watts, or 22.5GW. This is an important term to understand, as the nameplate capacity is the theoretical maximum, but rarely the actual maximum (see capacity factor below)

Capacity factor: The ratio of the amount of electricity actually produced by a generator over a given time period (typically a year) divided by the nameplate (design maximum) capacity over the same time period, given as a percent (or a decimal):

Capacity factor = actual generation (W)/nameplate (W) x 100

Capacity factors are important to understand: a wind turbine rated at 1.5MW could, over the course of a year, produce a theoretical maximum of

1.5 MW x 24hrs/day x 365 days/yr = 13,140 MWh

However, the wind does not blow constantly at a given location over a year's time. Therefore, the actual generation will be less than the theoretical maximum. Assuming (for simplified example only) the wind blows only 180 days, for 18 hours a day, the actual electrical generation would be

1.5 MW x 18hrs/day x 180 days = 4860 MWh and the capacity factor will be

4860 MWh actual/13,140 MWh theoretical maximum x 100 = 37%

Without a firm understanding of capacity factor, one might be tempted to assume that a 500 MW solar plant is capable of replacing a 500 MW coal-fired power plant; however, both plants' capacity factors must be taken into account in order to make a valid comparison.

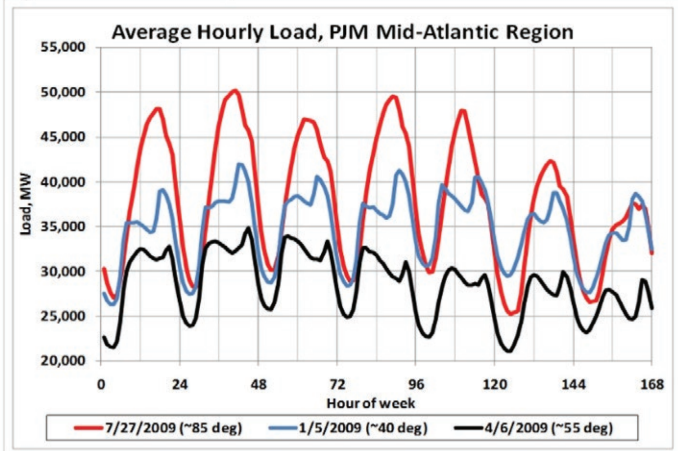
Dispatchable power generation: that electrical generation that can be delivered on demand, dispatched at the request of grid operators. Fast dispatchable plants can readily increase or decrease their power output, within fractions of, to whole, seconds. Hydroelectric plants, batteries and capacitors are examples. Intermediate dispatchable plants take longer (minutes) to ramp up or down. Natural gas turbines and some solar thermal plants are examples. Coal, geothermal, some gas and nuclear power have long times-frames to increase their power output, and thus are considered dispatchable only with enough lead time. Because of their slow-response timeframe and ability to run most efficiently at a steady rate, these plants have historically provided a constant baseline of power, called 'baseload' power.

Intermittent power generation: that generation that occurs only when the energy source is available. Wind and solar are intermittent generation due to the variability of wind, and the effect of clouds, seasonal angle of incidence and earth's rotation on the solar resource. Wind and solar by themselves are not considered dispatchable. With sufficient energy storage, interconnection over large geographic areas, and overbuilding and curtailment, wind and solar are anticipated to be dispatchable.

Grid dynamics: An illustration

To understand grid dynamics, we can use an example from a large grid operator. Figure 15 shows typical weekly electrical demand (in megawatts of power, MW) for the Pennsylvania-New Jersey-Maryland Interconnection regional transmission organization. Several salient features of this graph: the graph illustrates the daily fluctuations in electrical demand (in MW) over a seven day period (hour of the week), starting at 1 AM Monday morning and ending at 12 PM Sunday, for three different seasonal periods, August 27th, January 5th and April 6th in 2009. The blue and black lines represent winter and spring demand respectively, and show two daily demand peaks representing the morning (breakfast) and evening (dinner) periods. The winter line is higher overall than spring due to heating and lighting loads that are higher due to temperature and day length. Demand is highest during the summer months (red line), driven predominantly by air conditioning loads, which overshadows the breakfast-dinner peaks. Demand is lowest for the last two days, Saturday and Sunday, as overall demand is lower without the typical weekday business and industry use.

Figure 10. Electrical load profile



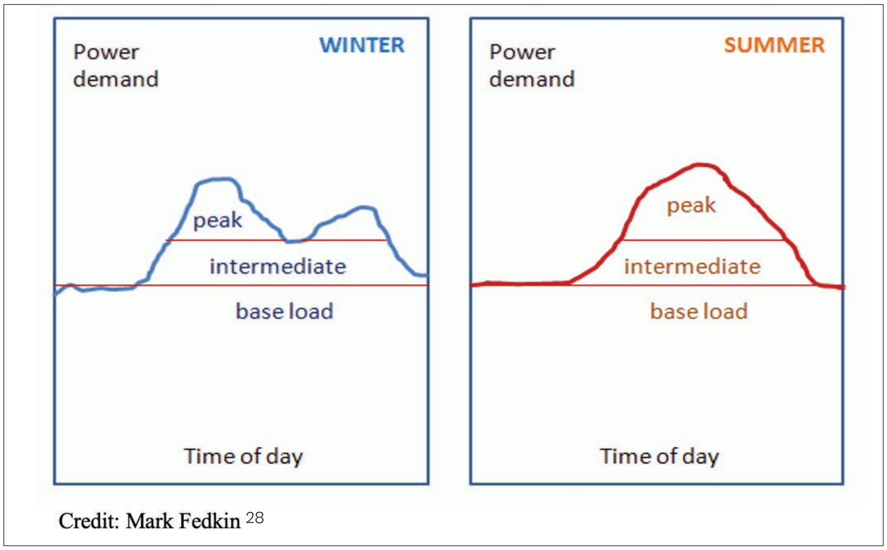
Average Hourly Load, PJM Mid-Atlantic Region Credit: B.Posner @ Penn State licensed under CC BY-NC-SA 4.0[27]

Grid operators must be capable of providing electricity to supply the load up to the peak demand (in above example, about 50,000 MW). Typically, extra generating capacity (23% total in the US in 2013 eia.gov) is built into the system to provide emergency power generation in the event of a peak demand anomaly or loss of power generation in the event of a power plant failure.

In figure 10, one will note that the demand curve never falls below the value of 20,000 MW (on the y-axis). Hence, it follows that the minimum electrical generating supply at any point in time must be 20,000 MW. We can define **baseload power** as that amount of electrical generating capacity required to meet this minimum. Historically, baseload power has been supplied by large thermal electrical generators, such as coal, nuclear, geothermal and some gas plants. These plants operate by heating water to steam that then drives electrical generators. Because it takes time to heat water to steam, these plants operate constantly at the same level of output, which provides steady power and a level of efficiency.

In addition to baseload power, operators must supply electricity as the load rises and falls above the minimum. The generating capacities to fill this demand are termed **intermediate** and **peak** capacities. Figure 11 illustrates this for winter and summer.

Figure 11. Example of base, intermediate and peak electrical loads profile

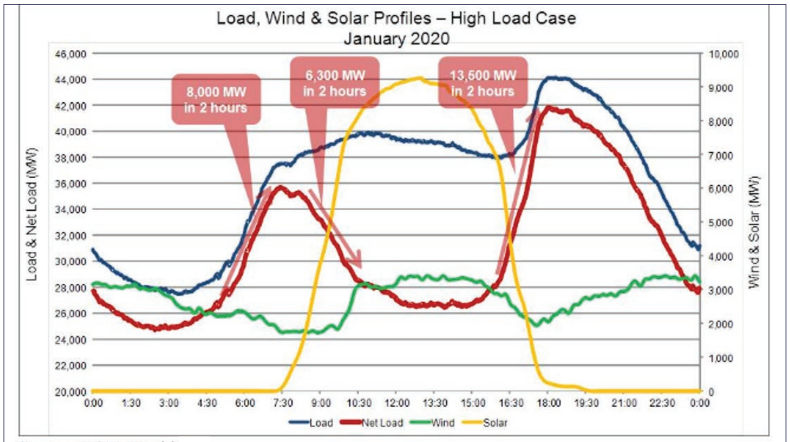


Intermediate capacity, also called load-following, comes from generation that can be ramped up and down readily, or may be too intermediate to supply baseload power reliably, but exists in sufficient supply to provide power when needed. Wind, solar, hydro power and natural gas can supply intermediate loads. Peak loads are short duration and require reliable and instantaneous power when needed. Natural gas, hydropower and batteries have this capacity.

Another important point to glean from the graph in Figure 16: during periods of minimal load (around midnight consistently throughout the year), peaking and intermediate power plants will have to "ramp down" or stop producing electricity, as there are typically few places to store the excess electricity (see storage for exceptions). This means power plants will sit idle during minimal load. In terms of economics, fixed costs, such as labor, loans, insurance, etc that are incurred during off-peak periods, will not be paid by electrical sales during this time. This area is under intense exploration and development in terms of reducing costs by generating and storing the (currently unused) electricity during off-peak periods.

The challenge for a decarbonized grid will be to provide sufficient electricity to meet current and projected demands with reliable power from renewable resources. Perhaps the largest hurdle will be the intermittent behavior of wind and solar. Figure 12 illustrates the challenge facing these technologies. The blue line illustrates a typical daily load in MW in January, with the dinnertime peak occurring around 6 PM. The yellow line represents the amount of electricity generated by a solar installation, starting with sunrise around 7:30 AM, peaking at noon and falling to zero as the sun sets at around 6 PM. The green line represents power generated by wind; note the up and down variability that is characteristic of this resource, and differs from the somewhat more predictable rising and setting of the sun. The red line indicates the net load on the grid after subtracting the power contributions from wind and solar.

Figure 12. Load, solar, wind and net profiles (California Independent System Operator)



Source: T&D World 29

Several important observations and conclusions can be made using this graph: First, that the total contribution from wind and solar in this scenario is insufficient to supply the entire load….the red line hits a minimum at about 26,000 MW midday. Something must make up this minimum. Second, there is an excess of power supplied by solar that exceeds the load by around 4000 MW at midday. If the electrical grid cannot store this excess much of it is curtailed (curtailment is the process of reducing or shutting off the generation of electricity from a plant for several reasons; in this case, supply exceeds demand and there is nowhere for the electricity to go). Storage of the excess is a critical area of research, development and demonstration. The excess power from an intermittent resource can be stored and released to the grid when the driving energy source is unavailable….e.g., the sun has set, during cloudy periods or when the wind is calm. Storage increases the capacity factor for renewables, and at a sufficient level, makes renewable energy dispatchable.

Pathways to 100% renewable electricity generation

Currently, around 20% of all US electrical generation is from renewables, with about 9.2% coming from wind, 6.3% coming from hydro and 2.8% from solar (2021, Dept. of Energy). Nuclear power contributes another 19.7%. Hence, around 37% of electrical generation can be considered carbon-emissions free from the fuel source/generation side of the equation. However, there are carbon emissions associated with the build-out of a renewable energy system or building and fueling a nuclear plant. Increasing the grid penetration by renewables to 100% will require a host of tools to create a flexible smart grid and deal with the inherent variability of these resources. These tools include, but are not limited to:

1. **Reduction of energy use through efficiency and conservation** The greenest energy is that which we never use.

2. **Reduction of energy use through demand-side management (DSM)**, which consists of tools employed by utilities that are designed to encourage modification of levels and patterns of electrical consumption by end-users. DSM is deployed with the goals of reducing electrical use by customers, thereby saving money; reducing emissions; and reducing the need to build extra electrical generating capacity to meet peak loads.

3. **Creating a smart grid** that will deploy digital technology and sensors to create a two-way communication between utilities and customers in an effort to more effectively respond to rapid changes in electrical demand. Goals are: increased efficiency in transmission, reduced peak demand, increased integration of both large-scale and distributed renewable electrical generation, and grid security.

4. **Large scale energy storage** to capture excess generation from renewables during low-demand periods.

5. **Strategically locating and interconnecting renewable resources across geographic regions** to reduce the effects of variability by capturing potential complementarity of these resources over large regions.

6. **Overbuilding and curtailing renewable resources.** As the cost of solar and wind generation continue to drop, there will be a point at which the costs of building storage systems to increase capacity factors (with the goal of providing firm generation) will exceed the costs associated with overbuilding solar or wind for the purpose of supplying firm generation by capturing lower quality resources with increased capacity. Such a strategy will require curtailing (shutting down) some generating capacity during periods of high resource (good wind or high solar radiance).

7. **Synergistic blending of solar PV and wind where the two resources are anti-correlated over large time-scales.** In some locations, solar PV has a higher capacity factor in the summer, lower in winter when cloud cover is more pronounced. Conversely, wind resources tend to be higher in the fall, winter and spring, and lower in summer. Combining both systems together at such a location can provide a higher aggregate capacity factor than either system alone.

8. **Power-to-X:** This strategy uses excess generation that might otherwise be curtailed to create synthetic fuels from captured CO2 or generate hydrogen through hydrolysis. These fuels can drive peaking turbines or provide fuels for transportation.

Each of these strategies is covered in more detail in the section below. In the following section, there are several graphs labeled with an *; these graphs are illustrative of effects, but are not quantitative.

1. Reducing personal consumption through efficiency and conservation.

This is covered in the wealth and consumption section of the paper. The impact on a general load profile is illustrated:

Figure 13: Illustrative example of effect of efficiency measures on load profile:

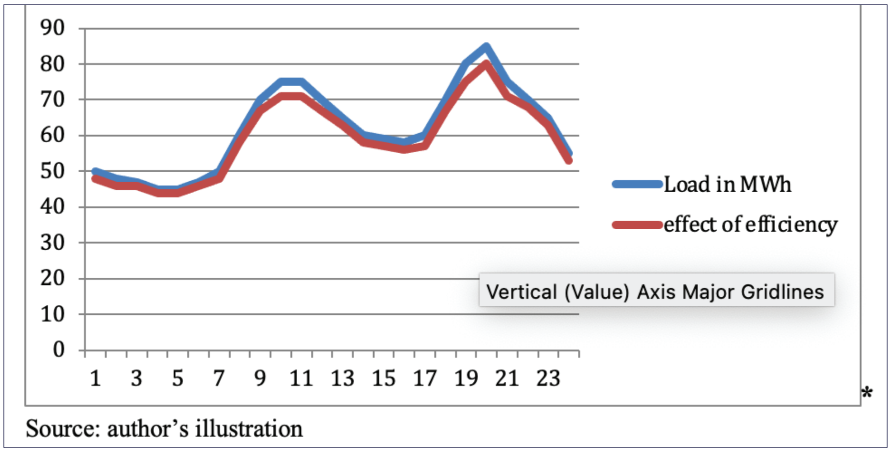
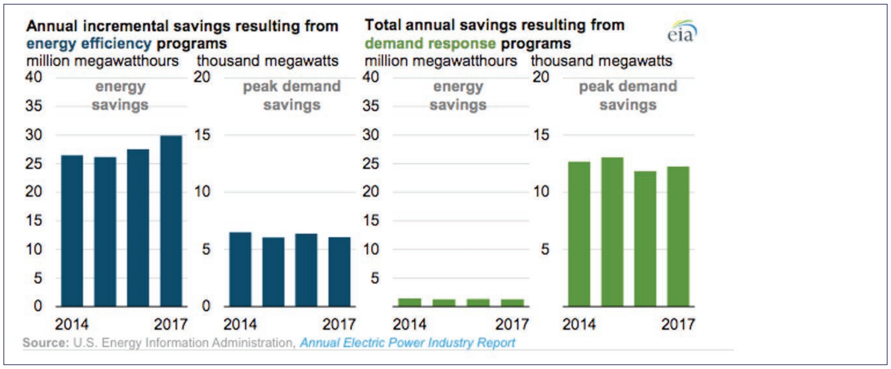


Figure 14: Energy savings and peak load reduction from efficiency measures and demand-side management programs[30]

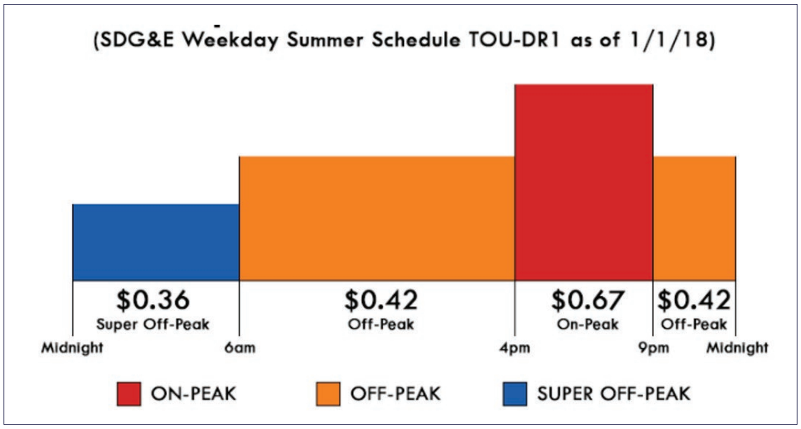


2. Demand-side management:

Utilities can manage (reduce) electrical consumption through various incentives that more transparently reflect the actual cost of electricity at a given time, and will encourage users to consider more efficient consumption as a pathway to reduced bills and emissions.

Time of use (TOU) rate: Utilities can shift the demand curve through innovative rate structures that encourage users to modify their consumption habits, thereby reducing the load. Time-of-use, or time varying rates, assign fixed rates to electricity that vary throughout the day and more accurately reflect the cost of generation at a given time (as opposed to an average rate which is constant throughout a 24 hour period). For instance, when demand is low (middle of the night), baseload power can supply the demand, and is typically less expensive than other times of the day. As demand increases throughout the morning, more intermediate generation must be brought on line, increasing the cost. As demand peaks in late afternoon, peaking power plants must be ramped up, increasing the value of the electricity again. As demand drops off into the night, generation costs return to minimum values. TOU rates may vary by season (higher in winter and summer due to heating/lighting and air conditioning), weekdays vs. weekends, and throughout the course of a day. Figure 15 illustrates time of use rate structure for a large utility:

Figure 15: Time of use pricing example for San Diego Gas and Electric[31]

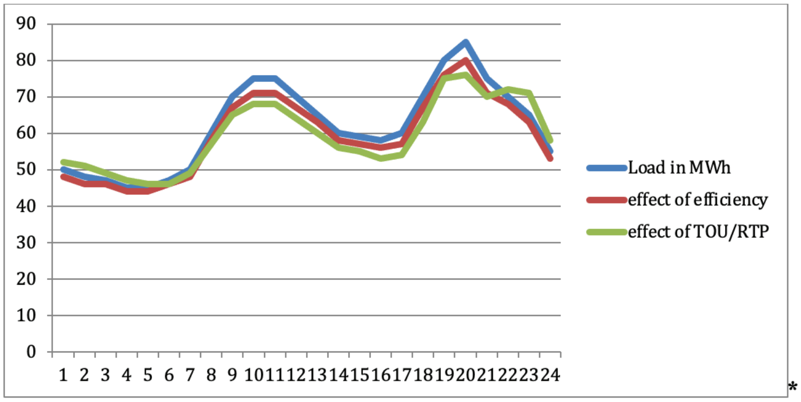


TOU strategies ensure that the rates that businesses and residences are paying more accurately reflect the actual value of the electricity generated during a given demand period. The costs for use are thereby transparent, and customers can adjust their consumption habits accordingly to reduce their bills (and reduce overall demand on the grid).

Dynamic or Real Time Pricing (RTP) An alternative to time-of-use is dynamic pricing, which uses smart technologies to forecast loads a day ahead and the resultant impacts on price to customers via email, text or phone. Additionally, such forecasting could help grid operators bring variable renewables and distributed energy resources into the electrical mix at optimal times.

Two trials on variable rates highlight their effects: Ontario Canada's utility offered time of use rates to 4 million customers that reduced the peak demand by 2.5 to 3%. Alternatively, Oklahoma Gas and Electric offered 100,000 of its 625,000 customers the option of dynamic pricing, with rates off-peak at $0.05/kWh to on-peak rates of $0.20/kWh, with maximum peak rate of $0.40/kWh. The average customer saved $150 for the summer; the rate schedule reduced OGE's average peak by 2.7% overall. For the program participants, their contribution to the peak load decreased by 38%. A study by the Brattle group concluded that the impact of such rate structures on decreasing the peak load is directly proportional to the size difference of the on-peak to off-peak ratio. E.g., the larger the difference in off and on-peak rates, the more incentive customers have to shift their consumption habits.[32]

Figure 16: Illustrative example of TOU and RTP on load profile



Source: author's illustration

3. Creating a Smart Grid:

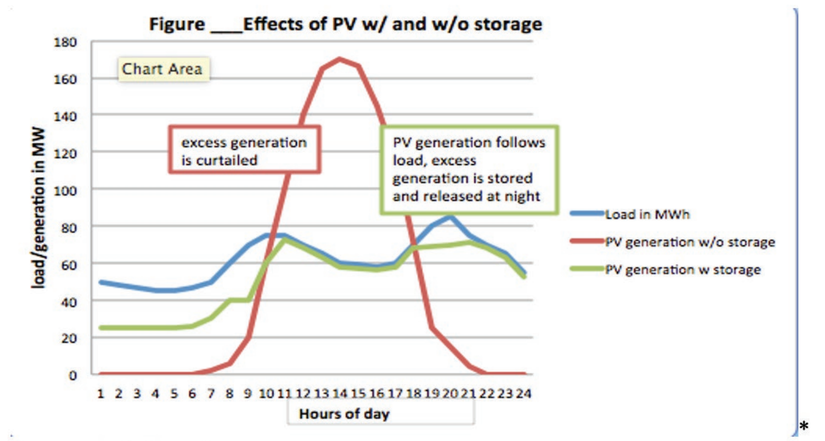
A Smart Grid integrates digital technology, sensors, and customer involvement in a strategy to increase security and reliability of electrical service, increase transparency of rate structures to customers, decrease peak load requirements and increase the integration of renewable and distributed generation into the grid. The components of a smart grid include:

- Two-way communication between utilities and customers that provide real-time information regarding demand and supply, increasing the response capabilities of grid operators to changing loads and their decisions regarding generation.
- Sensors that provide feedback to grid operators regarding grid stability.
- Advanced digital meters that provide consumers with ready access to their consumption data and current rates. With a smart grid, consumers are expected to adopt an active role in their own consumption habits and changes.
- Sensors that help recovery from system faults or reroute power around problems in the grid.
- Batteries and other storage technologies.

4. Grid electrical storage:

Stored electrical energy produced by renewables can be used for supplying the grid with power when the renewable driving resource is unavailable. The concept in simplest terms: when a wind or solar installation is producing more energy than the grid can use, that excess energy must be "curtailed", meaning that a portion of the generating source must be shut off, as there is no effective way to store energy on the grid (historically). Curtailment is undesired by generating station owners/ utilities, as it means that revenues from the sale of electricity are also curtailed, and the capacity factor is reduced. By channeling excess electricity to a storage device during high production periods, then discharging power to the grid during the low-to-no generating periods inherent with renewables, storage can effectively fill in the electrical generation gaps created by intermittency and increase the capacity factor of renewable generation, with the ultimate goal of making renewables dispatchable. Figure 17 illustrates this concept for solar PV.[33,34]

Figure 17: Graphic illustrating load, PV curtailed without storage and PV with storage



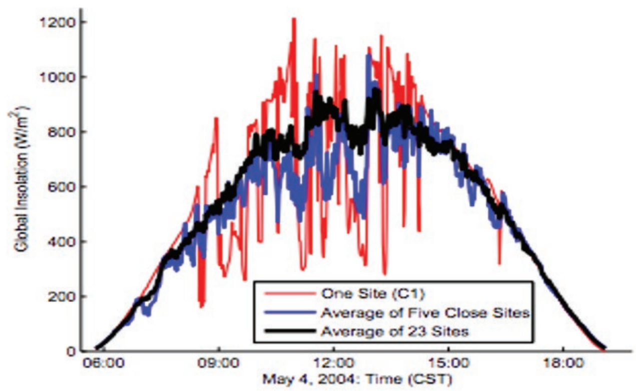
Source: author's illustration

5. Capturing resource complementarity through strategic geographic siting:

The challenge of intermittency lies in the variability of the resource (wind or solar) over timescales that range from seconds to seasonal at a given location. Furthermore, the resources vary over geographic regions. The wind may be howling across Wyoming this week, while it is relatively calm in Colorado. The next week, the situation might be reversed or at least complementary. The sun might be shining over the Great Plains today while a storm system moves eastward over Washington. Within 36 hours, the sun might be shining over Spokane while South Dakota sees gray skies and rain. Wind or PV installations in each region by themselves will experience their region-specific variability. However, taken as an aggregate system, the potential exists for individual installations in the greater region to complement each other. Increasing the geographic diversity of siting will decrease the aggregate variability. The timeframe for variability increases with increasing footprint: small footprints result in seconds to minutes variability, larger footprints in minutes to hours, and very large footprints vary on daily to seasonal timeframes.

Figure 18 below illustrates the variability of 23 PV plants sited on a 10 by 10 grid with 20 km spacing between the sites. The three colored lines represent production data (in minute increments) from a single site (red), an average of five sites (blue), and the overall production average of all 23 sites (black). Data collected indicates a six-fold reduction in variability relative to the variability measured at a single site on time scales less than 15 minutes.

Figure 18: Variability of solar irradiance over 1, 5 and 23 sites

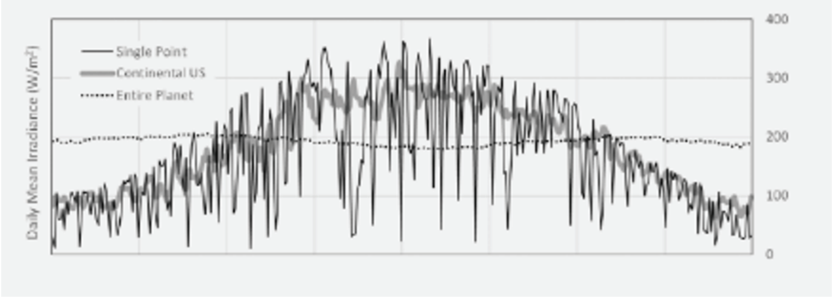


Source:[35]

Figure 19 below illustrates the effect of aggregating increasingly larger numbers of solar sites across the globe, comparing variability at a single point, over the continental US, and over the entire globe. At increasing scale, up to global, the solar insolation approaches a constant value of around 200 W/m2. The effect at this scale squares with our common sense: at any given time, the sun is shining intensely somewhere on earth. This figure at least offers an upper limit solution: Develop solar power over the entire planet and integrate the entire global system into one grid; the line at 200W/m2 is the resource equivalent of baseload and dispatchable power.[36]

Figure 24: Comparing the variability of daily global irradiance time series for one year as a function of considered footprint.

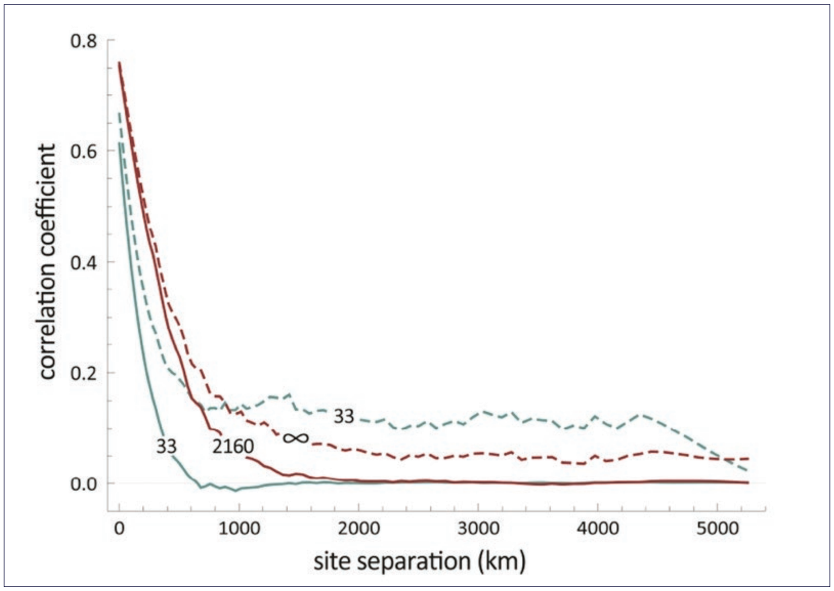
Figure 19: Comparing the variability of daily global irradiance time series for one year as a function of considered footprint.



Source: [37]

Studies on geographically diverse wind farms yield similar results: that the variability of wind energy can be smoothed out by increasing the number of generating units distributed over larger areas. The figure below illustrates the results of studies on correlation: i.e., how closely the variation in wind is correlated from one site to the next. For example, we would expect to find measurements in wind speed, and any variability, to be nearly identical for two turbines next to one another in an open flat field. In other words, their variabilities are correlated completely, and they would have a statistically significant correlation coefficient of 1.0. Conversely, measurements of wind speed, and any variability, at two turbines on different continents would be expected to differ widely, and therefore show little to no statistically significant correlation, and would have a correlation coefficient close to 0 (see figure 20 below).[38]

Figure 20: Wind correlation as a function of turbine separation distance[39]



Interconnecting closely located, and therefore closely correlated wind farms will do little to address the intermittency of the generation. However, interconnecting widely distributed wind farms with small correlations will effectively insure that at any given time, some wind generation will be available over the entire aggregate. If overbuilding and curtailment, as well as synergistic blending of PV and wind, are also pursued, then a fairly robust, dispatchable renewable grid could be realized.

Geographically diverse but interconnected wind generation provides various benefits to grid operators at different scales. Figure 21 lists the electric power system benefits for systems at various distances, correlations and time scales.

Figure 21: Summary of the Statistical Observations and Effects for Geographic Diversity of Wind Power

Distance (km)	Correlation (1 hr avg)	Time scale of benefit	Electric power system benefits
1	0.9	seconds-minutes	Voltage control
10	0.9	minutes-10 minutes	Regulation
100	0.7	1 hr	Regulation Operating reserves
500	0.35-0.7	hours	Operating reserves Forecasting Scheduling
1,000	0.1-0.5	hours	Operating reserves Forecasting Scheduling
2,000	0	days	Forecasting Scheduling Reliability
10,000	-0.1	days-weeks	Reliability

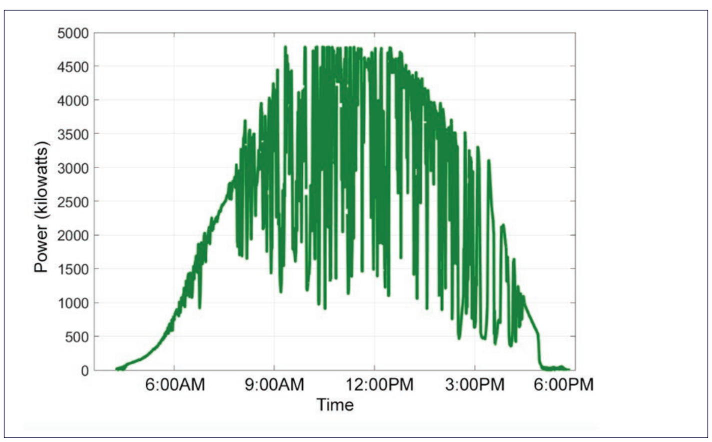
Source:[40]

The benefit of geographic diversity is dependent on the distance and time scale of interest. Geographically diverse wind benefits the electric power system depending on the relevant time scale. Correlations vary widely between 100 km and 1000 km depending on terrain and orientation of sites relative to the movement of weather systems.

6. Overbuilding and curtailing renewable resources:

Figure 22 illustrates a typical solar irradiance profile for a 12 hour period. Note the periodic power production variations throughout the day, reflecting decreases and increases in the amount of available sunlight due to cloud cover/shadow. Also note the minimum steady capacity of the system of around 1000kW between sunrise and sunset.

Figure 22: variability of solar irradiance throughout a 12 hr period[41]

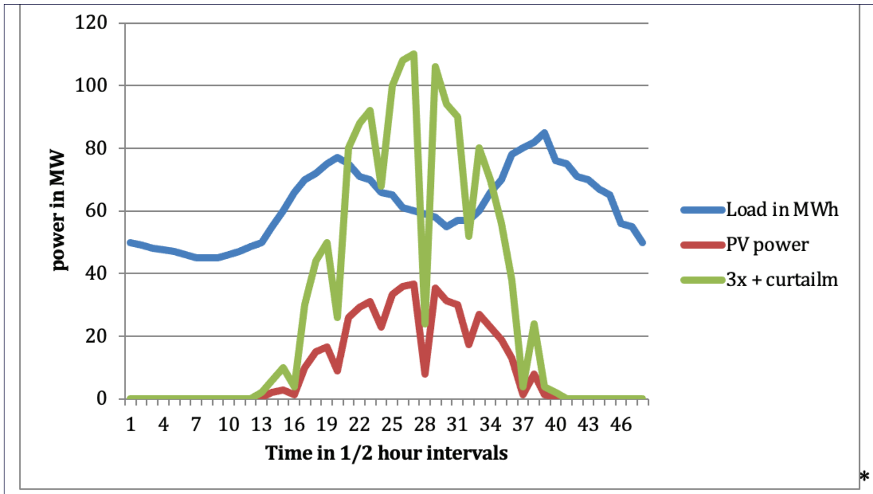


The variability in generation due to these spikes creates challenges for grid operators tasked with providing a steady voltage, frequency and current to customers, and such variability must be supplanted, currently with capacitors, spinning reserve natural gas plants and other dispatchable sources. Eliminating this variability is the biggest barrier to large-scale penetration of the grid by renewable resources (wind variability yields a similar analysis); filling in these gaps is the challenge of the current moment.

One method of dealing with solar (and by extension wind) intermittency is through overbuilding the generating capacity, then curtailing (removing from production, or "spilling") the excess generation of electricity during periods when supply exceeds demand.

The minimum generating capacity of a solar panel depends largely on the amount of incoming radiation, but would not be expected to be zero except when the sun is down or full shadow covers the entire system. For a suitably sized system, some generation would occur where cloud cover is random or, in the event of a large storm system, the amount of irradiance is low. Therefore, we would expect a system to produce some electricity throughout the day, illustrated by the minimum above in figure 22. This minimum can be exploited: if the system is doubled or tripled, then the minimum should also double or triple. In such an "overbuilt" system, at some point there will be enough generation to reliably meet the full load. Figure 23 illustrates this possibility: the blue line represents the load, and the red line represents electrical generation from a PV system. Note the periodic spikes in production from the PV; also, that although supplying part of the load, the system does not supply a major percentage. The green line represents the generation by a PV system that is three times larger, and is considered overbuilt because at peak generation it produces considerably more power than the load requires; generation beyond the demand must therefore be curtailed. The tripled system has the same spikes reflecting the conditions on the day illustrated; these would have to be met by a backup system capable of short bursts of generation, such as batteries or other dispatchable storage.

Figure 23: Illustration of load, PV and 3 times overbuild profiles

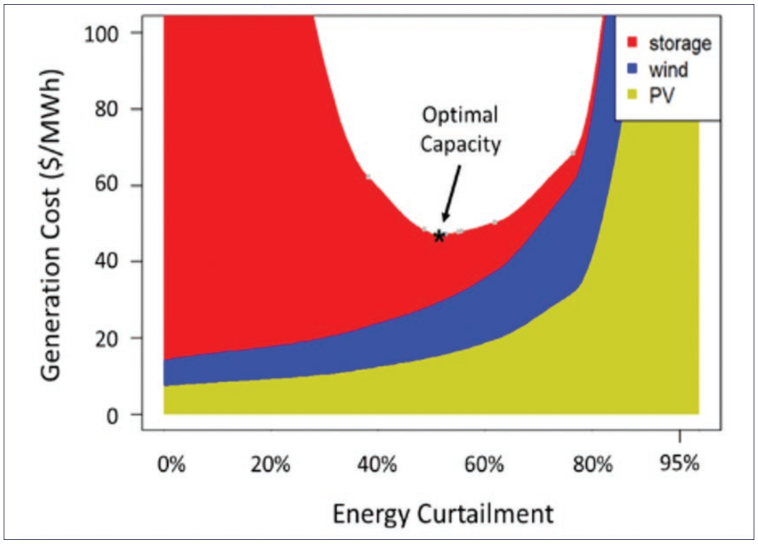


Source: author's illustration

The issue of course is cost. Overbuilding a system increases capital costs and surface area requirements for an installation. Owners of generating stations must ensure cash flow to meet fixed costs: payroll, debt, and operating and maintenance costs. Curtailing generation brings in zero revenue for the amount curtailed, even while fixed costs continue. Thus, curtailment is seen as a drawback to overbuilding.

Perez et. al. provide a different strategy: as solar installation costs continue to decrease, find an optimal combination of overbuilt solar and storage, whereby the increase in capacity meets demand in the earlier morning and later evening (when irradiance is low) as well as in the winter months when the sun is lower in the sky, thereby reducing the need for so much storage. There is a sweet spot where the added costs incurred by overbuilding and curtailment are offset by the savings in reduced storage requirements.[42] Figure 24 below illustrates this interplay: initially (left side of graph), solar and wind are deployed at some minimum amount, with a large amount of storage built to ensure a zero curtailment rate. Generation costs are high (>$100/MWh), driven primarily by the storage costs (red). As the amount of wind and solar installed begins to increase, the percent curtailment will increase, and the amount of storage required will begin to decrease. At around 30% curtailment, the costs for generation begins to drop steeply, primarily driven by the larger savings in avoided storage costs. At around 50% curtailment, a generation cost minimum is realized due to the optimal combination of storage and overbuilding.[43]

Figure 24. The influence of additional capacity coupled with energy curtailment on generation cost and resource deployment.[44]

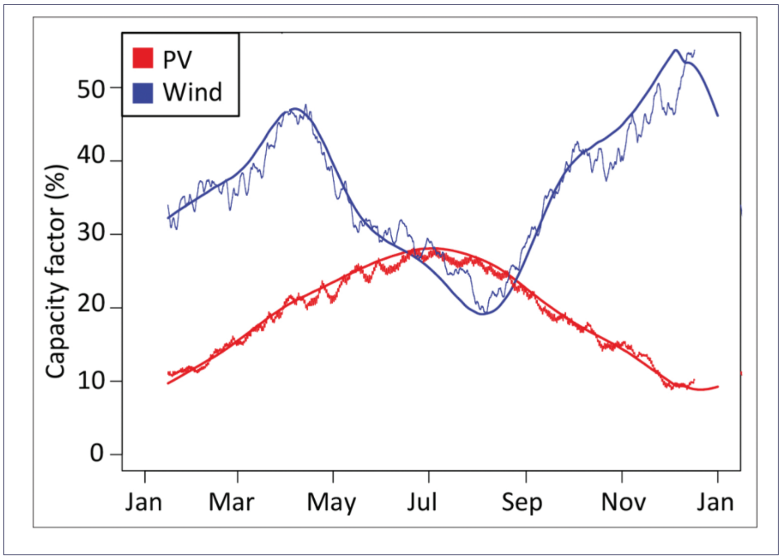


7. Synergistic blending of PV and wind where the two resources are anti-correlated over large time-scales

Another strategy for addressing the challenge of wind and solar intermittency, and the resultant limitation on being dispatchable, involves the synergistic blending of solar and wind resources that are complementary within both a given region or power grid, and within a fixed timeframe. Synergistic blending results in a combined capacity that is greater than the two resources as stand-alone facilities.

Figure 25 below illustrates the annual solar and wind generating capacity across the state of Minnesota for 2016. Note that the solar capacity increases and decreases inversely with the wind capacity; thus the two resources are anti-correlated and therefore complementary. Careful siting and interconnecting of both solar and wind generators for the state will yield a combined capacity factor that is higher than either resource alone.[45]

Figure 25. Solar vs. wind resource across the state of Minnesota at the monthly interval in 2016. Pictured is both a 30-day moving average and locally weighted trend line for each resource. Strongly visible is the seasonal anti-correlation between wind and solar resources across the state.[46]



Texas ERCOT study on two-resource complementarity:

In an assessment of the complementarity of solar and wind resources in Texas (Slusarewicz and Cohan 2018), average annual capacity factors for twelve state-wide wind or solar installations (Fig 26) were averaged over the period of 2007-2013.

Figure 26: Study sites for the assessment of wind and solar complementarity for resources in the Electric Reliability Council of Texas (ERCOT) grid

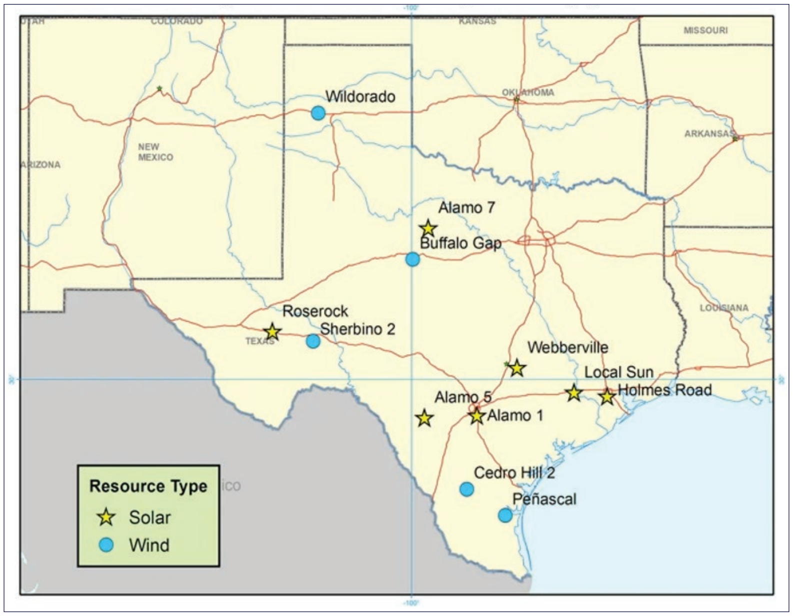


Figure 27 illustrates the resource complementarity during the summer and winter solstices. Each graph in Fig 27 quantifies the aggregate half-hourly average production/capacity factors during the years 2007-2013. On June 21, solar and West Texas wind exhibit complementarity over a 24 hour period, with south wind providing a peak in the evening centered between the solar and west wind peaks. On December 21, complementarity is evident, although solar and South Wind values are lower than summertime values.

Figure 27: Resource complementarity over a 24 hour period for June 21 and Dec 21
Half-hour average capacity factor for each site, 2007–2013, on June 21 (top) and December 21 (bottom)

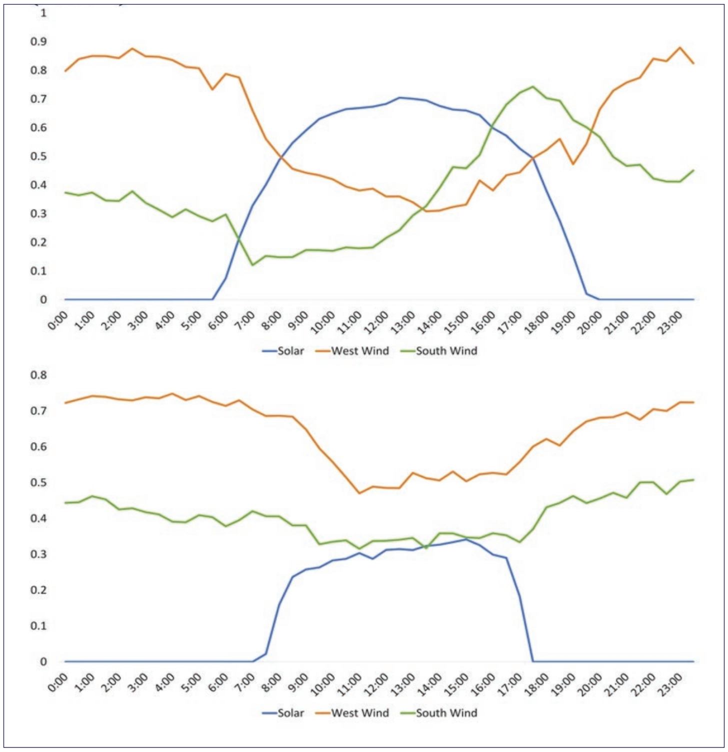
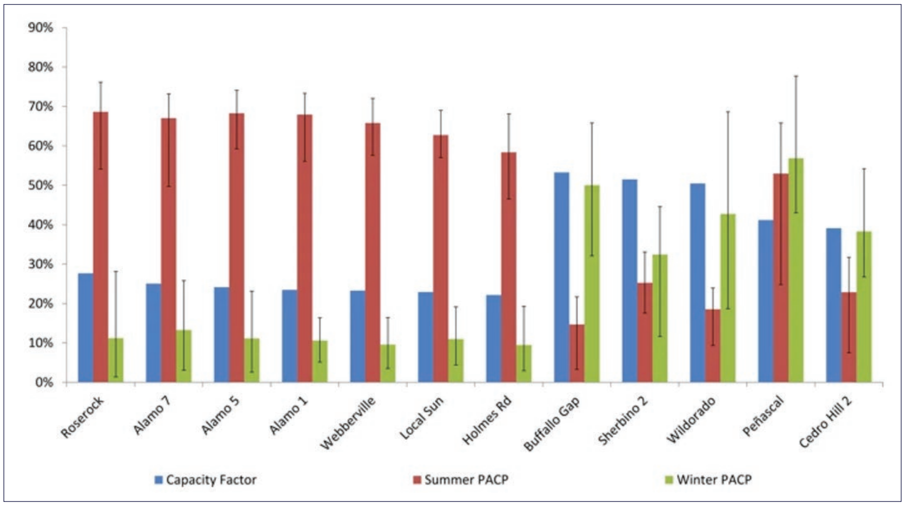


Figure 28 shows the annual average capacity factor (blue bars), and also includes data on the peak average capacity percentage (PACP), which is defined by ERCOT as "a facility's average capacity factor over the top 20 load (i.e., power demand) hours for the peak season (either summer or winter) (ERCOT 2018)" (Assessing solar and wind complementarity in Texas Joanna H. Slusarewicz & Daniel S. Cohan). Summer PACP are red bars, and illustrate a dramatic departure from average capacity factors for solar. Given that capacity factors are averages over a year's time, and provide little fine-grained information relating capacity to load at any given time, PACP provides a better snapshot of a facility's capacity to supply adequate power during peak loads. Roserock facility provides an example: the average capacity factor is around 28%, which includes the rather poor production values expected during winter months. However, in summer months, when solar output corresponds with summer peak loads, the PACP is around 69% (likewise the winter PACP hovers around 11%, reflecting a low capacity to meet winter heating and lighting loads). This high value of 69% more accurately quantifies Roserock's reliability as a generator in the summer season. Wind resources tend to increase in winter months and decrease in summer, reflected in the lower summer, and higher winter, PACP values for the five wind sites (Buffalo Gap to Cedro Hill 2). The fact that in general wind's winter PACP is lower than the average capacity factor implies that much of the generation occurs during off-peak hours and therefore would benefit from storage.

Figure 28: Capacity factors and summer/winter peak average capacity percentage (PACP)
Solar and wind farm capacity factors overall, and during summer and winter peak hours, averaged over 2007–2013. Error bars show the range of annual values.

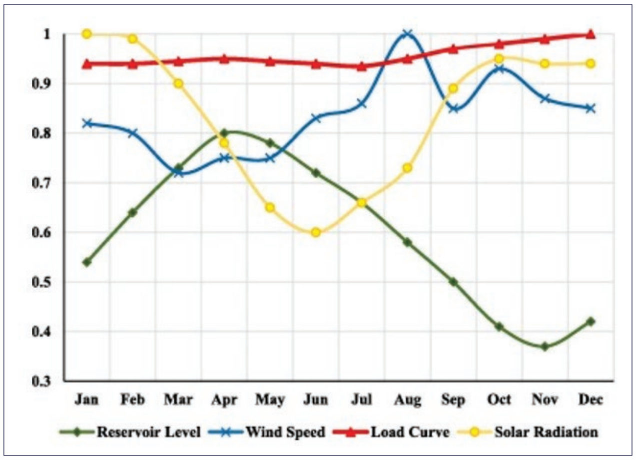


A study of three-resource complementarity

A study of resources in Brazil (de Jong et al. 2013) analyzed the potential synergistic blending of solar, wind and hydro in an effort to minimize the impacts on one resource that was used for multiple uses: in this case, hydro reservoirs served both hydro power as well as agricultural irrigation. Careful use of solar and wind resources in July through December can reduce demands on hydro power, thus maintaining reservoir levels for later use in irrigation. Similarly, replenished reservoirs in March and April can supply power to complement the decreased solar resource in the austral winter.

Clearly significant solar and wind generation from July to August can reduce the use of water in reservoirs, which later can be used for different purposes like irrigation. It must be noted that the figure presents monthly values and in consequence the actual (intraday) variability is not visible. Adapted from de Jong et al. (2013).[47]

Figure 29: Relationship between solar/wind and hydropower resources availability compared with the electrical load in Brazil.

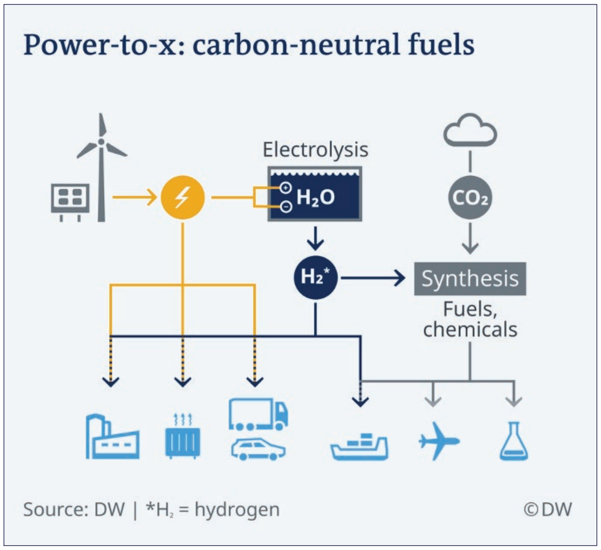


8. Power to X: Converting renewable electricity into hydrogen

Power-to-X, or P2X, refers to the process by which excess electricity is uncoupled from the grid and used to produce a variety of fuels, chemicals, mobility, heat, food and/or power (collectively, "X"). For the purposes here, we will limit the discussion to power to hydrogen as it applies to the electrical grid..

Figure 30 illustrates the potential for hydrogen produced in a power-to-H2 scenario. Hydrogen can complement raw electricity for industry, heating and transportation (yellow and blue lines); it can also be combined with atmospheric CO2 to create synthetic fuels for use in aviation and shipping. Hydrogen essentially stores the excess energy from wind and solar in chemical bonds.

Figure 30: Power to X pathways[48]



Electricity can power an electrolyzer, which splits water into hydrogen, H2, and oxygen, O2 via the following reaction:

$$2H_2O + \text{energy(electricity)} \rightarrow 2\,H_2 + O_2$$

The hydrogen can be dried, compressed and stored for use by the grid, transportation, industry and heating. The oxygen can be similarly processed for use in manufacturing, industry and medical uses, or harmlessly released.

Using the stored energy of hydrogen

In the reverse of the above reaction, hydrogen reacts with oxygen to form water:

$$2\,H_2 + O_2 \rightarrow 2\,H_2O + \text{energy}$$

The reaction is accompanied by the release of energy; kilogram for kilogram, H2 has about three times the energy density of gasoline, jet fuel or natural gas (volumetrically, hydrogen has a lower energy density than liquid fuels, by a factor of around 3.5, which is a large challenge for transportation design).[49]

Because the reaction can proceed explosively, hydrogen can be used in modified internal combustion engines for automotive use, and in turbines for aviation and electrical generation. Additionally, the reaction can take place in the far more controlled environment of fuel cells, creating electricity.

In all conversions of energy from one form to another, there are inherent energy losses. For the conversion of electricity to hydrogen, the process is about 65-70% efficient.[50]

Converting the hydrogen back to electricity results in losses, primarily to heat, with efficiencies of 50% for fuel cells and 60% in combined cycle gas turbines (CCGT). The resulting round-trip efficiency for power-to-H2-power is around 35 to 40%, meaning 60 to 65% of the original energy is lost. Though significant, this disadvantage is offset by several significant advantages:

- As a fuel, H2 produces zero carbon emissions (provided the electricity source for the electrolyzer is renewable).
- H2 can be stored in off-the-shelf existing technologies.
- Internal combustion engine and CCGT are mature technologies; fuel cells are near-term mature, but require reductions in costs.
- H2 can be stored at higher energy densities and lighter weights than batteries.
- H2 can be combined with CO2 (atmospheric) to create synthetic fuels.
- Green(renewably electrolyzed) hydrogen (RH2) is in the early stages of development, and currently makes up less than 4% of the total hydrogen market (most is made from steam reforming of hydrocarbons, resulting in significant CO2 emissions). Thus, we can expect RH2 to experience similar price reductions as that seen with solar, wind, batteries and any other technology that benefits from increased R&D and economies of scale that come with ramped up production.

As it applies to the electrical grid, electrolyzed hydrogen can be used as a storage form of energy, regenerating electricity when renewable resources are unavailable. Electrolyzers, dehydrators, compressors, storage tanks, and fuel cell/peaking turbines can be conveniently co-located with wind farms or solar arrays. Hydrogen can address the issue of curtailment: by utilizing electricity that would have been curtailed, revenue losses can be minimized, even with the low round-trip efficiency value.

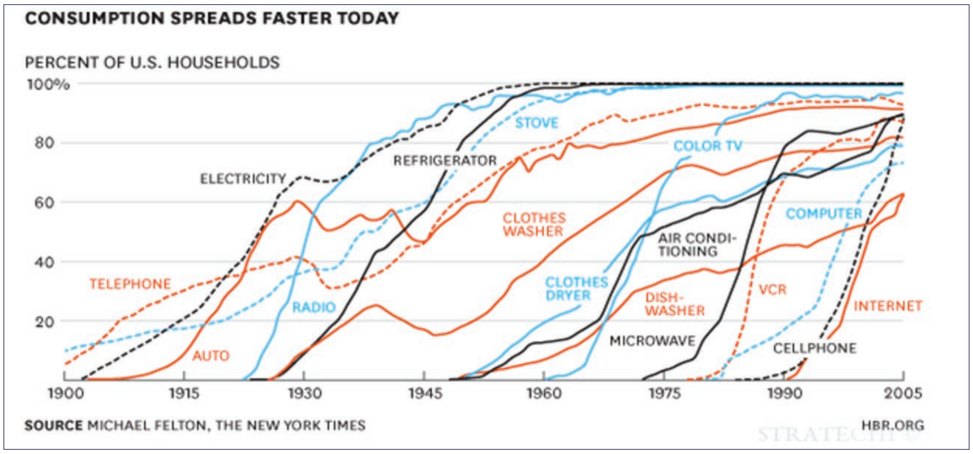
THE PACE OF TRANSITION

Scientists give us a rapidly closing window of opportunity to forestall the worst impacts of a climate-changed world. Action must be taken immediately, boldly and with an all-hands-on-deck approach: a war-time mobilization. How rapidly could these technologies be scaled up to create a modern, carbon-free energy system? The answer increasingly appears to be a policy issue, rather than a technology issue.

In attempting to answer the ‘how fast can we do this’ question, it is useful to consider both the adoption curve (Figure 55) and the historical growth curves for various technologies (Figure 56) below. The adoption curve is self-explanatory, and typically defines the various cohorts that adopt a given technology, behavior, or consumable over time. This curve can apply to all trends wherein a new idea goes from "fringe" to mainstream. The process may have a very slow start due to costs, risk assessment, belief systems, peer pressure, or unfamiliarity with a concept; as acceptance builds, the trend enters a logarithmic growth phase which results in large-scale adoption in a relatively short time frame.

Figure 31 illustrates the adoption curves for various technologies. We can all attest to the surprising rapidity that each of these technologies spread in our own lives; this rapidity creates the ground for that line "why, I remember when I was your age___"

Figure 31: Adoption curves for various historical technologies[51]



In asking how fast the transition from fossil fuels to renewable generation can occur, is it reasonable to apply this type of adoption dynamic to the utility and distributed energy systems in the US and globally?

Consider the growth curve for global cumulative and annual solar PV installations (Fig 32), utility-scale battery storage annual and cumulative additions (US) (fig. 33) and global wind power cumulative capacity (fig. 34). All of these technologies are experiencing logarithmic growth as costs drop, recognition grows about the urgency of addressing climate change, and utilities begin to accept their value to the grid. For comparison, Fig 35 illustrates the growth curve for coal, shown as net additions and retirements. 2020 was the first year in which more plants were retired than built.

These curves illustrate the potential for explosive growth, particularly with the support of government, investment and industry policies, as well as a groundswell of support by citizens. They are also proof of the robustness of these technologies that prevailed in spite of years of climate denial, skepticism of renewable energy by politicians and businesses, and the general inertia of a business-as-usual mindset that favors conservative risk management.

Figure 32: Solar PV:Global capacity and annual additions 2008 to 2018[52]

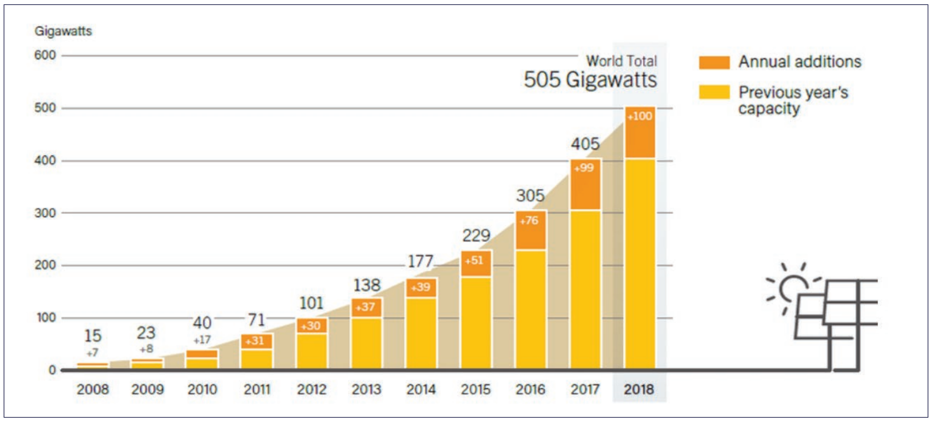


Figure 33: Utility scale battery storage cumulative and annual additions 2003-2020 plus projections (US)[53]

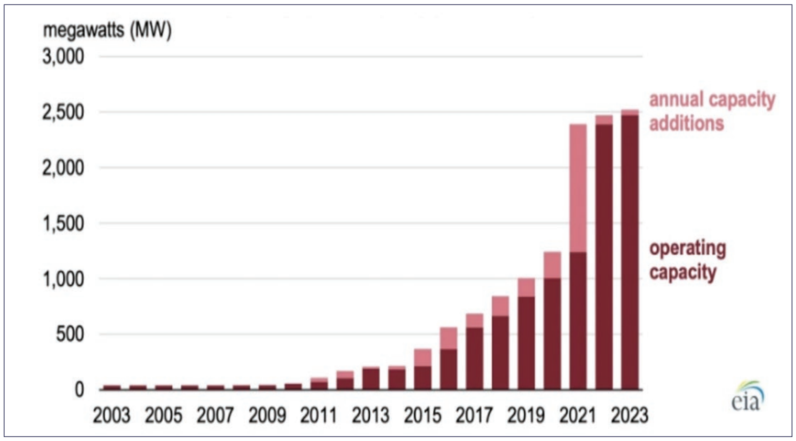


Figure 34: Global wind power cumulative capacity (data: Global Wind Energy Council)[54]

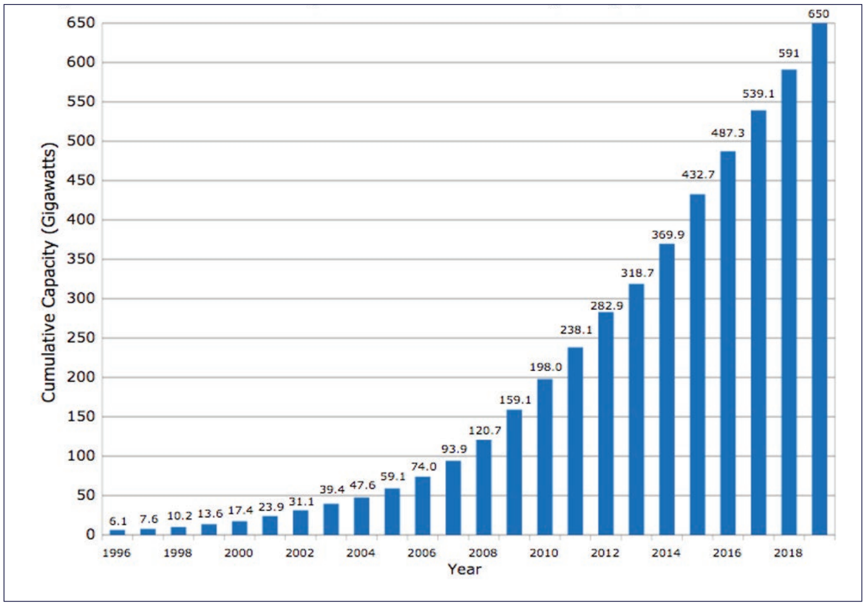


Figure 35: Global coal generating capacity changes[55]

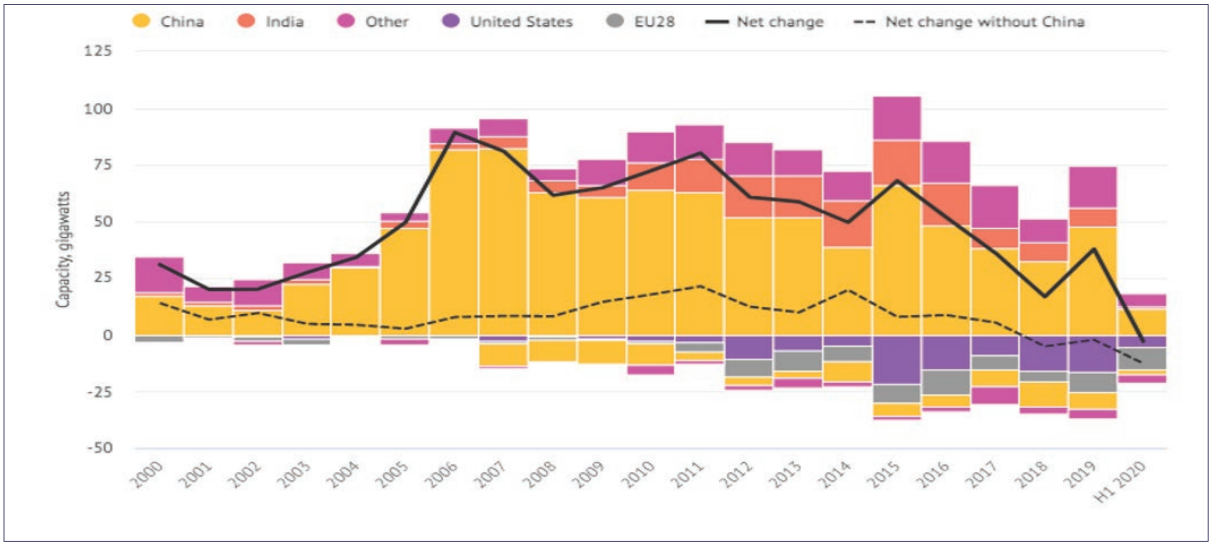
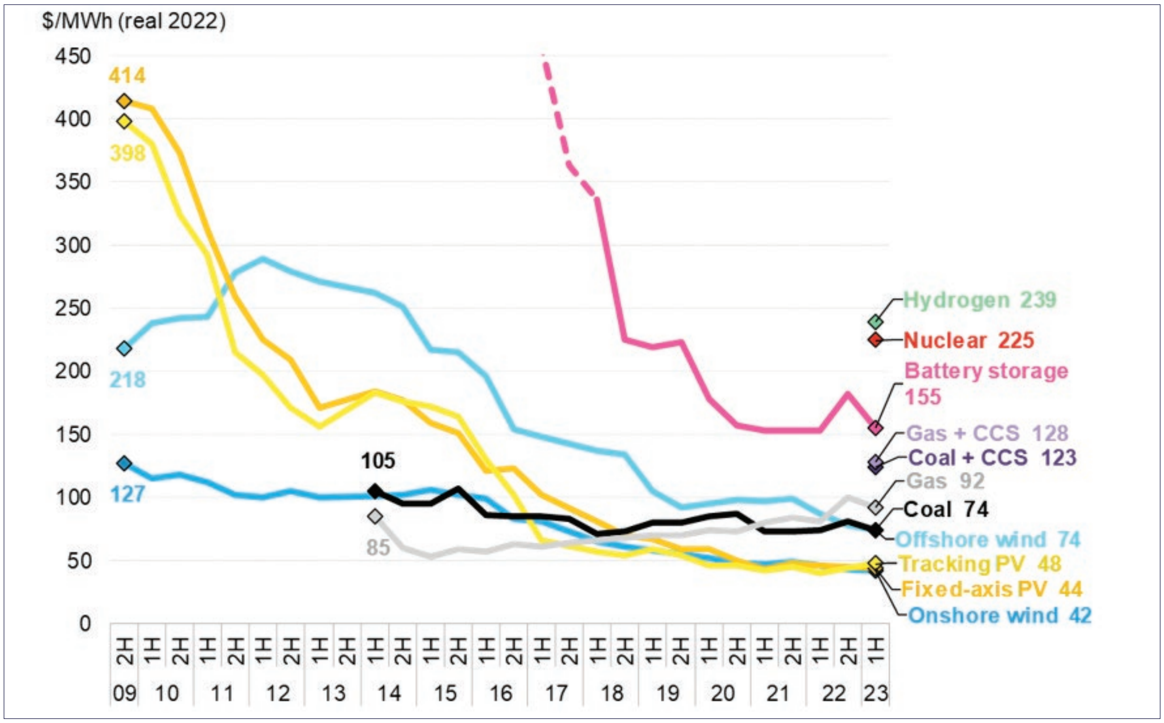


Figure 37 below shows comparative global levelized cost of electricity.

Figure 36: Global levelized cost of electricity benchmarks, 2009-2023s[56]



Solar and wind power are now the lowest cost sources of electricity. Energy analysts at prestigious RMI report that “clean energy portfolios” composed of solar, wind, battery storage, energy efficiency and demand flexibility can cost-competitively provide the same electricity, with the same reliability as fossil fuels.

Humanity stands with the wire of global energy demand in our left hand and the sparking wire of bountiful renewable energy in our right. It’s time to connect them.

Citations:

1. "Joint Declaration of the Global 100% RE Strategy Group (2021) (https://global100restrategygroup.org/)

2. "Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries" Mark Z Jacobson et.al. : Energy Environ. Sci., 2022, 15, 3343

3. (World Energy Resource Council 2013)

4. (ESMAP 2020 Global Photovoltaic Power Potential by Country, Washington, DC:World Bank)

5. https://www.forbes.com/sites/davidrvetter/2021/10/11/could-rooftop-solar-really-provide-enough-electricity-for-the-entire-world/?sh=7395fc9d22ee

6. "High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation" Siddharth Joshi et. al. Nature Communications volume 12, Article number: 5738 (2021)

7. https://www.energy.gov/eere/solar/large-scale-solar-siting#

8. https://www.unido.org/stories/what-industrialization-means-well-being-and-why-it-matters#:

9. op.cit Jacobson et.al.

10. (https://esmap.org/esmap_offshorewind_techpotential_analysis_maps)

11. "An Improved Global Wind Resource Estimate for Integrated Assessment Models", Kelly Eurek, Patrick Sullivan, Michael Gleason, Dylan Hettinger, Donna Heimiller, and Anthony Lopez National Renewable Energy Laboratory Feb 2017,(https://www.nrel.gov/docs/fy17osti/65323.pdf)

12. iea.org/reports/offshore-wind-outlook-2019)

13. (315PWh/yr x 106GWh/PWh x 0.67 x 1/0.4c.f. x 1/8760hrs/yr = 60,000GW).

14. op.cit. Eurek et.al.

15. (100,000TWh x 103 GWh/TWh x 1/.35c.f. x 1/8760 hr/yr =32,616 GW)

16. "Global potential for wind-generated electricity" (Xi Lu, Michael B McElroy and Juha Kiviluoma July 2009)

17. Fridleifsson, Ingvar B.; Bertani, Ruggero; Huenges, Ernst; Lund, John W.; Ragnarsson, Arni; Rybach, Ladislaus (11 February 2008). O. Hohmeyer and T. Trittin (ed.). The possible role and contribution of geothermal energy to the mitigation of climate change IPCC Scoping Meeting on Renewable Energy Sources. Luebeck, Germany. pp. 59–80.

18. op.cit. Jacobson et.al.

19. Hydropower Special Market Report, executive summary (https://www.iea.org/reports/hydropower-special-market-report/executive-summary)

20. op.cit. Jacobson et.al.

21. https://www.rechargenews.com/transition/new-zinc-air-battery-is-cheaper-safer-and-far-longer-lasting-than-lithium-ion/2-1-812068

22. op.cit. "Energy Storage Grand Challenge" USDOE 2020

23. "Zinc ion batteries could reach higher energy densities by avoiding traditional Anode" Chemical and Engineering News, Feb 3, 2021 https://cen.acs.org/materials/energy-storage/Zinc-ion-batteries-reach-higher/99/i5

24. www.wikipedia.org/wiki/sodium-sulfur_battery

25. https://cleantechnica.com/2019/02/03/

26. https://www.solarpowerworldonline.com/2021/02/ess-releases-customizable-iron-flow-battery-system-starting-at-3-mw-with-up-to-16-hour-duration/

27. https://www.e-education.psu.edu/ebf200/node/151 credit B. Posner

28. https://www.e-education.psu.edu/eme807/node/667 credit Mark Fedkin

29. https://www.tdworld.com/the-grid-optimization-blog/article/20968414/solar-will-shine-brighter-with-smarter-inverters

30. https://www.eia.gov/todayinenergy/detail.php?id=38872

31. https://solartechonline.com/blog/sdge-time-of-use-2019/

32. "Beyond TOU: Is more dynamic pricing the future of rate design?" https://www.utilitydive.com/news/beyond-tou-is-more-dynamic-pricing-the-future-of-rate-design/447171/

33. https://www.yaleclimateconnections.org/2019/12/an-introduction-to-the-state-of-energy-storage-in-the-u-s/

34. https://www.lazard.com/media/451087/lazards-levelized-cost-of-storage-version-50-vf.pdf

35. "Implications of Wide-Area Geographic Diversity for Short Term Variability of Solar Power " Andrew Mills and Ryan Wiser Environmental Energy Technologies Division September 2010 Ernest Orlando Lawrence Berkeley National Laboratory LBNL-3884E

36. "Spatial and Temporal Variability of Solar Energy" Richard Perez, Matthew David et. al. Foundations and Trends in Renewable Energy Vol. 1, No. 1 (2016) 1–44

37. "Spatial and Temporal Variability of Solar Energy" Richard Perez, Matthew David et. al. Foundations and Trends in Renewable Energy Vol. 1, No. 1 (2016) 1–44

38. "Variability of interconnected wind plants: correlation length and its dependence on variability time scale" Clara M St. Martin, Julie K Lundquist and Mark A Handschy Environmental Research Letters 10 (2015) 044004

39. "Variability of interconnected wind plants: correlation length and its dependence on variability time scale" Clara M St. Martin, Julie K Lundquist and Mark A Handschy Environmental Research Letters 10 (2015) 044004

40. "The Potential of Intermittent Renewables to Meet Electric Power Demand: Current Methods and Emerging Analytical Techniques", Elaine Hart, Eric Stoutenburg and Mark Jacobson, Proceedings of the IEEE Vol. 100, No 2, Feb 2012

41. "Can variable solar generation cause lights to flicker?" eprijournal.com

42. "Overbuild solar: it's getting so cheap curtailment won't matter." June 11, 2019 by Richard Perez and Karl Rabago https://energypost.eu/

43. "System design for a high-renewables future: Insights from the MN Solar Pathways Analysis" Brian Ross January 14 2019 https://betterenergy.org/

44. "System design for a high-renewables future: Insights from the MN Solar Pathways Analysis" Brian Ross January 14 2019 https://betterenergy.org/

45. Minnesota Solar Pathways Study 2016 http://asrc.albany.edu/people/faculty/perez/2019/PVTECH.pdf

46. Minnesota Solar Pathways Study 2016 http://asrc.albany.edu/people/faculty/perez/2019/PVTECH.pdf

47. A review on the complementarity of renewable energy sources: Concept, metrics, application and future research. J Juraasz, F.A. Canales, A. Kies, M. Guezgouz and A. Beluco Solar Energy Vol 195 1 January 2020, pp703-724 https://www.sciencedirect.com/science/article/pii/S0038092X19311831#b0085

48. Power-to-X: Clean energy to replace oil and gas. Gero Rueter December 19, 2019 Deutsche Welle dw.com

49. https://en.wikipedia.org/wiki/Hydrogen-powered_aircraft#/media/File:Energy_density.svg

50. (https://energystorage.org/why-energy-storage/technologies/hydrogen-energy-storage/)

51. https://www.stratechi.com/adoption-curves/

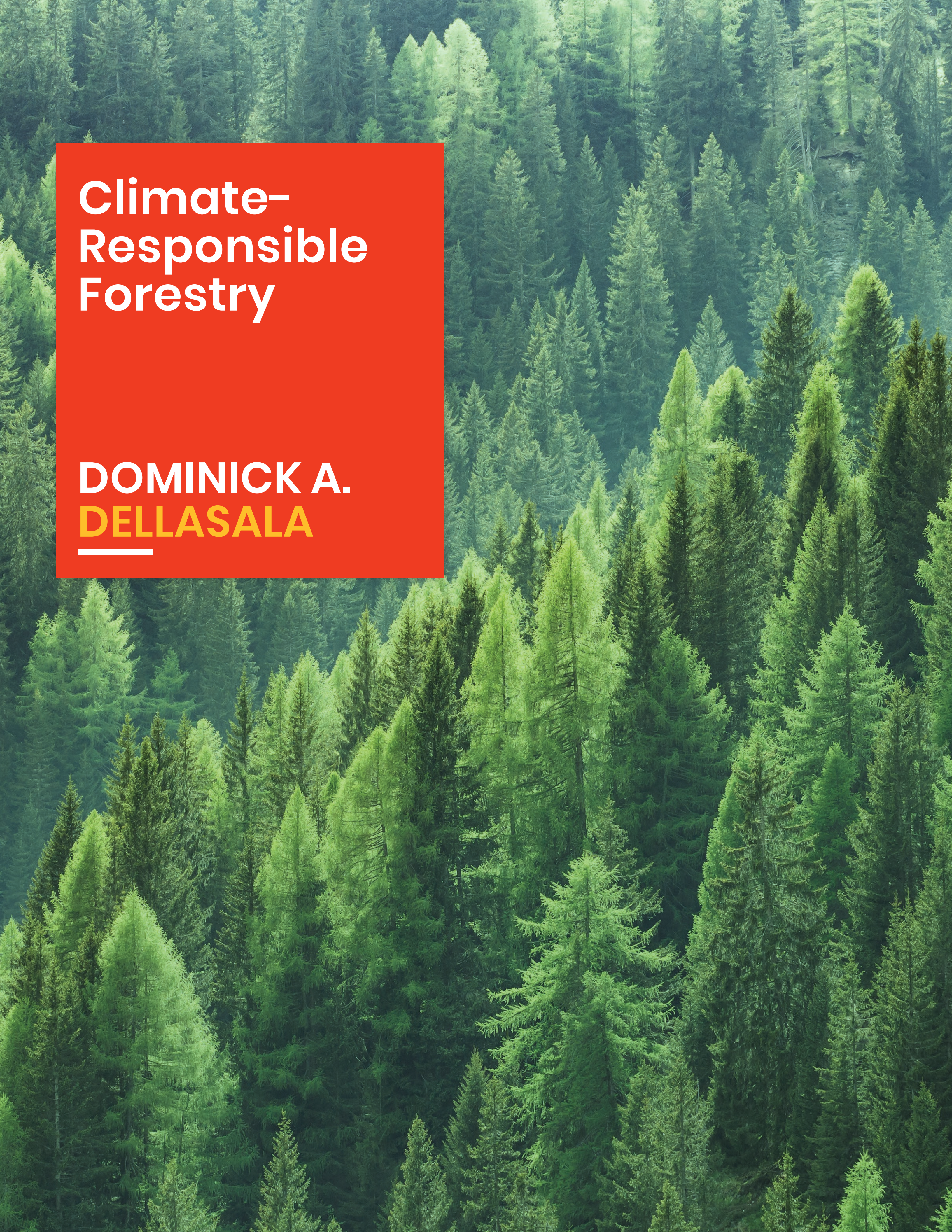
52. Renewable Energy: Environmental Impacts and Economic Benefits for Sustainable Development Sept 2019

53. https://electrek.co/2019/07/12/us-battery-capacity-triple-2023/

54. https://en.wikipedia.org/wiki/Wind_power_by_country

55. https://www.carbonbrief.org/analysis-the-global-coal-fleet-shrank-for-first-time-on-record-in-2020

56. IEA (2020), Projected Costs of Generating Electricity 2020, IEA, Paris https://www.iea.org/reports/projected-costs-of-generating-electricity-2020



Climate-Responsible Forestry

DOMINICK A. DELLASALA

Temperate-tropical rainforest mix in Victoria, Australia (D. DellaSala)

INTRODUCTION

Forests play a pivotal role in the uptake and long-term storage of atmospheric carbon. Protecting and properly managing forests comes with myriad biodiversity and ecosystem services that are essential in a rapidly changing climate. Forests are generally a net carbon sink, absorbing some 7.6 Gigatons (Gt = billion tons) CO_2 (e) per year, which is 1.5 times greater than US annual greenhouse gas emissions. Conversely, land use, land use change, and forestry (LULUCF) contribute some 11% of the annual global increase in CO_2 concentrations (5.8 + 2.6 Gt CO_2 e yr^{-1}) and 25% of CH4 and N2O emissions. To stabilize climate change, fossilized carbon must remain in the ground and atmospheric carbon absorbed and stored in terrestrial ecosystems, especially forests that are the most effective terrestrial carbon storage bank. I provide four forest carbon drawdown pathways to achieve climate stabilization through major forestry reforms: (1) protect the stocks in primary (unlogged) and mature-old growth forests (most important) by ending deforestation and forest degradation (DFD); (2) allow degraded forests time to reacquire stocks by reaching maturity through a process called proforestation; (3) plant trees (preferably natives) on fallow fields (afforestation); and (4) reforest (preferably natives) cutover lands where needed. To maximize mitigation potential, DFD would need to end immediately in the US/Canada immediately and globally by 2030, and forests protected for biodiversity and carbon at least tripled with half Earth protected by 2050. Ending DFD would represent a savings of 97 Gt C in avoided emissions. Regrowing the stock (proforestation) and allowing it to mature would sequester 120 Gt C by 2100, the equivalent of ~12 years of today's carbon emissions. Planting one-trillion trees by 2050 would sequester 42 Gt C by the time they mature although this strategy comes with ecological costs in terms of where to plant.. To save primary forests, timber consumption needs to shift to replanted areas with wood consumption levels greatly reduced along with widespread use of alternative fibers and recycling. Reforestation is estimated to sequester another 55 Gt C by 2100 worldwide. Forest carbon drawdown is therefore an effective means to avoid atmospheric-biosphere tipping points that could lock the planet into calamitous climate consequences in the coming decade(s) if not implemented. Each of these estimates is explained in detail herein.

FORESTS CARBON DRAWDOWN

I present four pathways by which forests can accelerate the drawdown of carbon, in conjunction with rapid decarbonization of the global energy supply and improved agricultural practices. The pathways build on published literature (Pan et al. 2011, Hansen et al. 2013, Mackey et al. 2013, 2014a,b, Griscom et al. 2017, Law et al. 2018, Hudiburg et al. 2019, Moomaw et al. 2019, Harris et al. 2021). It cannot be overstated that natural climate solution pathways are not a substitute for ending fossil fuel emissions. Ecosystems have limited capacity to draw down carbon (Griscom et al. 2017) and there is at least a decades-long lag in carbon uptake and storage from forest management improvements (Qin et al. 2020).

Given the global climate emergency, it is imperative that forestry practices are reformed to play a central role in climate mitigation as aptly recognized in the Paris Climate Agreement. For instance, Article 5.1 of the agreement calls on governments to protect and enhance "carbon sinks and reservoirs," while Article 21 of the UNFCCC COP26 Glasgow Climate Pact emphasizes "the importance of protecting, conserving and restoring nature and ecosystems, including forests… to achieve the long-term global goal of the Convention by acting as sinks and reservoirs of greenhouse gases and protecting biodiversity…" (UNFCCC 2021). Also, the Summary for Policymakers.(SPM.D.4) in the Intergovernmental Panel on Climate Change (2022) report mentions safeguarding biodiversity and ecosystem integrity as fundamental to climate resilient developments. Attention to the four pathways can inform implementation of these policy commitments.

Forest management worldwide is in need of a major paradigm shift via four fundamental pathways:

- **Protect the carbon stocks in older and primary forests** – cease logging in these forests and avoid forest conversion to plantations and other land uses (Mackey et al. 2014a,b, Griscom et al. 2017; DellaSala et al. 2020).

- **Proforestation** - allow degraded forests to regrow stocks over time by reaching maturity (Moomaw et al. 2019; "natural forest management," Griscom et al. 2017).

- **Afforestation** – plant trees (preferably natives) on fallow fields that can support trees.

- **Reforestation** - natural regeneration or planting of trees preferably natives on cutover lands (Griscom et al. 2017) along with a lengthening of timber harvest rotations (Law et al. 2018).

In addition to deforestation (permanent removal of forests), forest degradation (oversimplification of forest structure and species composition without an overall change in forest area) is a major contributor to loss of biodiversity and increase in carbon emissions. Although more difficult to measure, emissions from degradation range from 5 to 132% of total forestry emissions (Houghton et al. 2009). Pearson et al. (2017) estimated forest degradation from 2005 to 2010 across 74 developing countries with 2.2 billion ha of forests. Annual forestry emissions were 2.1 billion tons of CO_2, of which 53% came from logging, 30% woodfuel, and 17% forest fires. Of the total emissions, degradation accounted for 25% of emissions with 28 of the 74 countries exceeding deforestation emissions (Pearson et al. 2017).

FOUR PATHWAYS TO CLIMATE STABILIZATION

Climate smart forestry, a term in widespread use, is based on the premise that forests can be managed for negative net emissions (that is, they can serve as a carbon sink). However, this view omits the importance of protecting the stock and continues to send gross emissions to the atmosphere from logging during a climate emergency (see below). As society continues to consume vast quantities of wood products (IPCC 2020, FAO 2020), forestry can be more responsible ecologically, socially, and climatically but let's be honest about whether it is truly "climate smart" to be putting emissions into the atmosphere even if replanted trees sequester some of the emitted carbon.

Forest carbon drawdown is not a substitute or complete "offset" for continued use of fossil fuels, but should instead be seen as additive with decarbonization of the global energy supply. This is because the fossil fuel stock is enormous compared to that in forests that have a limited sink capacity in a rapidly changing climate (i.e., carbon saturation by century end, Griscom et al. 2017). The four pathways in forest carbon drawdown represent the necessary steps to *help* achieve climate stabilization. They are all important in aggregate, however, saving the stocks in a climate emergency needs to be the top priority implemented in lock-step with getting off fossil fuels (Keith et al. 2019, DellaSala et al. 2020). In general, carbon stock depletion from forests emits CO_2 to the atmosphere and contributes to overheating of the planet. Additionally, protecting primary forests (including old growth and mature forests where old growth is scarce) is the only effective carbon capture and storage approach that will work at scale immediately. The size and longevity (residence time) of the accumulated carbon stock in forests matters most for climate mitigation along with avoiding additional logging emissions. Thus, protecting the stocks is the top pathway priority.

PATHWAY 1: PROTECT THE STOCKS

Sinks vs. Stores - forests function as net *sinks* when the uptake of carbon in the forest exceeds that returned to the atmosphere via respiration and mortality. Forests are *stores* or reservoirs of carbon

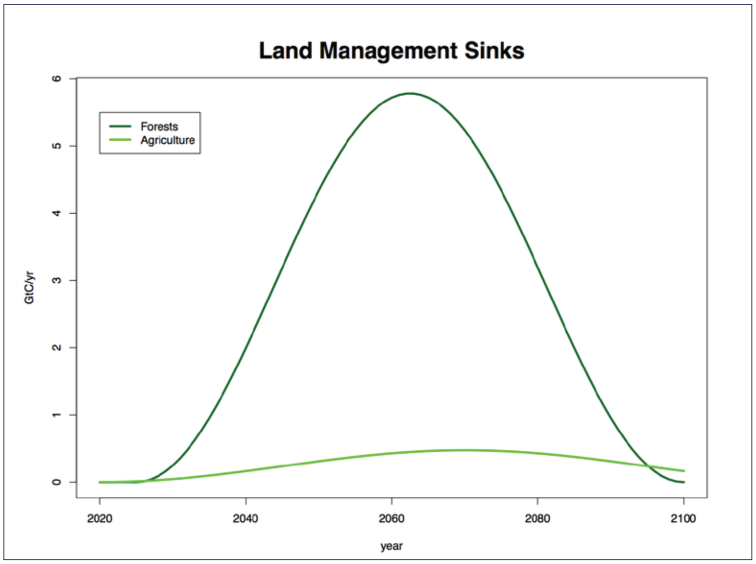
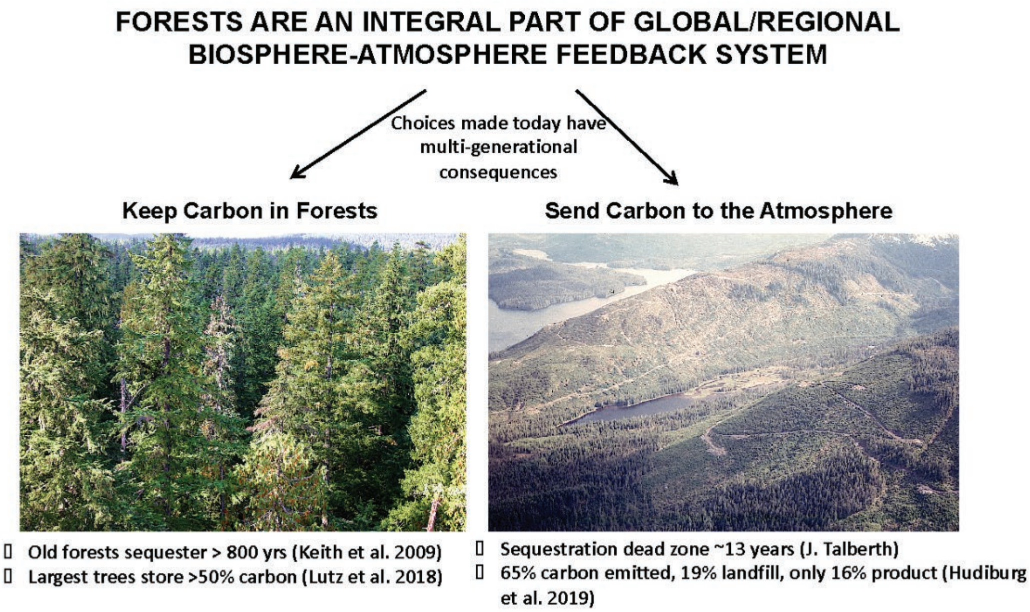


Figure 1: Time trajectory of Climate North Star Land Management Carbon Sinks due to improved forest and agricultural practices



that can be retained in living and dead biomass and soils for centuries if undisturbed. Both sinks and stores are vital in the forest pathways but stocks deserve more attention as they are most often neglected by forest managers and decision makers that are faced with economic choices that seldom include the true climate costs of industrial forestry (Figure 1).

Figure 1. Keeping carbon out of the atmosphere is essential in forest carbon drawdown and forestry has two choices – send it to the atmosphere by logging the forest, or keep it in the forests by protecting the stock as it matures. Clearcuts are sequestration dead zones for at least a decade as newly planted or reforested sites take time to start up carbon uptake.

When logged, forest regrowth will restart sequestration with a lag in uptake of carbon as logged forests act as a net source of emissions for at least a decade (Law et al. 2018, Qin et al. 2020, Figure 1) before young trees (or naturally regrown) start accumulating enough carbon to become a net sink (not considering the reduction in the stock). This period can be thought of as sequestration dead zones[16] (J. Talberth, pers. comm.). Even when sequestration eventually restarts, forest regrowth does not catch up to the emitted carbon stores for decades-centuries, especially if the forest is logged again on short timber rotation cycles (Law et al. 2018). We simply no longer have the luxury of time on our side to wait for the return of degraded carbon stocks.

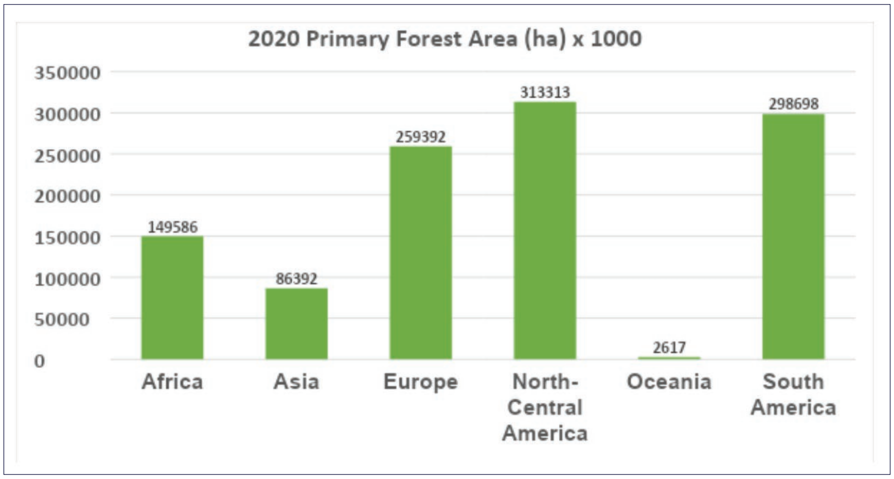
Importantly, old forests sequester carbon for centuries with most (e.g., >40%) of the carbon stored in the largest, oldest trees (Luyassert et al. 2008, Keith et al. 2009, Stephenson et al. 2014, Lutz et al. 2020, Mildrexler et al. 2020). Therefore, this pathway involves keeping atmospheric carbon in the oldest forests and large trees and needs to be implemented with efforts to keep fossilized carbon in the ground (e.g., Senate Bill 750 – Keep it in the Ground Act, Paris Climate Agreement Articles 4 and 5 in particular).

16. https://www.cbc.ca/news/canada/british-columbia/b-c-s-clear-cut-forests-are-dead-zones-emitting-more-greenhouse-gases-than-fossil-fuels-report-finds-1.5398660

Primary forests are carbon stock champions - Primary forests store 35-70% more carbon than logged forests (Keith et al. 2014, Mackey et al. 2014b, Keith et al. 2019) and therefore are irreplaceable for their carbon uptake and storage. In the tropics, primary forests hold 40 times more carbon compared to plantations (Moomaw et al. 2019). Saving primary forests comes with a "basket of benefits," including clean water, biodiversity, pollination, and soil integrity (e.g., Brandt et al. 2014, Keith et al. 2019) that are increasingly vital in a climate emergency.

Remaining primary forests are mostly in North-Central America (note: FAO combines these regions but most are in North America), followed by South America, Europe, Africa and Asia (Figure 2A). In North America, most of the primary forests are in the carbon rich (mostly soils) Canadian boreal with substantial concentrations in North Pacific coastal rainforests (among the most carbon dense in the world, Keith et al. 2009, Krankina et al. 2014). While the rate of primary forest losses has decelerated globally in the most recent decade (Figure 2B), primary forests cannot be replaced by tree planting as regrowth can take centuries to recover carbon stock and replanted forests in no way resemble the biodiversity or ecosystem services of primary forests (Kormos et al. 2019, DellaSala 2020).

(A)



(B)

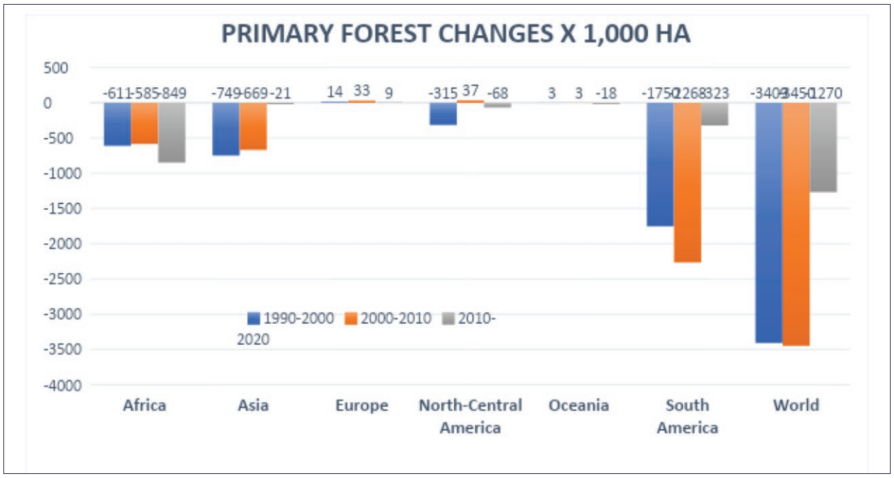


Figure 2. (A) Remaining primary forests and (B) rate of losses globally based on FAO (2020) with forests defined as tree cover >10% canopy. Small increases in Europe are the result of more countries reporting to FAO. Data quality limitations are described by FAO (2020), Hansen et al. (2013), and Keenan et al. (2015).

At the rate of logging globally (FAO 2020), very little tropical rainforest will remain by mid-century pushing the CO_2 ppm levels toward the limits implied by the Paris Agreement. The situation is especially urgent in Amazonia (the "lungs of the planet") where some 40% of tropical emissions originate (Pan et al. 2011) and because the Amazon is nearing a tipping point[17] where deforestation could lead to massive type conversion of rainforest to dry scrublands within just a decade.

Assessing trade offs - the stocks pathway comes with costs and tradeoffs (Keith et al. 2019). For instance, to avoid climate impacts from forest losses, carbon can be purchased as a partial "offset" for emissions elsewhere such as in the agricultural sector. Although more countries are putting a price on carbon currently valued at $10 USD/to ron (t) CO_2, for action at scale, prices may need to increase to $40-80/t CO_2 (World Bank Group 2017) or as high as $35-100/t CO_2 (Austin et al. 2020). Additionally, there is a social cost of carbon (SCC) in climate damages and human health impacts. Avoiding the SCC is not a trivial matter as costs range from $54/t CO_2 (mean value, Wang et al. 2019) to $417/t CO_2 (Ricke et al. 2018). For instance, hurricane damage, real estate losses, energy costs, and water losses may come with a price tag of 1.8% of the US GDP or nearly $2 trillion annually by 2100 (Ackerman and Stanton 2008) (also see Stern 2016 for 2% of the Global GDP annually in costs). Costs of climate impacts are typically underestimated due to uncertainties in disaster impacts with rising CO2 levels (DeFries et al. 2019),. By comparison, protecting the stock (Pathway 1) combined with proforestation (Pathway 2) is the cheapest path to mitigation (Griscom et al. 2017, Moomaw et al. 2019). For instance, Griscom et al. (2017) estimated costs of implementing 20 natural climate solutions at around $100 USD ton CO_2^{-1}.

Forgoing timber harvest and other land uses would represent lost timber value and associated jobs (trade offs). Interestingly, countries experiencing the highest forest losses also have the greatest population growth and lowest economic levels (Keenan et al. 2015). Thus, stabilizing population growth (even bending the growth curve down) in a culturally appropriate manner is vital, which would also need to be linked to dietary changes in meat consumption that is associated with expansive tropical deforestation (IPCC 2018, FAO 2020).

PATHWAY 2: REGROW THE STOCKS OVERTIME (PROFORESTATION)

Regrowing degraded forests to maximize carbon potential (drawdown) by allowing forests to mature optimizes atmospheric CO_2 removal via sequestration while restoring degraded ecosystem services (Moomaw et al. 2019). A single large tree (100-cm diameter at breast height) adds the equivalent annual biomass of an entire 10-20 cm tree (Moomaw et al. 2019). Carbon stored in trees increases dramatically in some regions when trees achieve a diameter of ~50-cm (Mixlerod et al. 2020). Letting forests recover large trees is a climate emergency priority.

17. https://www.unsdsn.org/leading-scientists-gather-before-the-un-climate-summit-to-highlight-the-sense-of-urgency-in-the-amazon

It is estimated that forests currently store only half their potential capacity due to losses of stored carbon from repeat short-interval logging (see Erb et al. 2018). Thus, the proforestation pathway could double the forest carbon stock over a century so that large trees are returned to the forest overtime (also see Law et al. 2018). Doing so, would sequester 120 Gt C by 2100, the equivalent of ~12 years of today's carbon emissions (Moomaw et al. 2019).

For this pathway to be viable, countries experiencing ongoing deforestation and shrinking primary forest stocks would need to transition timber operations to a portion of the previously cut over and reforested sites (Meyfroidt and Lambin 2011) (in addition to alternative fibers, recycling, and reduced consumption, see below). A handful of tropical countries and New Zealand, for instance, have made that transition to log reforested lands but this took place only after deforestation exhausted nearly all primary forests. It is important to note that "transition" in the climate sense refers to cessation of primary forest logging and not just reforestation, afforestation, or a net increase in planted forest as planting trees in no way is a substitute for forest losses (see trillion trees below).

The proforestation pathway is a more viable (realistic) alternative than afforestation that requires an estimated 10 million km^2 (slightly larger than Canada) to meet mitigation goals, which would compete with other land uses (Moomaw et al. 2019). As noted, newly planted areas require over a decade to restart sequestration and decades-centuries to recover stocks (Moomaw et al. 2019).

Tradeoffs are similar to those discussed for protecting the stocks, however, costs are lower than forgoing logging in primary forests as younger trees have a lower net present value.

PATHWAY 3 & 4: AFFORESTATION AND REFORESTATION

These pathways are treated together as they have similar climate consequences and tradeoffs. Over 90% (3.75 billion ha) of the global forest area is composed of naturally regenerating forests and 7% (290 million ha) are planted (FAO 2020). These two categories are headed in the opposite direction with natural reforestation declining and planted forests increasing in response to global wood product demand, although the annual rate of planted forest slowed in the last decade (FAO 2020). Global projections show the area of planted forests will likely increase by 2030 (Figure 3), providing additional sequestration benefits. Notably, the accrued stores are lacking in planted forests given they are generally logged again on short cycles (DellaSala 2020).

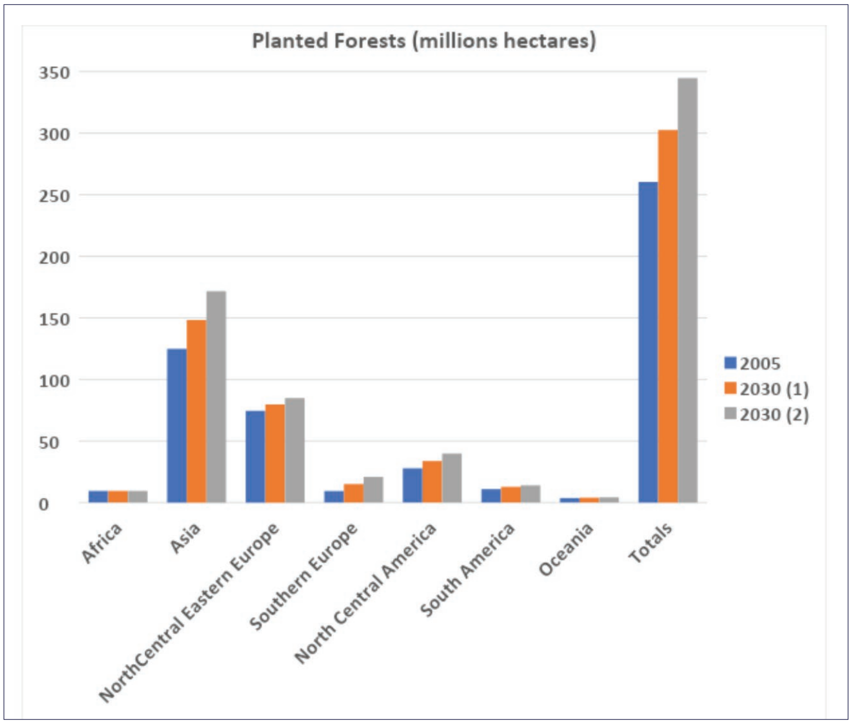


Figure 3. Area of planted forests (x 106 hectares, y axis) in 2005 vs. two projected scenarios for 2030 (from Carle and Holmgren 2008). Scenario 1 (orange) assumes no increase in productivity and the current expansion of planted forests slows down. Scenario 2 (gray, combined scenarios 2 and 3 of Carle and Holmgren 2008) assumes planted areas continue at the current rate and/or increase as a result of genetic modifications and management/technological improvements.

It is important to distinguish the reforestation pathway from proforestation. The main difference is forest regrowth by natural means or planting does not produce a continuously growing stock as these forests are most often in a production cycle. Nonetheless, Cook-Patton et al. (2020) estimated that 30 years of natural regrowth across 349-678 million ha would capture 1.08-1.60 PgC yr^{-1} in above ground biomass and 0.37-0.54 Pg C yr^{-1} in below ground carbon[18]. Maximizing this pathway, however, would require dietary shifts (trade offs) to accommodate agricultural land reverting to forests (trade offs).

18. For carbon units: ! Gigaton is 1 billion tons (or 109); 1 Petagram (Pg) = 1015 or 103 Gigatons

In the US, additional carbon sequestration and storage via forestry improvements (replanting and lengthening harvest rotation intervals) would reduce net emissions by 11-21% (Fargione et al. 2018, also see Law et al. 2018 for doubling rotation lengths).

Plantations – a subset of planted – plantations cover about 131 million ha, 3% of the global forest area and 45% of the total planted area (FAO 2020). Most are in South America (non-native trees) with substantial amounts in the US (mostly native trees of commercial value), especially the southeast. The area of plantations increased by 55.8 million ha 1990-2020 with the biggest jump in the past decade (FAO 2020). Advancements in silviculture and tree planting are projected to keep pace with wood demand for a decade or so until a tipping point is reached as silviculture can only achieve so much output without depleting soil nutrients. Thus, while plantations will be increasingly relied on for wood products, alternative fibers (see below), recycling, and reduced waste will need to come up to speed to flatten and bend down the wood consumption curve and alleviate deforestation pressures.

In the meantime, tradeoffs in these pathways include the continued loss of primary forests due to conversion of these natural forests to planted areas and plantations. For instance, the total carbon stock in forests decreased from 668 Gt in 1990 to 662 Gt in 2020 due to deforestation and forest conversion (FAO 2020).

Trillion trees – since planting trees is one of the pathways by which drawdown can be partially achieved, it is noteworthy to call out the trillion trees initiative that is gaining traction globally. The project aims to plant 1 trillion trees worldwide by 2050 to offset deforestation losses and is supported by some conservation groups[19], the World Economic Forum, US legislators, and even former President Donald Trump (although his approach is coupled with increased logging). Bastin et al. (2019) estimated that planting that many trees on ~223 million ha could sequester ~200 Gt C (20 x current annual fossil fuel emissions) within 100 years but Veldman et al. (2019) questioned these numbers as five times too high due to an overestimate of soil carbon gains, underestimate of albedo effects, and impractical and ecologically damaging tree planting in savannas and grasslands.

Planting trees would need to be planned carefully taking into account native species, native ecosystems, and competition with other land uses (agricultural lands were excluded from Bastin's calculations). Additionally, while this pathway can play an important role in mitigating climate change, it is by no means a substitute for drastically cutting emissions from fossil fuels and the forestry sector writ-large from gross emissions due to deforestation and degradation/ conversion of primary forests.

ALTERNATIVES TO WOOD PRODUCTS

While not an explicit pathway analyzed, alternative fibers are needed in the consumption mix to reduce demand on primary forests, stretch the ability of plantations and planted forests to meet growing fiber consumption demand, and provide sequestration benefits. Alternatives are partially compensatory for increased fiber demand from a growing human population and concomitant demands on forests.

19. https://trilliontrees.org/

For instance, Kerr (2020) recommended substantial replacement of forest fiber in the US with farm fiber via a combination of shifts in market demand, government procurement policies, government regulation, and reallocation of government subsidies. He documented 53 alternative fiber sources for building materials and agricultural waste fibers as pulp. Nearly 700 million tonnes of US farm fiber – of which 200 million tons is agricultural waste – could be available to replace forest fiber. Another 500 million tons annually could come from intentional fibers grown on farmland without competing with other uses. Adding value to agriculture waste fibers would reduce emissions from burning waste materials with additional mitigation benefits from avoiding logging.

WHAT WILL IT TAKE?

To maximize forest carbon drawdown, what matters most is compressing the timeline for forested nations to transition to already cut over lands instead of relying on dwindling primary forests. Nearly all forestry transitions begin too late if at all (Rudel et al 2005), when deforestation has liquidated most primary forests (e.g., New Zealand has a ban on native forest logging but little native forests remain). Given the climate emergency, one cannot wait for forest gain to eclipse loss in a climate emergency. Drastic changes are needed now to save the climate, forests, and the myriad benefits primary forests provide.

Mackey et al. (2014b) offer recommendations for linking primary forest protections to UN Sustainability goals. For instance, under the Convention on Biodiversity, parties have agreed to a Strategic Plan for Biodiversity 2011-2020 that includes 20 Aichi Biodiversity Targets. Primary forest protection is key to achieving at least 5 of the targets: natural habitat loss (Target 5), protected areas (Target 11), ecosystem services (Target 14), biodiversity contributions to climate change mitigation and adaptation (Target 15), and traditional local communities (Target 18). One potential incentive for primary forest conservation is the UN REDD+ Programme (Reducing Emissions from Deforestation and Forest Degradation). However, it only applies to developing countries and there are substantial gaps in primary forest protections, definitions of forests, monitoring and compliance, cultural and social inequalities, and leakage effects from increased logging elsewhere (Hess 2014). Nonetheless, according to some estimates (Nepstad et al. 2007) reducing deforestation in the Brazilian Amazon to nearly zero within a decade would cost $100 to $600 million USD yr^{-1} under a carbon credits program in REDD+ (based on $3/t carbon in 2007 but carbon pricing would need to increase at least 3-fold to current pricing). Notably, President Joe Biden pledged $20 billion[20] to end deforestation in the Amazon but at the abject rejection of Brazilian President Bolsonaro who's policies have embraced deforestation at the expense of aboriginal land rights.

Articles 4 and 5 of the Paris Climate Agreement[21] encourage nations to conserve and enhance C sinks and *reservoirs* (stocks) of greenhouse gasses, including forests. And while countries are keeping an accounting of their primary forests via periodic inventory, thus far, none have conserved them as part of the agreement. Thus, the forest drawdown pathways represent untapped potential to pressure governments to maintain stocks and not just sinks.

20. https://earthinnovation.org/2020/03/joe-biden-offers-20-billion-to-protect-amazon-forests/
21. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

About 10% of the world's forests (424 million ha) is designated primarily for biodiversity conservation and the rate of increase in forests in this management category has slowed in the past decade (FAO 2020).

Notably, some regions, like the Tongass rainforest in Alaska, are at the brink of a transition out of old-growth logging to young forest timber management that could save millions of hectares of primary forests (DellaSala and Furnish 2020). If implemented at scale, this would represent a global example of moving the logging footprint out of carbon dense areas and into young forests with low carbon stock well before the primary forest loss inflection point is reached.

The cost of implementing all four pathways globally is considerable but pales in comparison to the hardship and even higher costs of status-quo emissions. Austin et al. (2020) estimated that for natural climate solutions (planting, preserving, and managing forests for mitigation), carbon pricing would need to be \$50-\$100/t CO_2 (at least 5-x current pricing) to provide a mitigation savings of 0.6-6 Gt CO_2 yr^{-1}. That would amount to a total impact avoidance of \$2-393 billion USD yr^{-1}. Up to at least half of the climate savings would come from avoiding tropical DFD where carbon stores are maximized. Keeping in mind these costs are still far less than the ~\$2 trillion USD annual in climate impacts by the end of this century. In sum, an ounce of prevention is well worth a pound of cure but the window for cure is rapidly closing (climate emergency).

The carbon we emit today has consequences for generations to come and represents a social injustice and moral imperative. It is in humanity's best interest to jumpstart forest carbon drawdown now while there is precious time remaining. I close this forest drawdown paper with a moral imperative and appeal to humanity's spiritual and religious proclivities as science alone will not solve our planetary problem. Many religions and spiritual beliefs hold Nature in reverence and humanity's role as tending "Creation." The most dire state of the planetary climate and biodiversity emergencies are a social and moral imperative upon which we must act swiftly before time runs out on viable options.

LITERATURE CITED

Abatzoglou, J.T. and A. Williams. Impact of anthropogenic climate change on wildfire across western US forests. https://www.pnas.org/content/113/42/11770.

Ackerman, F., and E.A. Stanton. 2008. The cost of climate change. What we'll pay if global warming continues unchecked. https://www.nrdc.org/sites/default/files/cost.pdf.

Austin, K.G, et al. 2020. The economic costs of planting, preserving, and managing the world's forests to mitigate climate change. Nature Communications 11: 5946 https://doi.org/10.1038/s41467-020-19578-z.

Bastin, J.F. et al. 2019. The global tree restoration potential. Science 365:76-79. DOI: 10.1126/science.aax0848.

Brandt, P., D.J. Abson, D.A. DellaSala, R. Feller, and H. von Wehrden. 2014. Multifunctionality and biodiversity: ecosystem services in temperate rainforests of the Pacific Northwest, USA. Biological Conservation 169:362-371.

Cook-Patton, S.C., et al. 2020. Mapping carbon accumulation potential from global natural forest regrowth. Nature 585 https://doi.org/10.1038/s41586-020-2686-x.

DeFries, R. et al. 2019. The missing economic risks in assessments of climate change impacts. Grantham Research Institute on Climate Change and the Environment, The Earth Institute Columbia University, and Potsdam Institute for Climate Impact Research. https://www.lse.ac.uk/granthaminstitute/publication/the-missing-economic-risks-in-assessments-of-climate-change-impacts/.

DellaSala, D.A., J. Furnish, and E. Steinkamp. 2010. Hope in an era of climate change. Roadless areas in national forests. https://forestlegacies.org/wp content/uploads/2010/08/climatechangewhitepaper10.25.10.pdf

DellaSala, D.A. 2020. "Real" vs. "fake" forests: why tree plantations are not forests. In: Goldstein, M.I., DellaSala, D.A. (Eds.), Encyclopedia of the World's Biomes, vol. 3. Elsevier, pp. 47–55.

DellaSala, D.A., and J. Furnish. 2020. Can young-growth forests save the Tongass Rainforest in Southeast Alaska? In: Goldstein, M.I., DellaSala, D.A. (Eds.), Encyclopedia of the World's Biomes, vol. 3. Elsevier, pp. 218–225.

DellaSala, D.A., C.F. Kormos, H. Keith, B. Mackey, V. Young, B. Rogers, and R.A. Mittermeir. 2020. Primary forests are undervalued in the climate emergency. Bioscience. doi:10.1093/biosci/biaa030.

Dinerstein, E. et al. 2019. A global deal for nature: guiding principles, milestones, and targets. Science Advances 19 Apr 2019:Vol. 5, no. 4, eaaw2869 DOI: 10.1126/sciadv.aaw2869.

Erb, K.H., et al. 2018. Unexpectedly large impact of forest management and grazing on global vegetation biomass. Nature 553:73–76. doi: 10.1038/nature25138.

FAO. 2020. Global Forest Resources Assessment 2020: Main report. Rome.

https://doi.org/10.4060/ca9825en

Fargione, et al. 2018. Natural climate solutions for the United States. Sci Adv. 4:eaat1869. doi: 10.1126/sciadv.aat1869.

Griscom, B. W. et al. 2017. Natural climate solutions. Proc. Natl. Acad. Sci. U.S.A 114:11645–11650. doi: 10.1073/pnas.1710465114.

Hansen, J. et al. 2008. Target atmospheric CO2: where should humanity aim? Atmospheric and Oceanic Physics 2:217-231. DOI: https://arxiv.org/ct?url=https%3A%2F%2Fdx.doi.org%2F10.2174%2F1874282300802010217&v=0e9e598b.

Hansen, M.C., et al. 2013. High-resolution global maps of 21st-century forest cover change. Science 342:850-853.

Harris, N. L. et al. 2016. Attribution of net carbon change by disturbance type across forest lands of the conterminous United States. Carbon Balance Management 11:24. doi: 10.1186/s13021-016-0066-5.

Harris, N.L. et a. 2021. Global maps of twenty-first century forest carbon fluxes. Nature Climate Change 11:234-240.

Hess, J. S., 2014. Is REDD+ the right approach to reducing deforestation in tropical forest countries? https://climate-exchange.org/2014/02/02/is-redd-the-right-approach-to-reducing-deforestation-in-tropical-forest-countries-3.

Houghton, R. A., and A.A. Nassikas. 2018. Negative emissions from stopping deforestation and forest degradation, globally. Glob. Change Biol. 24: 350–359 doi: 10.1111/gcb.13876.

Hudiburg, T.W., B.E. Law, W.R. Moomaw, M.E. Harmon, and J.E. Stenzel. 2019. Meeting GHG reduction targets requires accounting for all forest sector emissions. Environ. Res. Lett. 14 (2019) 095005https://doi.org/10.1088/1748-9326/ab28bb.

Intergovernmental Panel on Climate Change (IPCC). (2022). Climate change 2022: impacts, adaptation and vulnerability. https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/; accessed March 22, 2022.

Kelly, L.T., et al. 2020. Fire and biodiversity in the Anthropocene. Science 370, eabb0355

(2020). DOI: 10.1126/science.abb0355.

Kerr, A. 2020. Migrating most US fiber production from forests to farms. Encyclopedia of the world's biomes:185-202. https://doi.org/10.1016/B978-0-12-409548-9.11828-7.

Intergovernmental Panel on Climate Change (IPCC). 2018. Summary for policymakers, in global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://www.ipcc.ch/sr15/.

Intergovernmental Panel on Climate Change (IPCC). 2020. Climate change and land. An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Summary for policymakers. https://www.ipcc.ch/srccl/.

Keenan, R.J. et al. 2015. Dynamics of global forest area: results from the FAO global forest resources assessment 2015. Forest Ecology and Management 352:9-20.

Keith, H., B.G. Mackey, and D.B. Lindenmayer. 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. Proc. Natl. Acad. Sci. U.S.A. 106, 11635–11640. doi: 10.1073/pnas.0901970106.

Keith, H., et al., 2014. Managing temperate forests for carbon storage: impacts of logging versus forest protection on carbon stocks. Ecosphere 5 (6), 75.

Keith, H., M. Vardon, J.A. Stein, D. Lindenhmayer. 2019. Contribution of native forests to climate change mitigation – a common approach to carbon accounting that aligns results from environmental-economic accounting with rules for emissions reduction. Environmental Science and Policy 93:189-199.

Kormos, C.F., et al. 2017. Primary Forests: Definition, Status and Future Prospects for Global Conservation. In D. A. DellaSala and M.I. Goldstein (eds.). 2017. Encyclopedia of the Anthropocene http://dx.doi.org/10.1016/B978-0-12-409548-9.09711-6

Krankina, O., D.A. DellaSala, J. Leonard, and M. Yatskov. 2014. High biomass forests of the Pacific Northwest: who manages them and how much is protected? Environmental Management. 54:112-121.

Law, B. E., Hudiburg, T. W., Berner, L. T., Kent, J. J., Buotte, P. C., and M.E. Harmon. 2018. Land use strategies to mitigate climate change in carbon dense temperate forests. Proc. Natl. Acad. Sci. U.S.A. 115, 3663–3668. doi: 10.1073/pnas.1720064115

Le Quéré, C., et al. 2018. Global carbon budget 2017. Earth Syst. Sci. Data 10: 405–448.

doi: 10.5194/essd-10-405-2018.

Lutz, J. A., et al. 2018. Global importance of large-diameter trees. Glob. Ecol. Biogeogr. 27:

849–864. doi: 10.1111/geb.12747

Luyssaert, S. et al. 2008. Old-growth forests as global carbon sinks. Nature 455, 213–215.

doi: 10.1038/nature07276.

Mackey, B., et al. 2014a. Untangling the confusion around land carbon science and climate change mitigation policy. Nature Climate Change | Vol 3 | June 2013 | www.nature.com/natureclimatechange.

Mackey, B. et al. 2014b. Policy options for the world's primary forests in multilateral environmental agreements. Conservation Letters, March/April 2015, 8:139–147.

McEvoy, D. J., D.W. Pierce, J.F. Kalansky, D.R. Cayan, and J.T. Abatzoglou.

2020. Projected changes in reference evapotranspiration in California and Nevada: Implications for drought and wildland fire danger. Earth's Future, 8,e2020EF001736. https://doi.org/10.1029/2020EF001736.

Meyfroidt, P., and E.F. Lambin. 2011. Global forest transition: prospects for an end to deforestation. Annu. Rev. Environ. Resour. 36:343-71 doi:10.1146/annurev-environ-090710-143732.

Mildrexler, D.J., et al. 2020. Large trees dominate carbon storage in forests east of the Cascade Crest in the United States and Pacific Northwest. Frontiers in Forests and Global Change https://www.frontiersin.org/journals/forests-and-global-change#articles.

Moomaw, W.R., S.A. Massino, and E.K. Faison. 2019. Intact forests in the United States: proforestation mitigates climate change and serves the greatest good. Frontiers in Forests and Global Change June 2019 Volume 2 Article 27.

Nepstad, D.C. et al. 2007. Brazil: The costs and benefits of reducing carbon emissions from the Brazilian Amazon region in Final Report to The William and Flora Hewlett Foundation From The Woods Hole Research Center: Linking Climate Policy with Development Strategy in Brazil, China, and India. November 15, 2007.

Pan, Y., J.M. Chen, R. Birdsey, K. McCullough, L. He, and F. Deng. 2011. Age structure and disturbance legacy of North American forests. Biogeosciences 8:715–738. doi: 10.5194/bg-8-715-2011.

Parks, S.A., and J.T. Abatzoglou. 2020. Warmer and drier seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. Geophysical Res. Letters https://doi.org/10.1029/2020GL089858.

Pearson, T.R.H., S. Brown, L. Murray, and G. Sidman. 2017. Greenhouse gas emissions from tropical forest degradation: an underestimed source. Carbon balance and Management 12 article number:3 (2017). DOI: 10.1186/s13021-017-0072-2.

Qin, Z. et al. 2020. Delayed impact of natural climate solutions. Global Change Biology 23 October 2020 https://doi.org/10.1111/gcb.15413.

Ricke, K, L. Drouet, K. Caldeira, and M. Tavon. 2018. County-level social cost of carbon. Nature Climate Change 8:895-900.

Ripple, W.J., et al. 2020. World scientists' warning of a climate emergency. January 2020 / Vol. 70 No. 1 https://academic.oup.com/bioscience

Rudel, T., et al. 2005. Forest transitions: towards a global understanding of land use change. Global Environmental Change 15:23-31.

Sanderson, B.M. and B.C. O'Neill. 2020. Assessing the cost of historical inaction on climate change. Science Reports 10: article number:9173 (2020).

Steffen, W., et al. 2018. Trajectories of the earth system in the Anthropocene. PNAS | August 14, 2018 | vol. 115 | no. 33 www.pnas.org/cgi/doi/10.1073/pnas.1810141115.

Stephenson, N. L. et al. 2014. Rate of tree carbon accumulation increases continuously with tree

size. Nature 507, 90–93. doi: 10.1038/nature12914.

Stern, N. 2016. Stern review: the economics of climate change. http://mudancasclimaticas.cptec.inpe.br/~rmclima/pdfs/destaques/sternreview_report_complete.pdf.

UNFCCC. (2021). United Nations Glasgow Climate Summit. https://unfccc.int/process-and-meetings/conferences/glasgow-climate-change-conference-october-november-2021/outcomes-of-the-glasgow-climate-change-conference; accessed May 28, 2022.

Veldman, J.W. et al. 2019. Comment on "the global tree restoration potential." Science 366 (6463) DOI:10.1126/science.aay7976.

Wang, P., X. Deng, H. Zhou, and S. Yu. 2019. Estimates of the social cost of carbon: a review based on metaanlysis. J. Cleaner Production 209:1494-1507 https://doi.org/10.1016/j.jclepro.2018.11.058.

Westerling, A.L. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philosophical Transactions of the Royal Society B: Biological Sciences, 371(1696), 20150178. https://doi.org/10.1098/rstb.2015.0178.

World Bank Group. 2017. State and trends of carbon pricing 2017. https://openknowledge.worldbank.org/handle/10986/28510.

World Meteorological Organization. 2020. WMO provisional report on the state of the global climate 2020. https://library.wmo.int/index.php?lvl=notice_display&id=21804#.X842PqpKhTY.

APPENDIX 1

National Forest logging in Montana (pers. comm. Mike Garrity, Wild Rockies, Arlene Montgomery, Friends of the Wild Swan). No carbon life cycle analysis has been performed by the Forest Service but these projects will create substantial emissions.

Kootenai National Forest draft decision for the Black Ram logging project of 3904 acres total, of which 2444 acres are clearcuts.

https://www.fs.usda.gov/nfs/11558/www/nepa/107949_FSPLT3_5365378.pdf

https://www.fs.usda.gov/project/?project=52784

Kootenai National Forest draft decision for the Ripley Project of 10,854 acres of logging with 3223 acres as clearcuts, 1544 acres of precommercial logging, and 19 miles of new roads

https://www.fs.usda.gov/project/?project=55001.

Helena-Lewis and Clark National Forest signed a decision for the Castle Mountains Project includes 22,550 acres of logging and prescribed fire with 19 miles of new roads

https://www.fs.usda.gov/project/?project=41955.

Helena-Lewis and Clark National Forest signed a decision for the Horsefly Project of 10,754 acres of logging and prescribed fire with 40 miles of new roads

https://www.fs.usda.gov/project/?project=53578.

Helena-Lewis and Clark National Forest proposed the Boulder Baldy Project of 6,043 acres of logging with 3549 acres of clearcuts and 32.8 miles of new roads

https://www.fs.usda.gov/project/?project=57479.

Helena-Lewis and Clark National Forest released an Environmental Assessment (EA) for the Middleman Project calling for 10800 acres of logging with 6444 acres of clearcuts, 47,467 acres of prescribed burning, and 61 miles of new roads

https://www.fs.usda.gov/project/?project=57506.

Lolo National Forest released an EA for the Redd Bull Project proposing 24,744 acres of logging, 13,136 acres of commercial logging and 14,791 acres of non-commercial logging, in bull trout habitat. There will be 9194 acres of clearcuts and 27 miles of new roads

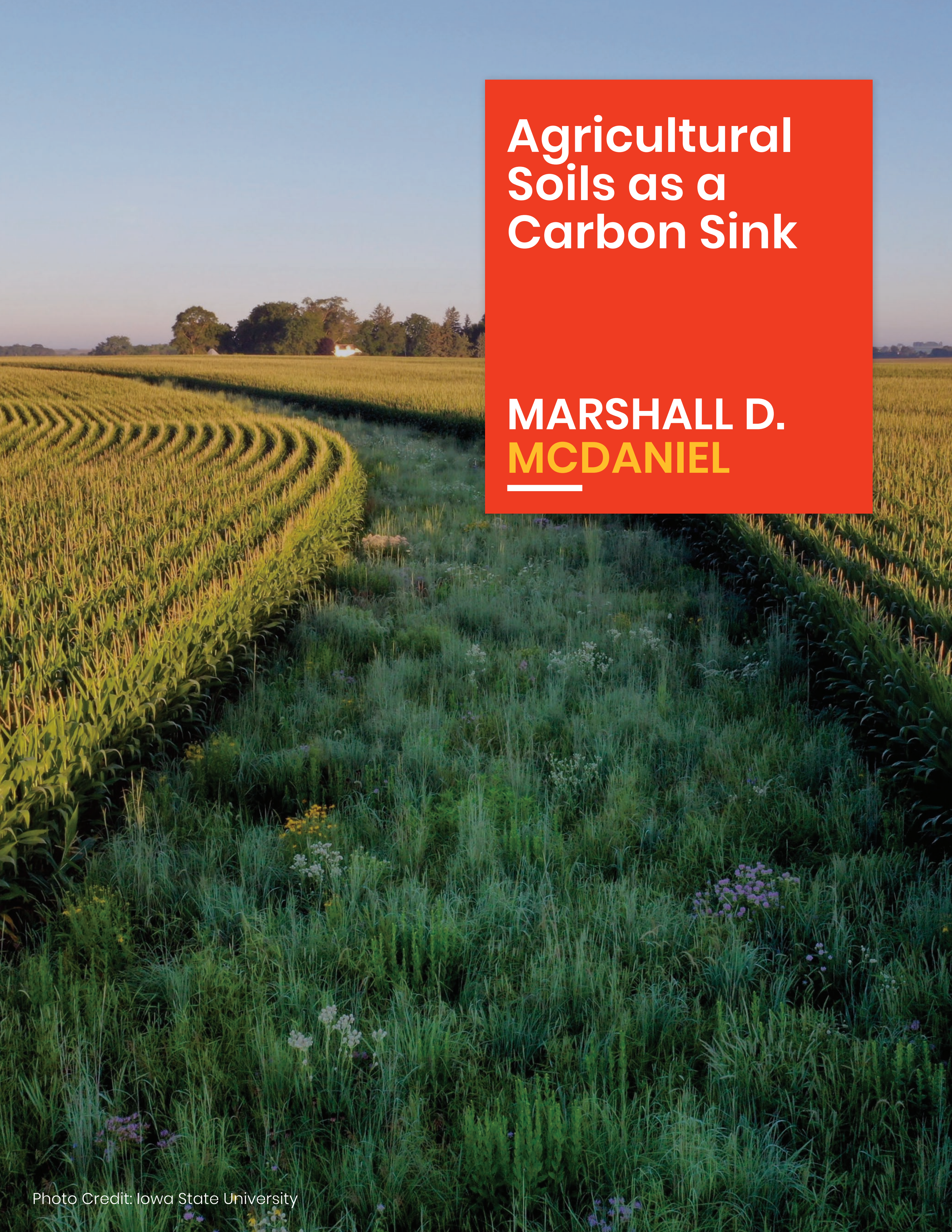
https://www.fs.usda.gov/project/?project=56574.

Lolo National Forest released an EA for the Sawmill Petty Project proposing 19,274 acres of logging and prescribed fire with 1522 acres of clearcuts and 13,231 acres of small tree thinning

https://www.fs.usda.gov/project/?project=57030.

Custer-Gallatin National Forest released an EA for the South Plateau Project proposing 19,600 acres of logging with 4600 acres of clearcuts and 56 miles of roads on the border of Yellowstone National Park. https://www.fs.usda.gov/project/?project=57353.

Flathead National Forest proposed the Mid Swan Landscape Restoration Project of 174,000 acres and Frozen Moose Project of 151,000 acres.



Agricultural Soils as a Carbon Sink

MARSHALL D. MCDANIEL

Photo Credit: Iowa State University

SECTION OVERVIEW

(Note: Although this chapter has a global section, below, the overall analysis is focused on US soils.)

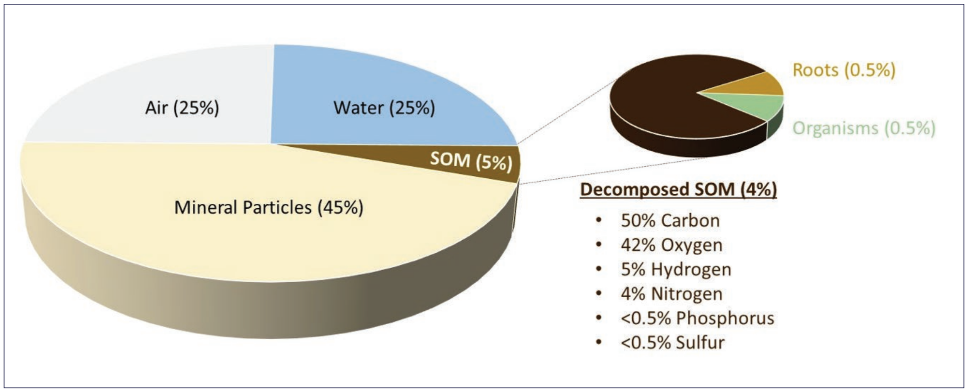
- United States' agricultural soils show a capacity to increase soil organic carbon (SOC) by an average of 17.3 petagrams (Pg, 10^{15} grams) with a range of 1.2 to 21.6 Pg C.
- Increasing SOC in the U.S., and globally (9.7 to 37.6 Pg C), will only have small effects on climate change mitigation without a concurrent reduction in emissions which are estimated to be 8.9 Pg C per year.
- Climate change itself will have relatively minor effects on SOC in agricultural soils compared to changes in management, but greater effects in non-agricultural soils.
- • We need to move away from myopic focus on SOC. There are other direct and indirect soil ecosystem service benefits that occur when regenerative agriculture practices are implemented (sometimes referred to as *co-benefits*). But there are also unintended negative consequences for increasing SOC too (*tradeoffs*).
- More research is needed on: how management practices increase SOC (especially when combined), biophysical processes that result in greater stabilization of SOC, and effects of management on deeper SOC.
- A "Regenerative Organic Agriculture" is possible, but will have to include scientific consensus and international government involvement. Standardization and third-party verification is also needed.

INTRODUCTION & BACKGROUND

Soil Carbon – Forms and Function

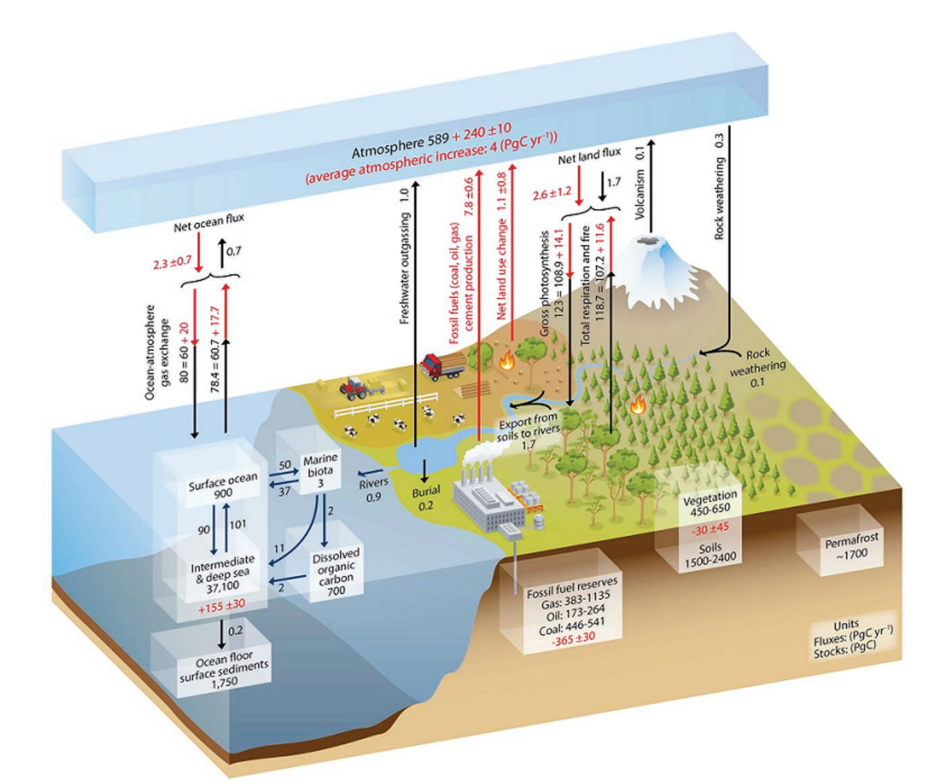
Soils are critical to life on Earth. They provide a substrate for plants to grow, foundation for human infrastructure, a reservoir of plant nutrients, and nexus for elements that cycle between the biosphere-lithosphere-atmosphere. Soils are comprised of three phases (Figure 1) – solid (mineral and organic), liquid (water), and gases (air in pore spaces).

Figure 1. Composition of soils by volume, but chemical composition of 'Decomposed Soil Organic Matter (SOM)' is expressed on a per mass basis.



Soil carbon (C) is one of many elements contained in soil organic matter – the others are hydrogen, oxygen, nitrogen, phosphorus, and sulfur (Figure 1). Carbon makes up nearly 50% of soil organic matter [1], and many soils can also have large concentrations of inorganic C typically in form of calcite (calcium carbonate or $CaCO^3$) [2]. The global soil C reservoir is more than twice the combined C stocks in the atmosphere and all plants on Earth [3] (Figure 2).

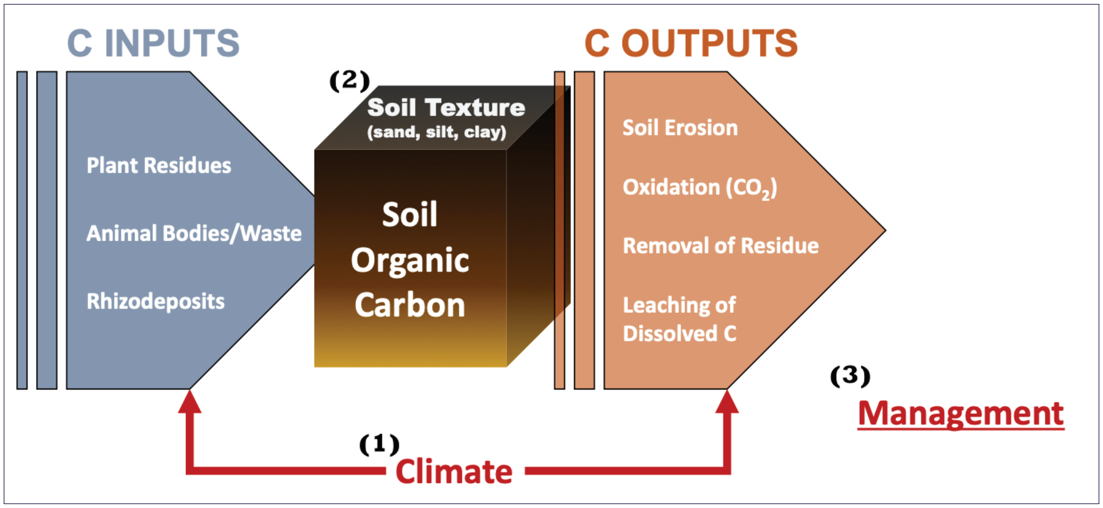
Figure 2. Global carbon cycle. Units are in peta grams (Pg), and arrows indicate annual fluxes. 1 Pg = 10^{15} g. For example, net human emissions are 8.9 Pg y-1. Black numbers and arrows indicate reservoir mass and exchange fluxes estimated for the time prior to the Industrial Era, about 1750. Figure from IPCC [4] and https://www.ipcc.ch/report/ar5/wg1/carbon-and-other-biogeochemical-cycles/.



Globally, soils are estimated to store ~2,000 Pg (10^{15} grams) of carbon (Figure 2). **Human activities, e.g. fossil fuel burning and other activities, contribute approximately 8.9 Pg C per year (Figure 2). This report will cover the United States' potential to increase carbon in soils through management practices.**

Not all soil C is distributed evenly. There are three main factors determining the concentration of soil organic C (SOC): 1) climate – temperature and precipitation, 2) soil texture – distribution of sand/silt/clay sized particles, and 3) management. These factors are interacting and controlling SOC concentration at different scales from global, to regional, to field, or even plant scales [5] (Figure 3).

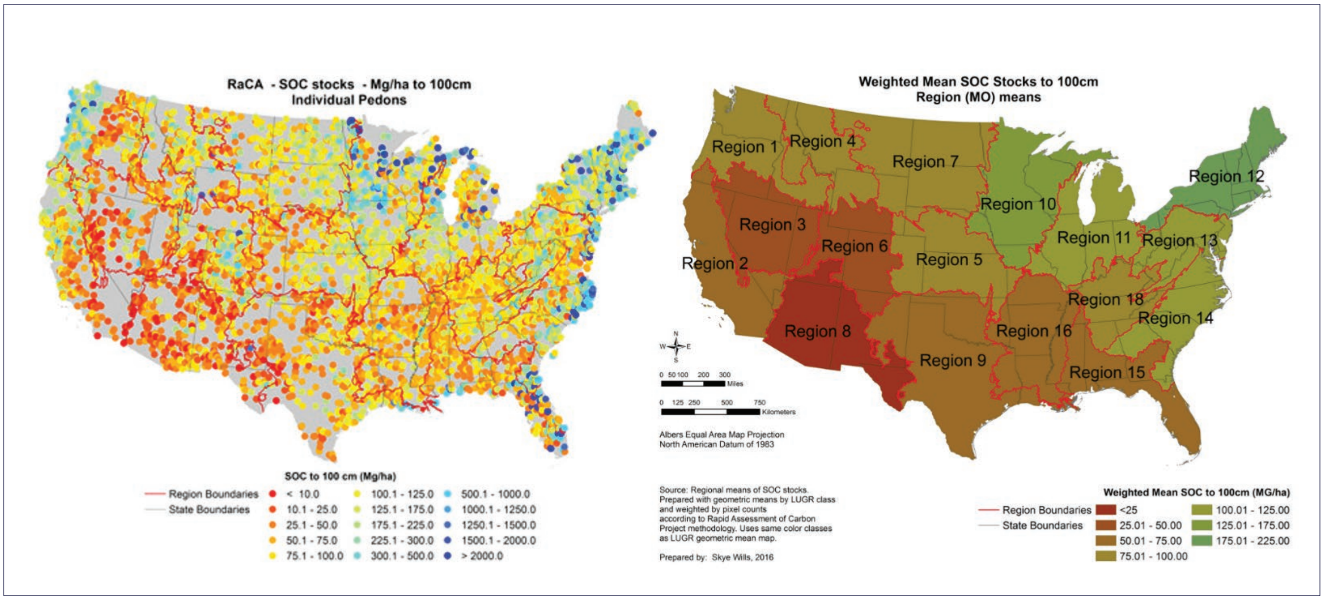
Figure 3. Three factors regulating net soil organic carbon (SOC). Climate regulates SOC at global scale, soil texture is inherent soil property that is rather immutable but will limit maximum SOC at given climate, and management can increase/decrease SOC at local scale. Increases in SOC are result of carbon inputs being greater than carbon outputs, but other management factors can also help to increase SOC.



Greater SOC concentrations are found in soils that are typically cold and wet. The global climate is changing and this will affect SOC storage, but not as strong as management practices at the local scale. Management practices can change microclimate, or the climate that plants and soil microorganisms experience, this may however change SOC concentrations in soils. For example, tile-draining previously water-logged soils – a common practice in many Midwestern US fields to increase crop yields – dry soil out adding oxygen to soils that were often too wet for aerobic decomposition to proceed. Therefore, this practice is likely to have contributed to decreases in SOC.

Soil texture is the proportion of sand, silt, and clay sized particles in soils. This is a more or less immutable property of soils, i.e., we are unable to change it. Generally, soils with more fine-textured particles (e.g., clay) hold more SOC [6]. The maximum capacity of a soil to 'hold' SOC will be a function of its texture. A 2010 project organized through the USDA-NRCS Soil Science Division set out to inventory SOC across the US [7]. This project collected 144,833 samples collected from top 1 m of soil (Figure 4).

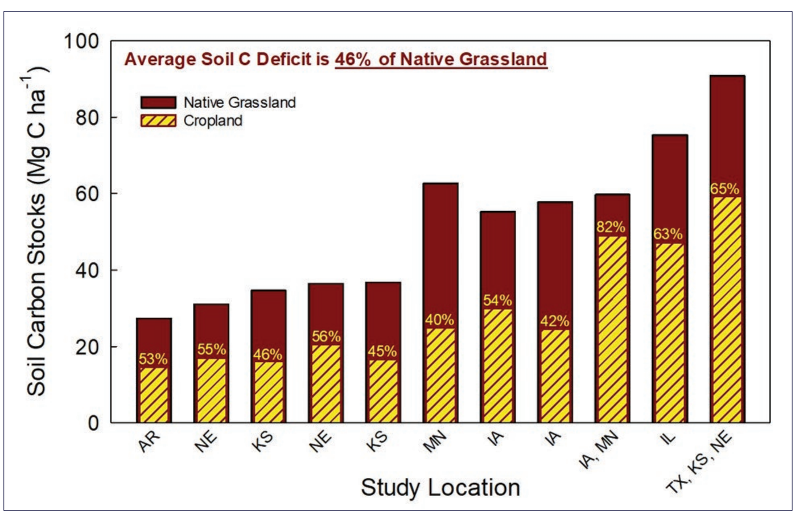
Figure 4. Soil organic carbon (SOC) stocks measured (LEFT) and estimated by region (RIGHT) from the USDA-NRCS Rapid Carbon Assessment (RaCA) [7].



WHY FOCUS ON SOIL CARBON?

The recent urgency of mitigating global warming, combined with a realized potential of soils to remove (or sequester) atmospheric C, has intensified attention on transforming agricultural practices. There is good evidence that many soils, in the Midwest U.S., are on average 46% of their capacity (Figure 5) [8]."

Figure 5. Soil organic carbon stocks in native grassland and cropland soils from 11 independent studies. The state(s) the studies took place in are indicated. The range in SOC stocks is due to inherent soil differences but also different depths of sampling (from 10 cm to 300 cm). Data from De et al. (2020) [8].



HISTORICAL CONTEXT OF SOIL ORGANIC CARBON

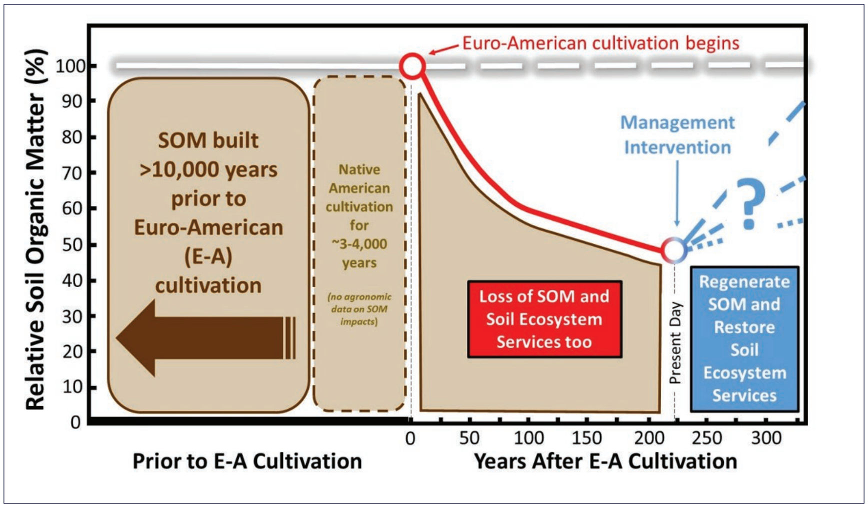
Let us look at the soils in northcentral Iowa after the last glaciation (Figure 6). After last glacial era, Wisconsinan glaciation, soils began to form 12,000 to 15,000 years ago. Native Americans farmed these soils for 3,000 to 4,000 years prior to Euro-American settlers. After Euro-American settlement, soil organic matter (~50% carbon) began declining over several generations to what now is believed to be about 50% of original concentration. This intensive cultivation included tile drainage, tillage, liming, and crop residue removal with annual crops. Also, we know that many soil ecosystem services (Box 1, [9]) are directly related to the SOM concentrations. Therefore, increasing SOC (50% of SOM), should have other unintended benefits to humans and the rest of life on planet Earth. Benefits in addition to the decrease in atmospheric CO_2 – sometimes called co-benefits *(discussed later)*.

BOX 1. SOIL ECOSYSTEM SERVICES

Soil ecosystem services are functions that enable life on Earth, including human well-being [8]. A list of these soil ecosystem services from the United Nations Food and Agriculture Organization include:

- Carbon sequestration
- Provisioning food, fiber, and fuel
- Water purification and soil contaminant reduction
- Climate regulation
- Nutrient cycling
- Habitat for organisms
- Flood regulation
- And more...

Figure 6. Hypothetical loss of soil organic matter (SOM) after Euro-American cultivation begins in northcentral Iowa (i.e., the Des Moines Lobe). This figure is based on real data (including Figure 4). A management intervention has shown at present day and measuring and verifying changes in SOM and ecosystem services are central to soil C reduction programs and soil health monitoring.



SHORT-TERM RATES OF INCREASING SOIL CARBON

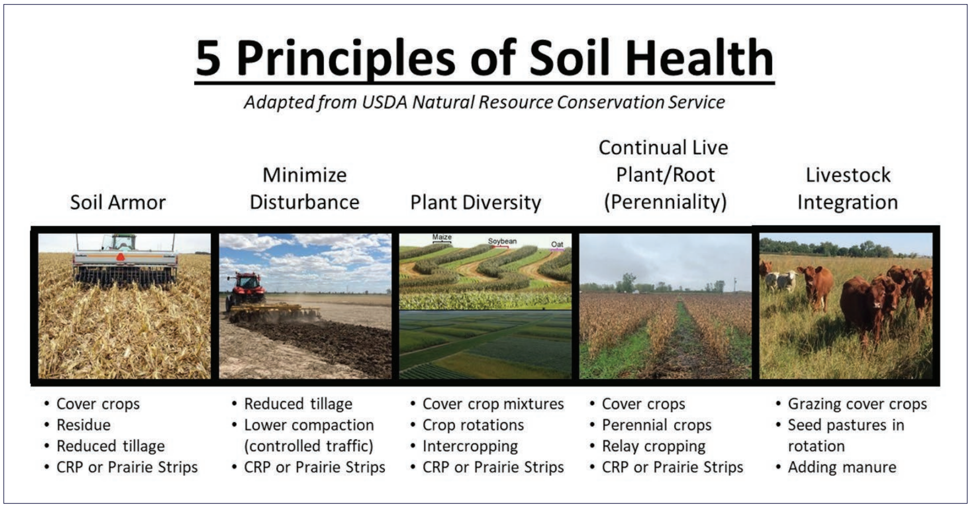
Conservation Management Practices Increase Soil Organic Carbon (SOC)

There are two major paths toward restoring SOC that has since been lost due to intensive agricultural production (Figures 3,5,6) – increasing inputs or decreasing losses (or both). Since SOC is dynamic and net result of a balance between inputs and losses (Figure 3). Increasing SOC inputs like plant residues, rhizodeposits, dead animals, animal waste, and other imported bioproducts all increase

SOC. Losses of primarily SOC include: oxidation of C and release as CO_2, soil erosion, and leaching of dissolved C. Thus any practice that increases the former (inputs) and decreases the latter (losses), or both, will increase SOC over time.

Most of these practices can be categorized according to the Natural Resource Conservation Service's (NRCS) principles of soil health (Figure 7). These practices either increase SOC either through increasing inputs, decreasing ouputs, or in many cases both. The range in SOC gain from these management practices in the US ranges from 0.02 up to 2.90 Mg C ha^{-1} y^{-1} [10].

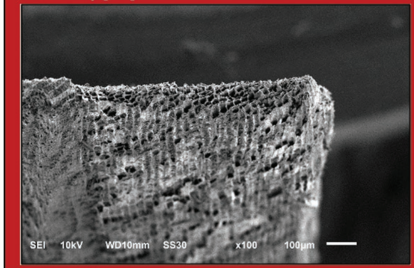
Figure 7. The five principles of soil health, adapted from USDA NRCS. These principles also relate to practices that increase soil organic carbon (SOC).



There is a strong scientific consensus that increasing C-containing organic matter inputs (plant biomass, manure, etc...) increases SOC [5],[9]. Thus management practices that increase these C inputs will also increase SOC over time, given the losses stay the same or even lessen. For example, adding animal manure can increase SOC [11]. As a proportion of the cumulative added, an average of 12% ± 4 of that manure C is retained over 18 years [11]. This relates to rate of increase of 0.31 ± 0.16 Mg C ha^{-1} y^{-1} across all studies. A second imported bioproduct, biochar (Box 2, [12]), also shows great promise for increasing SOC but is not as economical as manure [13]. Bai et al. (2019), using a synthesis of 222 observations, showed that adding biochar can increase SOC by as much as 39% [13].

BOX 2. Biochar

Biochar is defined as a high-carbon, fine-grained residue that is produced via pyrolysis, or direct thermal decomposition of biomass in the absence of oxygen (usually at ≤ 700 °C) [11].



Pine wood biochar shown at 100× magnification with scanning electron microscope (photo: Jake Nash)

The 2nd pathway to increase SOC is to reduce oxidation of soil organic matter, or prevent/slow erosion losses of SOC. The process of heteotrophic respiration by soil organisms releases SOC as CO_2 Thus, managing soils to slow this process will increase SOC given inputs stay the same (and this last assumption complicates this 2nd pathway for SOC accrual). Respiration is slowed when soils remain wet (i.e., soil organisms lack oxygen), cool (i.e., cold temperatures limit process), or lack chemical conditions to carry out respiration. These chemical conditions includes lack of other essential limiting nutrients (e.g., N, P, S) or non-optimal pH can both inhibit or slow respiration of SOC.

Soil erosion rates in the U.S. can range between <1 to >20 Mg ha^{-1} y^{-1} [10],[11]. Of course with this loss of soil from fields, SOC will be lost as well. However, there is debate whether erosion is a net positive, at least with regard to being a SOC sink [12],[13]. Soil organic C that is submerged in streams, lakes, and oceans is not as likely to be oxidized and converted to CO_2. Regardless of the argument of whether erosion is good for sequestering C or not, losing soil has other detrimental effects on ecosystem services [18].

MAXIMUM CAPACITY OF SOIL CARBON

A solid body of evidence shows that we can increase SOC with changes in management practices, but this begs the question: will this rate of SOC change continue infinitely? Here I cover the idea of 'Soil C Saturation' and what it means for C reduction through soils.

Is There a Limit to Soil Carbon Storage?

The answer is, '*it depends*'. Based on previous research, SOC accrual rates for many management practices will likely slow as a soil reaches this SOC storage limit (Figure 8). This phenomenon has been conceptualized and termed 'Soil C Saturation' for a few decades now [19],[20]. What governs this SOC storage limit is still debated but soil texture, esp. clay content, soil pH, and climate are important drivers at global scale [21]–[24]. At field scale where management has more influence, regulators of microbial activity seem to be important [25]. However, there are studies that show a limit is never reached perhaps because long-term studies are lacking [26].

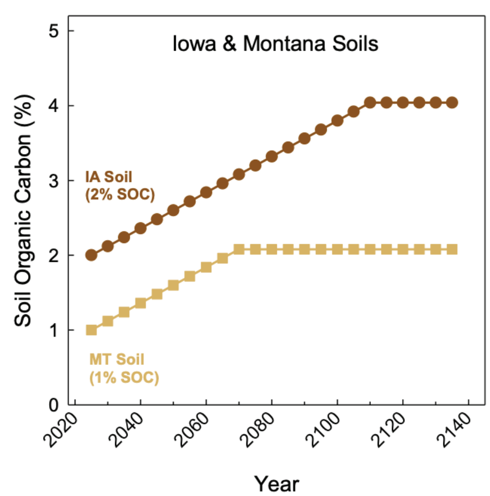


Figure 8. Example of two soils increasing to their theoretical capacity or the 'Soil C Saturation' concept.

Alternatively, some management practices may not follow the rules of 'Soil C Saturation'. In other words, these practices increase inputs of a particular type of C that is not susceptible to plateauing because of the mechanism of how it is stabilized [27]. Forms of C inputs that are not easily decomposed and protected physically, rather than chemically protected on fine soil particles, may persist in soils longer and thus not conform to '*Soil C Saturation*' theory. A good example of this type of C is biochar which is porous, particulate and not easily decomposed to mineral constituents by soil organisms. These properties make it persist longer in soils and may be, in part, why biochar is an effective way to increase SOC.

CAPACITY OF U.S. SOILS TO STORE CARBON – CROPLAND & GRAZING/PASTURE/RANGELAND

The US has nearly 159 million ha of cropland (Table 1). If we use minimum and maximum SOC stocks estimated by USDA-NRCS RaCA (Figure 4), and a continental estimate of 50% soil C deficit of croplands (Figure 5, [8]), we can calculate rough estimate of SOC capacity of US cropland soils (Table 1). Iowa for example, has nearly 11 million ha of cropland, SOC stocks from 125-175 Mg C ha^{-1}, and can roughly sequester 1.351 to 1.892 petagrams (Pg) of SOC. Montana has 6.7 million ha of cropland, lower SOC stocks (75-100 Mg C ha-1), and accordingly might sequester 0.504 to 0.672 Pg. The US total potential of SOC storage if all cropland were converted to climate smart or regenerative agriculture is 13.100 to 20.187 Pg of carbon (Table 1).

The US has nearly 265 million ha of grazing, pasture, and rangeland (GPR, Table 2). The research on increasing SOC in GPR is sparse. It is evident that overgrazing actually decreases SOC [29], but light grazing can have slight benefits of 0.4 to 6.9% increases over a 15 year average experiment length. GPR, again, if we use minimum and maximum SOC stocks estimated by USDA-NRCS RaCA (Figure 4),

Table 1. Cropland coverage, soil organic carbon stocks, and SOC storage potential.

	Major Land Use Area†	Existing Soil Organic Carbon (SOC) Stocks‡			Cropland SOC Storage Potential⁋		
State	Cropland	Min.	Max.	MEDIAN	Min.	Max.	MEDIAN
	------ ha -----	-------------	Mg C ha^{-1}	------------	-----------------	Pg	-----------------
Alabama	1,135,746	50	125	88	0.057	0.142	0.1
Alaska	31,984	ND	ND	ND	ND	ND	ND
Arizona	459,092	1	25	13	0.001	0.011	0.006
Arkansas	3,332,488	50	75	63	0.167	0.25	0.21
California	3,875,696	50	75	63	0.194	0.291	0.244
Colorado	4,317,385	50	100	75	0.216	0.432	0.324
Connecticut	49,595	175	225	200	0.009	0.011	0.01
Delaware	177,197	125	175	150	0.022	0.031	0.027
Florida	1,147,024	50	75	63	0.057	0.086	0.072
Georgia	1,774,500	50	175	113	0.089	0.311	0.201
Hawaii	150,628	ND	ND	ND	ND	ND	ND
Idaho	2,347,554	75	100	88	0.176	0.235	0.207
Illinois	9,685,904	125	175	150	1.211	1.695	1.453
Indiana	5,143,714	75	125	100	0.386	0.643	0.514
Iowa	**10,810,680**	**125**	**175**	**150**	**1.351**	**1.892**	**1.622**
Kansas	11,570,706	75	100	88	0.868	1.157	1.018
Kentucky	2,577,610	75	100	88	0.193	0.258	0.227
Louisiana	1,855,320	50	75	63	0.093	0.139	0.117
Maine	157,987	175	225	200	0.028	0.036	0.032
Maryland	557,359	125	175	150	0.070	0.098	0.084
Massachusetts	60,044	175	225	200	0.011	0.014	0.012
Michigan	3,142,825	125	175	150	0.393	0.550	0.471
Minnesota	9,085,855	125	175	150	1.136	1.590	1.363

State	Major Land Use Area†	Existing Soil Organic Carbon (SOC) Stocks‡			Cropland SOC Storage Potential₱		
	Cropland	Min.	Max.	MEDIAN	Min.	Max.	MEDIAN
	------ ha -----		------------- Mg C ha^{-1} -------------			----------------- Pg -----------------	
Mississippi	2,093,831	50	75	63	0.105	0.157	0.132
Missouri	6,323,842	50	175	113	0.316	1.107	0.715
Montana	**6,719,692**	**75**	**100**	**88**	**0.504**	**0.672**	**0.591**
Nebraska	8,845,354	75	175	125	0.663	1.548	1.106
Nevada	233,440	25	50	38	0.006	0.012	0.009
New Hampshire	37,814	175	225	200	0.007	0.009	0.008
New Jersey	181,777	100	125	113	0.018	0.023	0.021
New Mexico	788,349	1	75	38	0.001	0.059	0.03
New York	1,718,664	175	225	200	0.301	0.387	0.344
North Carolina	1,810,134	100	125	113	0.181	0.226	0.205
North Dakota	10,975,191	75	100	88	0.823	1.098	0.966
Ohio	4,382,298	125	175	150	0.548	0.767	0.657
Oklahoma	4,568,782	50	75	63	0.228	0.343	0.288
Oregon	1,887,464	75	100	88	0.142	0.189	0.166
Pennsylvania	1,827,894	125	175	150	0.228	0.320	0.274
Rhode Island	10,188	175	225	200	0.002	0.002	0.002
South Carolina	770,353	100	125	113	0.077	0.096	0.087
South Dakota	7,833,082	75	100	88	0.587	0.783	0.689
Tennessee	2,128,998	75	100	88	0.160	0.213	0.187
Texas	11,822,991	50	75	63	0.591	0.887	0.745
Utah	597,167	25	50	38	0.015	0.030	0.023
Vermont	166,878	175	225	200	0.029	0.038	0.033
Virginia	1,209,731	125	175	150	0.151	0.212	0.181
Washington	3,050,776	75	100	88	0.229	0.305	0.268
West Virginia	315,938	100	125	113	0.032	0.039	0.036
Wisconsin	4,075,568	100	175	138	0.408	0.713	0.562
Wyoming	803,777	25	100	63	0.020	0.080	0.051
TOTAL Contiguous 48 States	**158,626,866**	**4,302**	**6,425**	**5,377**	**13.100**	**20.187**	**16.690**

†: Major land use from USDA-NASS database [28]

‡: Soil organic carbon stocks from USDA-NRCS Rapid Carbon Assessment [7]. Mg C ha^{-1} = Megagrams of carbon per hectare to 100 cm depth. 1 Mg = 10^9 grams

₱: Maximum storage potential based on De et al. 2020 [8] and only cropland is converted to regenerative practices (not grazing, pasture, or rangeland). Assumes all cropped soils are approximately 50% of total capacity. Pg = Petagrams. 1 Pg = 10^{15} grams

and a continental estimate of potential to increase SOC by 3.6% on average [29], we can calculate rough estimate of SOC capacity of US GPR soils (Table 2). Iowa for example, has only ~1.1 million ha of GPR, SOC stocks from 125-175 Mg C ha^{-1}, and can roughly sequester 0 to 0.012 Pg of SOC under GPR. Montana has 19.3 million ha of GPR, lower SOC stocks (75-100 Mg C ha^{-1}), and accordingly might sequester 0.004 to 0.116 Pg. The US total potential of SOC storage if all cropland were converted to climate smart or regenerative agriculture is 0.034 to 1.387 Pg of carbon (Table 2).

Table 2. Grazing/Pasture/Rangeland (GPR) coverage, soil organic carbon stocks, and SOC storage potential.

State	Grazing, Pasture, and Rangeland (GPR)	Existing Soil Organic Carbon (SOC) Stocks‡			GPR SOC Storage Potential⁋		
		Min.	Max.	MEDIAN	Min.	Max.	MEDIAN
	------ ha ------	-------------- Mg C ha^{-1} -------------			------------------ Pg ------------------		
Alabama	1,170,247	50	125	88	0	0.009	0.004
Alaska	281,807	ND	ND	ND	0	0	0
Arizona	17,636,093	1	25	13	0	0.026	0.008
Arkansas	1,670,100	50	75	63	0	0.008	0.004
California	10,791,611	50	75	63	0.002	0.049	0.024
Colorado	12,842,497	50	100	75	0.002	0.077	0.034
Connecticut	8,863	175	225	200	0	0	0
Delaware	7,445	125	175	150	0	0	0
Florida	2,063,900	50	75	63	0	0.009	0.005
Georgia	680,068	50	175	113	0	0.007	0.003
Hawaii	311,643	ND	ND	ND	ND	ND	ND
Idaho	7,442,527	75	100	88	0.002	0.045	0.023
Illinois	699,490	125	175	150	0	0.007	0.004
Indiana	670,061	75	125	100	0	0.005	0.002
Iowa	**1,165,252**	**125**	**175**	**150**	**0**	**0.012**	**0.006**
Kansas	7,195,721	75	100	88	0.002	0.043	0.023
Kentucky	1,919,209	75	100	88	0	0.012	0.006
Louisiana	920,593	50	75	63	0	0.004	0.002
Maine	64,477	175	225	200	0	0.001	0
Maryland	180,929	125	175	150	0	0.002	0.001
Massachusetts	31,818	175	225	200	0	0	0
Michigan	802,129	125	175	150	0	0.008	0.004
Minnesota	1,444,037	125	175	150	0.001	0.015	0.008
Mississippi	1,098,531	50	75	63	0	0.005	0.002
Missouri	3,962,508	50	175	113	0.001	0.042	0.016
Montana	**19,274,797**	**75**	**100**	**88**	**0.004**	**0.116**	**0.06**

State	Grazing, Pasture, and Rangeland (GPR)	Existing Soil Organic Carbon (SOC) Stocks‡			GPR SOC Storage Potential₱		
		Min.	Max.	MEDIAN	Min.	Max.	MEDIAN
	------ ha ------	--------------	Mg C ha^{-1}	-------------	------------------	Pg	------------------
Nebraska	9,581,656	75	175	125	0.002	0.101	0.043
Nevada	21,176,950	25	50	38	0.002	0.064	0.029
New Hampshire	47,097	175	225	200	0	0.001	0
New Jersey	31,756	100	125	113	0	0	0
New Mexico	21,992,074	1	75	38	0	0.099	0.03
New York	969,842	175	225	200	0.001	0.013	0.007
North Carolina	638,919	100	125	113	0	0.005	0.003
North Dakota	5,396,842	75	100	88	0.001	0.032	0.017
Ohio	867,821	125	175	150	0	0.009	0.005
Oklahoma	7,994,940	50	75	63	0.001	0.036	0.018
Oregon	9,657,094	75	100	88	0.002	0.058	0.03
Pennsylvania	520,672	125	175	150	0	0.005	0.003
Rhode Island	2,910	175	225	200	0	0	0
South Carolina	395,057	100	125	113	0	0.003	0.002
South Dakota	10,105,828	75	100	88	0.002	0.061	0.032
Tennessee	1,385,748	75	100	88	0	0.008	0.004
Texas	42,331,426	50	75	63	0.006	0.19	0.095
Utah	13,263,045	25	50	38	0.001	0.04	0.018
Vermont	123,558	175	225	200	0	0.002	0.001
Virginia	1,130,672	125	175	150	0	0.012	0.006
Washington	2,959,718	75	100	88	0.001	0.018	0.009
West Virginia	546,695	100	125	113	0	0.004	0.002
Wisconsin	1,158,892	100	175	138	0	0.012	0.006
Wyoming	18,650,525	25	100	63	0.001	0.112	0.042
TOTAL Contiguous 48 States	**265,266,090**	**4,302**	**6,425**	**5,377**	**0.034**	**1.387**	**0.641**

†: Major land use from USDA-NASS database[28]

‡: Soil organic carbon stocks from USDA-NRCS Rapid Carbon Assessment [7]. Mg C ha^{-1} = Megagrams of carbon per hectare to 100 cm depth. 1 Mg = 10^9 grams

₱: Maximum storage potential based on Lai & Kumar 2020 [29] and for 15-year average study. Pg = Petagrams. 1 Pg = 10^{15} grams

Thus, if we tally cropland and GPR, the US has a total capacity of 13.134 to 21.574 Pg of C in SOC (Table 3). This has many caveats and seems to be over estimate compared to a recent inventory by Lal et al. (2018) [30]. From Lal et al. (2018), if all cropland and GRP soils have same capacity, then the proportion from contiguous US would only be from 1.764 to 7.215 (Table 3).

Table 3. US soil carbon capacity compared to other estimates.

State	Estimate for total Soil Organic Carbon Potential of US (Pg)	U.S. Estimate from Lal et al. (2018) †
	---------- Pg ----------	
Iowa	1.628 (1.351-1.904)	NA
Montana	0.651 (0.508-0.788)	NA
Total Contiguous 48 States	**17.331 (13.134-21.574)**	**4.490 (1.764-7.215)**

†: Assuming that all cropland and grazing/rangeland/pasture soil accrue C at same rate and at equilibrium [30].

BREAKING THE CARBON CARRYING CAPACITY

While there appears to be a maximum C content, or SOC carrying capacity, there are practices that may exceed this capacity. One proposed method is adding particulate, recalcitrant forms of C – like biochar (Box 2) [31]. This addition of difficult-to-decompose biochar can allow land owner to exceed a given soil's SOC carrying capacity or limit (Figure 9). Other management practices may be able to exceed the SOC carrying capacity, or geoengineering methods changing soil's texture and SOC-binding ability, and other technologies may improve a given soil's ability to sequester SOC.

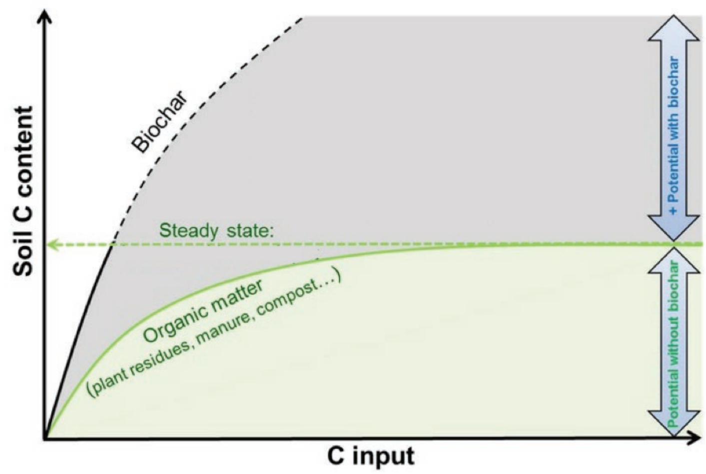


Figure 9. Soil organic carbon content as a function of C inputs. Graph shows theoretical potential with organic matter from plants and animals and biochar [Box 2]. Figure from Wang et al. (2016) [24].

CAPACITY OF GLOBAL AGRICULTURAL SOIL C REMOVAL

If the NRCS Soil Health Promoting practices (Figure 7) are implemented on cropland and best management practices on grazing/pasture/rangelands across the globe, **we might expect C storage potential of 23.67 Pg C (Range: 9.72 to 37.63 Pg C)** [30]. This is just a combined 26% of total global potential (Cropland plus Grass/steppe). Forests and 'Other Soils', according to Lal et al. (2018), make up the majority of SOC sequestration potential (Figure 9).

This C removal potential, keep in mind, is 1× to 4× the global C emissions in just one year (8.9 Pg y^{-1}, Figure 2). Thus removing atmospheric C from the atmosphere via soils, can only be part of the solution to mitigating global warming. As a global community, we must focus on reducing the emissions of C (8.9 Pg y^{-1}), but also other even more potent greenhouse gases like nitrous oxide (N2O) and methane (CH4).

How will climate change affect global soil C carrying capacity on agriculture soils?

A classic paper using the prolific model used for soil C cycling, Century model, estimated warming effects (1-4 °C) on SOC are negative and reach a steady state of -11.1 Pg C [23]. This was confirmed with data-based calculation with similar loss of -14.1 Pg C. It is important that to consider that this study did not include histosols, very wet organic rich soil, nor dry soils that contain inorganic C.

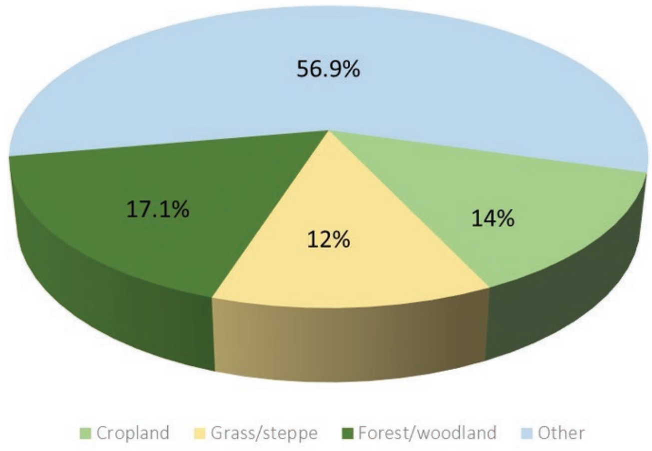


Figure 9. Global potential of all soil organic carbon storage -- 178.0 Pg C (Range: 114.4 to 241.5) [25]. Cropland and Grazing/Pasture/ Rangeland (Grass/steppe) have global potential of 23.76 Pg C (Range: 9.72 to 37.63 Pg C).

As a case-study and at a more refined scale under climate change, researchers in Wisconsin estimated that WI has a baseline SOC stock of 90 Mg C ha^{-1} but could increase SOC by 20 Mg ha^{-1} between 2018 to 2050 [32]. This is a 22% increase under ideal management and predicted climate change. However, this change was widely distributed across their soil orders in Wisconsin. Some soil orders such as Spodosols and Histosols, where farming does not occur, decreased SOC by -4 to -19 Mg C ha^{-1} respectively. While Mollisols, one of optimal soils for growing corn and soybeans, increase potential was +62 Mg C ha^{-1}.

LIMITATIONS & FURTHER CONSIDERATIONS

This report accounts for only the C sequestration potential of soils. Other management practices – like efficient nitrogen fertilizer use or reducing methane emissions from livestock – may have just as great a potential to reduce agriculture's net contribution to climate change. Here I outline some limitations and further considerations here.

Co-benefits and Tradeoffs with Increasing Soil Carbon

A ***co-benefit*** is an unintentional benefit to a practice that is increasing SOC. There are some co-benefits unrelated to the increase in SOC, or *indirect co-benefits*, that occur via the management practice that is leading to increase in SOC. For example, using winter cover crops (like cereal rye) is documented to increase SOC by a moderate rate of 0.21 Mg C ha^{-1} y^{-1} [33] , on average, but has major benefits to mitigating water quality issues. These winter cover crops reduce nutrient delivery to ground and surface waters by up to -21.7% over a 10-year time-frame in Iowa [34]. On the other hand, there are also *direct co-benefits* of increasing SOC, or the benefits that arise from the increase in SOC itself. One of the best examples of this is the increase in soil water holding capacity with increases in organic matter in general [35], [36]. Generally, these studies find a 0.02 g H_2O per g dry soil increase with 1% increase in SOM.

The results of the climate smart agricultural are not entirely rosy. In contrast to co-benefits there are ***tradeoffs*** with some SOC-increasing management practices, or negative impacts on other agroecosystem services. First, it is well documented that no-tillage, a practice that has moderate-to-high impact on SOC accrual, can actually decrease cereal crop yields by 2.6 to 7.6% on average [37]. This tradeoff seems particularly acute in colder regions [38]. Second, using no-tillage as an example again, some soils and studies show that no-tillage generally increases soil C storage, it may also be increasing N_2O emissions (a greenhouse gas with nearly 300× more potent) [39]. The latter example is one where the goal of mitigating climate change via SOC accrual is actually offset by the unintended increase in N_2O emissions – this is very critical to minimize and understand this tradeoff if we are to use climate smart agricultural management.

Monitoring, Reporting, and Verification of Soil Organic Carbon

As C markets garner more and more attention, it is critical to have robust monitoring, reporting, and verification (MRV). Because we cannot sample every inch of agricultural soil to verify the practice is being used and effectively increasing SOC, we need to use a combination of modeling, remote sensing, and soil sampling. Newer technologies like visible near-infrared spectroscopy show promise for in-situ SOC measurements, however, some issues still remain [40]–[42]. There are further advantages of putting the power of data collection in the farmer or land manager's with mobile phone applications to potentially measure SOC change [43].

Quality of Soil Organic Carbon

Another consideration is thinking beyond quantity of SOC change, but also considering the quality of SOC. There are many ways to separate or fractionate total SOC into refined measurements but generally fall under three categories [44]: physical – using sieving or dense fluids, chemical – using extractions or equipment that characterize the chemical nature of SOM, or biological – typically using an incubation method to allow indigenous soil microorganisms to respire CO_2 (a portion of total SOC, typically < 10%). Although these methods are currently laborious, and thus not likely adopted by commercial laboratories, they do show potential for a few reasons.

First, many of these more refined fractions of total SOC are likely to respond to changes in management earlier that total SOC [8], [45]–[47]. This is especially the case of what is sometimes referred to as '*labile*' or '*active*' SOC. This smaller pool of SOC, is thought to be more rapidly cycled by microorganisms and thus show strong links to many other soil ecosystem services other than soil C sequestration. Second, measuring *labile* SOC may be the "canary in the coal mine" of slow SOC changes, or in other words early changes in this *labile* C may portend longer-term changes in more difficult to monitor total SOC.

A "REGENERATIVE ORGANIC AGRICULTURE" STANDARD

We are seeing the increase of certified standards and labeling for food/fiber/fuel coming from farms that are *regenerative* or *climate smart* agriculture as the science on SOC cycling deepens and general public awareness broadens. A couple of examples include: 1) Regenerative Organic

Certified™, or ROC™, by Rhodale Institute [48], 2) Carbon Neutral certification [49], and 3) the Carbon Trust [50]. The goal of these certifications is to give consumers more knowledge about the products they buy. The concern from scientists is how the certifications are verified, and calculations of the rankings and scores.

These scores or rankings in particular rely on a combination of models, life-cycle assessments, and estimates that are only as good as the data they are based on (which often is very sparse). Without standardization or some kind of government regulation/involvement it allows producers to create their own 'certifications' that may be an attempt to provide a greenwashed image or put an extra premium on a product. Also, more research is needed on how these labels affect consumer behavior [51], [52].

In order to provide consumer trust in standards, it will probably require verification from a third party or government. Consumer's trust will erode without verification on results of a "Regenerative Organic Agriculture" certification on labels. It is unclear of what this verification will look like, but is required for the standard to succeed.

FINAL CONCLUSIONS

Overall, US agricultural soils show a capacity to increase SOC with a range of 1.2 to 21.6 Pg C (Table 3). Increasing SOC in the U.S., and globally (9.7 to 37.6 Pg C), will only have small effects on climate change mitigation without a concurrent reduction in emissions which are estimated to be 8.9 Pg C per year (Figure 2, [4])! Climate change itself will have relatively minor effects on SOC in agricultural soils compared to changes in management, but greater effects in non-agricultural soils.

More research is needed in: 1) understanding interactions among treatments, sometimes called stacking treatments, since most studies compare only one management change at a time; 2) improving understanding of management on soil inorganic C, 3) understanding how management practices affect deeper SOC 4) improving monitoring, reporting, and verifying changes in SOC (which occur very slow) rapidly and inexpensively ; 5) measuring/balancing gains or losses in SOC with concurrent beneficial or detrimental effects of management to other ecosystem services (e.g., co-benefits or tradeoffs).

A "Regenerative Organic Agriculture" is possible, but will have to include scientific consensus and international government involvement. Standardization and third-party verification is also needed.

REFERENCES

1. D. W. Pribyl, "A critical review of the conventional SOC to SOM conversion factor," Geoderma, vol. 156, no. 3–4, pp. 75–83, 2010.
2. R. R. Weil and N. Brady, The Nature and Properties of Soils, Fifteenth. New York, NY: Pearson, 2017.
3. W. H. Schlesinger and E. S. Bernhardt, Biogeochemistry: An analysis of Global Change, Fourth Edi. London, UK: Elsevier, 2020.
4. D. Q. Stocker, "Climate change 2013: The physical science basis," Work. Gr. I Contrib. to Fifth Assess. Rep. Intergov. Panel Clim. Chang. Summ. Policymakers, IPCC, 2013.
5. Z. Luo, W. Feng, Y. Luo, J. Baldock, and E. Wang, "Soil organic carbon dynamics jointly controlled by climate, carbon inputs, soil properties and soil carbon fractions," Glob. Chang. Biol., vol. 23, no. 10, pp. 4430–4439, 2017.
6. D. R. P. Gonçalves, J. C. de Moraes Sá, U. Mishra, C. E. P. Cerri, L. A. Ferreira, and F. J. F. Furlan, "Soil type and texture impacts on soil organic carbon storage in a sub-tropical agro-ecosystem," Geoderma, vol. 286, pp. 88–97, 2017.
7. SoilSurveyStaff, "Rapid Carbon Assessment (RaCA) project.," National Resource Conservation Service, 2020. [Online]. Available: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054164.
8. M. De et al., "Soil health recovery after grassland reestablishment on cropland–the effects of time and topographic position," Soil Sci. Soc. Am. J., 2020.
9. FAO, "No Title," (Food and Agriculture Organization) of the United Nations, 2015. [Online]. Available: http://www.fao.org/resources/infographics/infographics-details/en/c/284478/.
10. M. D. Eve, M. Sperow, K. Howerton, K. Paustian, and R. F. Follett, "Predicted impact of management changes on soil carbon storage for each cropland region of the conterminous United States," J. Soil Water Conserv., vol. 57, no. 4, pp. 196–204, 2002.
11. É. Maillard and D. A. Angers, "Animal manure application and soil organic carbon stocks: A meta-analysis," Glob. Chang. Biol., vol. 20, no. 2, pp. 666–679, 2014.
12. N. Jamaludin, S. A. Rashid, and T. Tan, "Chapter 5 - Natural Biomass as Carbon Sources for the Synthesis of Photoluminescent Carbon Dots," in Micro and Nano Technologies, S. A. Rashid, R. N. I. Raja Othman, and M. Z. B. T.-S. Hussein Technology and Applications of Carbon Nanomaterials, Eds. Elsevier, 2019, pp. 109–134.
13. X. Bai et al., "Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis," Glob. Chang. Biol., vol. 25, no. 8, pp. 2591–2606, 2019.
14. P. Borrelli et al., "An assessment of the global impact of 21st century land use change on soil erosion," Nat. Commun., vol. 8, no. 1, pp. 1–13, 2017.
15. J. M. García-Ruiz, S. Beguería, E. Nadal-Romero, J. C. González-Hidalgo, N. Lana-Renault, and Y. Sanjuán, "A meta-analysis of soil erosion rates across the world," Geomorphology, vol. 239, pp. 160–173, 2015.
16. K. Van Oost et al., "The Impact of Agricultural Soil Erosion on the Global Carbon Cycle," Sci. , vol. 318, no. 5850, pp. 626–629, Oct. 2007.
17. S. Doetterl, A. A. Berhe, E. Nadeu, Z. Wang, M. Sommer, and P. Fiener, "Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes," Earth-Science Rev., vol. 154, pp. 102–122, 2016.
18. D. R. Montgomery, "Soil erosion and agricultural sustainability," Proc. Natl. Acad. Sci., vol. 104, no. 33, pp. 13268–13272, 2007.
19. J. Hassink, "The capacity of soils to preserve organic C and N by their association with clay and silt particles," Plant Soil, vol. 191, no. 1, pp. 77–87, 1997.
20. C. E. Stewart, K. Paustian, R. T. Conant, A. F. Plante, and J. Six, "Soil carbon saturation: concept, evidence and evaluation," Biogeochemistry, vol. 86, no. 1, pp. 19–31, 2007.
21. J. M. Oades, "The retention of organic matter in soils," Biogeochemistry, vol. 5, no. 1, pp. 35–70, 1988.
22. C. Rasmussen et al., "Beyond clay: towards an improved set of variables for predicting soil organic matter content," Biogeochemistry, vol. 137, no. 3, pp. 297–306, 2018.
23. D. S. Schimel et al., "Climatic, edaphic, and biotic controls over storage and turnover of carbon in soils," Global Biogeochem. Cycles, vol. 8, no. 3, pp. 279–293, 1994.
24. S. Wagner, S. R. Cattle, and T. Scholten, "Soil-aggregate formation as influenced by clay content and organic-matter amendment," J. Plant Nutr. Soil Sci., vol. 170, no. 1, pp. 173–180, 2007.
25. M. E. Craig, M. A. Mayes, B. N. Sulman, and A. P. Walker, "Biological mechanisms may contribute to soil carbon saturation patterns," Glob. Chang. Biol., vol. 27, no. 12, pp. 2633–2644, 2021.
26. W. Feng et al., "Testing for soil carbon saturation behavior in agricultural soils receiving long-term manure amendments," Can. J. Soil Sci., vol. 94, no. 3, pp. 281–294, 2014.
27. M. J. Castellano, K. E. Mueller, D. C. Olk, J. E. Sawyer, and J. Six, "Integrating plant litter quality, soil organic matter stabilization, and the carbon saturation concept," Glob. Chang. Biol., vol. 21, no. 9, pp. 3200–3209, 2015.
28. USDA, "National Agricultural Statistics Service," 2020. [Online]. Available: https://www.nass.usda.gov/.
29. L. Lai and S. Kumar, "A global meta-analysis of livestock grazing impacts on soil properties," PLoS One, vol. 15, no. 8, p. e0236638, 2020.
30. R. Lal et al., "The carbon sequestration potential of terrestrial ecosystems," J. Soil Water Conserv., vol. 73, no. 6, pp. 145A-152A, 2018.
31. J. Wang, Z. Xiong, and Y. Kuzyakov, "Biochar stability in soil: meta-analysis of decomposition and priming effects," Gcb Bioenergy, vol. 8, no. 3, pp. 512–523, 2016.
32. K. Adhikari, P. R. Owens, Z. Libohova, D. M. Miller, S. A. Wills, and J. Nemecek, "Assessing soil organic carbon stock of Wisconsin, USA and its fate under future land use and climate change," Sci. Total Environ., vol. 667, pp. 833–845, 2019.
33. S. C. McClelland, K. Paustian, and M. E. Schipanski, "Management of cover crops in temperate climates influences soil organic carbon stocks: a meta-analysis," Ecol. Appl., vol. 31, no. 3, p. e02278, 2021.
34. E. R. Waring, A. Lagzdins, C. Pederson, and M. J. Helmers, "Influence of no-till and a winter rye cover crop on nitrate losses from tile-drained row-crop agriculture in Iowa," J. Environ. Qual., vol. 49, no. 2, pp. 292–303, 2020.
35. B. Minasny and A. B. McBratney, "Limited effect of organic matter on soil available water capacity," Eur. J. Soil Sci., vol. 69, no. 1, pp. 39–47, 2018.
36. B. D. Hudson, "Soil organic matter and available water capacity," J. soil water Conserv., vol. 49, no. 2, pp. 189–194, 1994.
37. C. M. Pittelkow et al., "When does no-till yield more? A global meta-analysis," F. Crop. Res., vol. 183, pp. 156–168, 2015.
38. W. Sun et al., "Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture," Glob. Chang. Biol., vol. 26, no. 6, pp. 3325–3335, 2020.
39. B. Guenet et al., "Can N2O emissions offset the benefits from soil organic carbon storage?," Glob. Chang. Biol., vol. 27, no. 2, pp. 237–256, 2021.
40. J. R. England and R. A. Viscarra Rossel, "Proximal sensing for soil carbon accounting," Soil, vol. 4, no. 2, pp. 101–122, 2018.
41. R. J. Gehl and C. W. Rice, "Emerging technologies for in situ measurement of soil carbon," Clim. Change, vol. 80, no. 1, pp. 43–54, 2007.
42. B. H. Kusumo, "In Situ Measurement of Soil Carbon with Depth using Near Infrared (NIR) Spectroscopy," in IOP Conference Series: Materials Science and Engineering, 2018, vol. 434, no. 1, p. 12235.
43. Y. Fu et al., "Predicting soil organic matter from cellular phone images under varying soil moisture," Geoderma, vol. 361, p. 114020, 2020.
44. C. A. Cambardella and E. T. Elliott, "Methods for physical separation and characterization of soil organic matter fractions," in Soil Structure/Soil Biota Interrelationships, Elsevier, 1993, pp. 449–457.
45. S. W. Culman, S. S. Snapp, J. M. Green, and L. E. Gentry, "Short-and long-term labile soil carbon and nitrogen dynamics reflect management and predict corn agronomic performance," Agron. J., vol. 105, no. 2, pp. 493–502, 2013.
46. -A. S. Grandy, D. S. Salam, K. Wickings, M. D. McDaniel, S. W. Culman, and S. S. Snapp, "Soil respiration and litter decomposition responses to nitrogen fertilization rate in no-till corn systems," Agric. Ecosyst. Environ., vol. 179, no. 0, pp. 35–40, Oct. 2013.
47. -M. D. McDaniel and A. S. Grandy, "Soil microbial biomass and function are altered by 12 years of crop rotation," Soil, vol. Discussion, p. doi:10.5194/soil-2016-39, 2016.
48. -ROC, "Regenerative Organic CertifiedTM," 2022. [Online]. Available: https://regenorganic.org/.
49. -C. Neutral, "Climate Neutral," 2021. [Online]. Available: https://www.climateneutral.org/.
50. -CarbonTrust, "The Carbon Trust," 2022. [Online]. Available: https://www.carbontrust.com/.
51. -A. M. Leach et al., "Environmental impact food labels combining carbon, nitrogen, and water footprints," Food Policy, vol. 61, pp. 213–223, 2016.
52. -A. Rondoni and S. Grasso, "Consumers behaviour towards carbon footprint labels on food: A review of the literature and discussion of industry implications," J. Clean. Prod., vol. 301, p. 127031, 2021.

Wealth, Consumption, & Waste

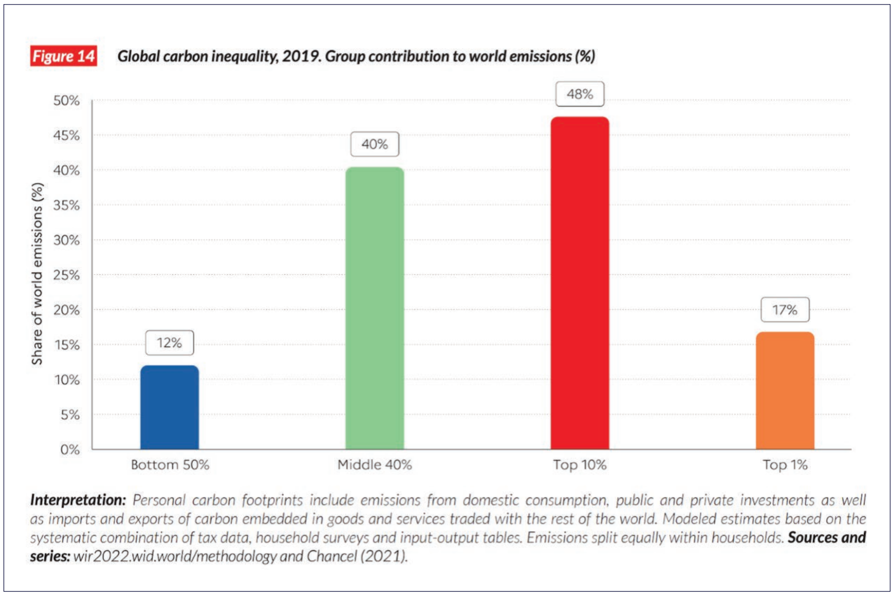
JEREMY
DRAKE

INTRODUCTION

As we shift now to examine the role of wealth, consumption, and waste in climate change, consider this:

The world's wealthiest 10 percent is responsible for 48 percent of global carbon emissions.[22] The poorest 50 percent is responsible for only 12 percent of global carbon emissions.[23]

Figure 1. Global Carbon Inequality, 2019 (credit: World Inequality Report 2022)



The link between wealth, consumption of energy and resources, and the subsequent carbon emissions that have driven and continue to drive climate change is clear and undeniable. The historical and ongoing inequities at the intersection of wealth, consumption, waste, and climate require redress.

How can we equitably reduce global energy use, waste, and the associated carbon emissions? What does climate justice look like as we take bold, swift action toward a decarbonized world?

The Haves and the Have Lesses

The world's wealthiest 10 percent, or those responsible for 48 percent of global carbon emissions, comprises individuals with annual incomes between $52k and $173k USD.[24] Roughly 27 percent of Americans are in the world's wealthiest 10 percent.[25]

The poorest 50 percent of the world's population responsible for only 12 percent of global carbon emissions are people with annual incomes under $9.4k USD.[26] In America, this group is about 17 percent of the total population.[27]

22. https://www.oxfam.org/en/press-releases/worlds-richest-10-produce-half-carbon-emissions-while-poorest-35-billion-account; https://wir2022.wid.world/
23. ibid/
24. https://www.oxfam.org/en/press-releases/worlds-richest-10-produce-half-carbon-emissions-while-poorest-35-billion-account; https://wir2022.wid.world/www-site/uploads/2022/03/WIR2022TablesFigures-Chapter.zip
25. https://en.wikipedia.org/wiki/Personal_income_in_the_United_States
26. https://www.oxfam.org/en/press-releases/worlds-richest-10-produce-half-carbon-emissions-while-poorest-35-billion-account; https://wir2022.wid.world/
27. https://en.wikipedia.org/wiki/Personal_income_in_the_United_States

In between, the world's middle 40 percent are responsible for 40 percent of global carbon emissions.[28] The roughly 56 percent of Americans earning between $9.4k and $52k USD per year are a part of the world's middle 40 percent. [29]

The Have Way, Way Mores

Millionaires and billionaires are another story altogether. Millionaires emit carbon at 175 times the rate of the poorest 10 percent of the planet's population.[30] The world's 2,153 billionaires have more wealth than 4.6 billion people, or 60 percent of the planet's population.[31] That level of wealth is absurdly difficult to comprehend as is the claim a billionaire has on the world's resources. If we consider that Americans on average earn $41k per year and use four times more energy than the average global citizen, imagine the energy use of someone like Jeff Bezos who earns $133k per minute or Elon Musk whose net worth is $219 billion.[32] Or if we simply consider a millionaire emits carbon at 175 times that of the poorest 10 percent, would then a billionaire whose lifestyle tracks with wealth emit 175,000 times the carbon? Is such profligacy sustainable or even ethical?[33]

ENERGY USE AND CARBON EMISSIONS

Energy Use Around The World

The Intergovernmental Panel on Climate Change has identified wealth as a key driver of energy demand.[34] A review of available global per capita energy use data tracks with global wealth disparity largely on a nation-by-nation basis. Average global per capita energy use is about 80 gigajoules per annum (gj/a).[35] Average per capita energy use in 23 of the world's wealthiest nations is about 210 gj/a.[36] Pushing up the wealthy nations average, the United States comes in at roughly 325 gj/a per person. Meanwhile, the average energy use of a resident of one of the world's 23 poorest nations in Africa, Asia, and Latin America is closer to 20 gj/a.[37] While it would appear that wealthy nations such as ours substantially raise the global average, it is important to consider regional climate variances, population densities, transportation mode mix, and other non-wealth factors in understanding the full picture of differences in energy use.

28. https://www.oxfam.org/en/press-releases/carbon-emissions-richest-1-percent-more-double-emissions-poorest-half-humanity

29. https://en.wikipedia.org/wiki/Personal_income_in_the_United_States

30 https://www.oxfam.org/en/press-releases/worlds-richest-10-produce-half-carbon-emissions-while-poorest-35-billion-account

31. https://www.oxfam.org/en/press-releases/worlds-billionaires-have-more-wealth-46-billion-people; As of March 2022, Forbes reported the number of billionaires is 2,668 - https://www.forbes.com/billionaires/

32. https://www.businessinsider.com/how-rich-is-jeff-bezos-mind-blowing-facts-net-worth-2019-4#2-bezos-makes-2219-per-second-more-than-twice-what-the-median-us-worker-makes-in-one-week-2; https://www.forbes.com/billionaires/

33. Current research on the intersection of income and lifestyle-based carbon emissions suggest that incomes are more unevenly distributed than lifestyle-based CO2 due to the fact that the carbon emissions intensity of consumption per unit of expenditure is higher in poorer households than in wealthier ones. Despite that, income remains the strongest driver of carbon inequality [Sager, 2019].

34. https://www.ipcc.ch/sr15/

35. https://www.eia.gov/tools/faqs/faq.php?id=85&t=1 – 2018 data; Climate North Star converted BTUs to gigajoules (gj) by isolating the three primary CO2-producing energy sources used in the United States and calculating a blended average of 14.65 gj/MtCO2 based on EIA data available from https://www.eia.gov/energyexplained/us-energy-facts/

36. EIA data for energy consumption in United States, Canada, United Kingdom, Italy, Germany, Japan, New Zealand, Australia, Luxembourg, Belgium, Austria, Switzerland, France, Denmark, the Netherlands, Finland, Sweden, Norway, Spain, Portugal, Israel, Ireland, and Iceland accessed via https://en.wikipedia.org/wiki/List_of_countries_by_energy_consumption_per_capita

37. EIA data for energy consumption in Democratic Republic of Congo, Mozambique, Uganda, Tajikistan, Yemen, Haiti, Ethiopia, Tanzania, Kyrgyzstan, Uzbekistan, Zambia, Pakistan, Myanmar, Cambodia, Bangladesh, Cote d'Ivoire, Kenya, Nicaragua, India, Nigeria, Ghana, Vietnam, and Honduras accessed via https://en.wikipedia.org/wiki/List_of_countries_by_energy_consumption_per_capita

Figure 2. Comparing Per Capita Energy Use – 2017/2018
Average amount of energy used per capita in gigajoules per year (gj/a)

PER CAPITA GROUPING	GJ/A
United States	325
Wealthy Nations	210
Global Average	80
Poor Nations	20

source: eia.gov

Inequities In The United States

While there are indeed wealthy nations and poor nations, extreme differences in wealth also occur among a nation's own people. In a country like the United States, a map of socioeconomic status is in effect a map of energy use. When we consider the contributors to the current climate crisis through the lens of social justice, we see that our poor have contributed less than our middle class who have contributed less than our wealthy. Research based on expenditure data from a recent U.S. Bureau of Labor Statistics Consumer Expenditure Survey suggests that high income American households generate more than 10 times the emissions of low income ones.[38] With that in mind, there exists a disproportionate responsibility on the part of our nation's wealthiest citizens to reduce emissions.[39] In fact, the largest reductions must come from those of us who are among the most wealthy no matter what nation we call home. Regardless of the level of reduction necessary to avoid the most catastrophic effects of climate change based on relative socioeconomic status, nearly all residents of the United States and the world's other wealthiest countries should reduce their energy use from a little to a lot.

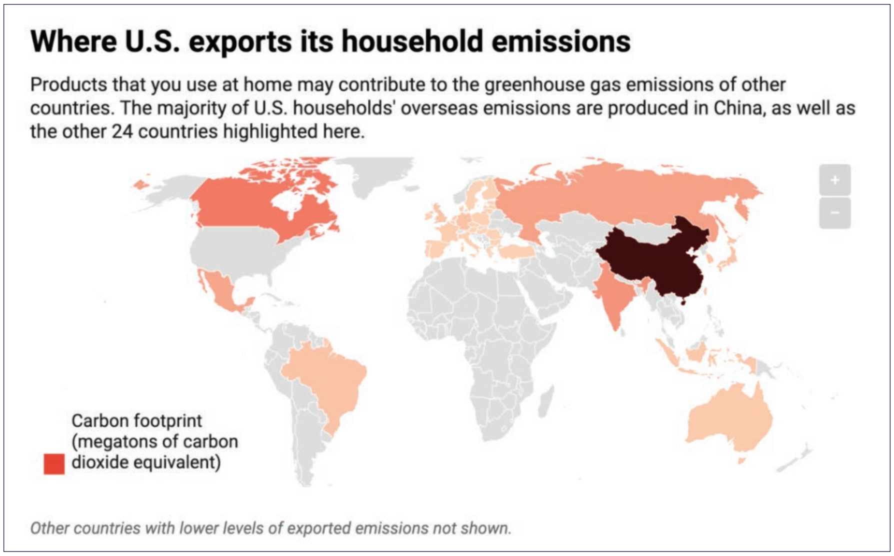
Accounting For Consumption-based Energy

The per capita energy use figures above *(see Figure 2. Comparing Per Capita Energy Use – 2017/2018)* represent total terrestrial energy use across residential, commercial, industrial, and transportation sectors in relation to population. They do not include consumption-based energy, which is often expressed as consumption-based emissions, trade-adjusted emissions, or emissions embodied in trade. Consumption-based energy use adds 10+ percent to the overall figure for residents of the

38. Weber and Matthews. (2008).
39. Chancel and Piketty. (2015).

United States, 15+ percent for those in Japan, and 20-30+ for Europeans.[40] That embodied energy is exported from the world's poorest nations where the lion's share of manufacturing takes place, namely China, to high-consuming nations in the form of materials and consumer goods. As a result, more than one fifth of China's emissions, on net, are exported. By and large, the world's poorest nations do not have measurable consumption-based emissions as they do not at this time consume at the level of wealthy nations.

Figure 3. Where the U.S. Exports its Household Emissions[41]



Source: pbs.com; The Conversation (CC BY-ND)

FAIR COMMON GLOBAL PERSONAL ENERGY USE

For perspective, consider that 100 gigajoules per annum (gj/a) for every person in the world would represent a rough estimation of a fair common energy use standard. This target is intentionally decoupled from wealth, yet wealth remains at the center of this solution. We must employ our understanding of the relationship between wealth and energy use to guide the quality and intensity of actions needed to reach the target.

Using observed per capita energy use data as a starting point, it is clear that this common target would require the wealthy of the world, starting with many of us in the United States, to cut consumption *(see Figure 4. Global Per Capita Energy Use: Observed to Target)*. Considering the wealthy bear the historical burden of creating the climate crisis, their meaningful reduction in energy use is a top priority. Meanwhile, those whose historical energy use has been relatively insignificant in terms of climate change, such as those people living on 20 gj/a, will increase consumption, ideally in ways aligned with the Climate North Star, to the extent necessary to attain a decent standard of living.[42]

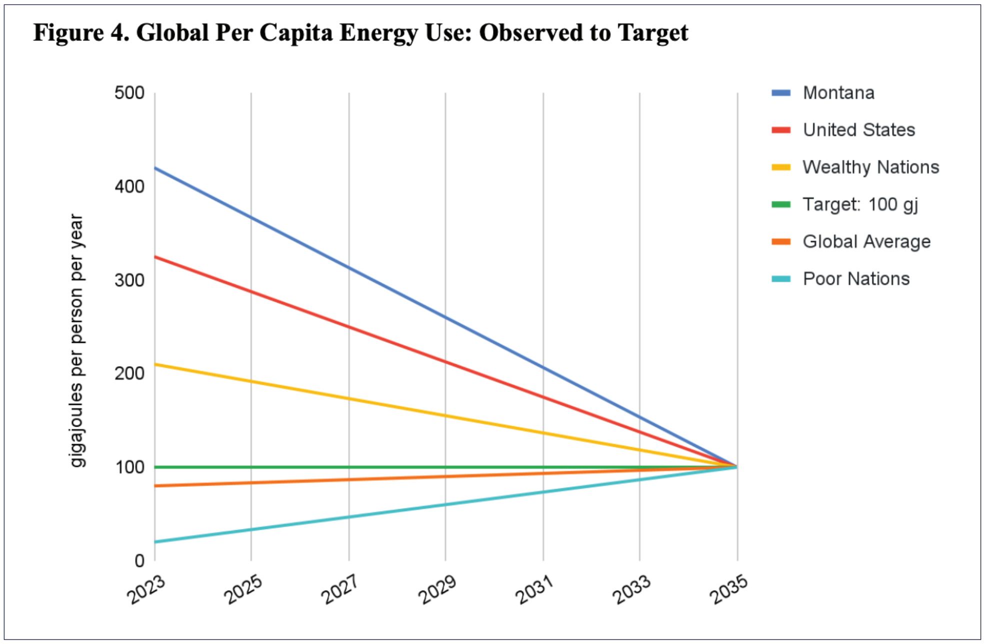
40. Peters, et al, 2012; Davis and Caldeira. (2010).

41. Kaihui Song, Shen Qu, Morteza Taiebat, Sai Liang, Ming Xu, Scale, distribution and variations of global greenhouse gas emissions driven by U.S. households, Environment International, Volume 133, Part A, 2019, 105137, ISSN 0160-4120, https://doi.org/10.1016/j.envint.2019.105137.

42. Druckman and Jackson (2010) estimate minimal GHG emissions requirements based on "minimum income standard" budgets needed to provide a "decent life".

This common global energy use target approach is rooted in the belief that a prosperous future for all of humanity is one that wholeheartedly embraces social justice across all borders and all cultures.

Figure 4. Global Per Capita Energy Use: Observed to Target



TARGET: 100 GIGAJOULES

We think that a fair global per capita energy use standard would be 100 gigajoules per year. As demonstrated in Figure 2 the current average is 80 gigajoules per year. The greatest energy use reductions must come from the wealthy nations whose emissions triggered the climate crisis. As demonstrated in Figure 4 one of the world's largest per capita energy users, the United States, faces a steep energy use reduction challenge indeed.

Over the next ten years, the poorest nations will likely continue to increase their energy use. This 100 gj/yr per capita target encompasses energy use across four major sectors that together account for total global energy demand: residential, commercial, industrial, and transportation.[43]

43. https://www.eia.gov/totalenergy/data/monthly/pdf/sec2.pdf

OUR PERSONAL ENERGY USE

Our energy use as individuals represents only a fraction of the energy use of the whole of society. For example, the energy used to build airplanes, manufacture concrete, and supply the military cannot be directly attributed to our day-to-day lives. However, many of us live in homes and many of us use and rely on transportation in our day-to-day lives. If we combine residential and transportation sector energy use, which accounts for 40 percent of total global energy use, with consumption-based energy use, which adds another 10 percent to the total for Americans, we begin to define what we call *lifestyle-based energy use*.

A Carbon Reduction Accelerator

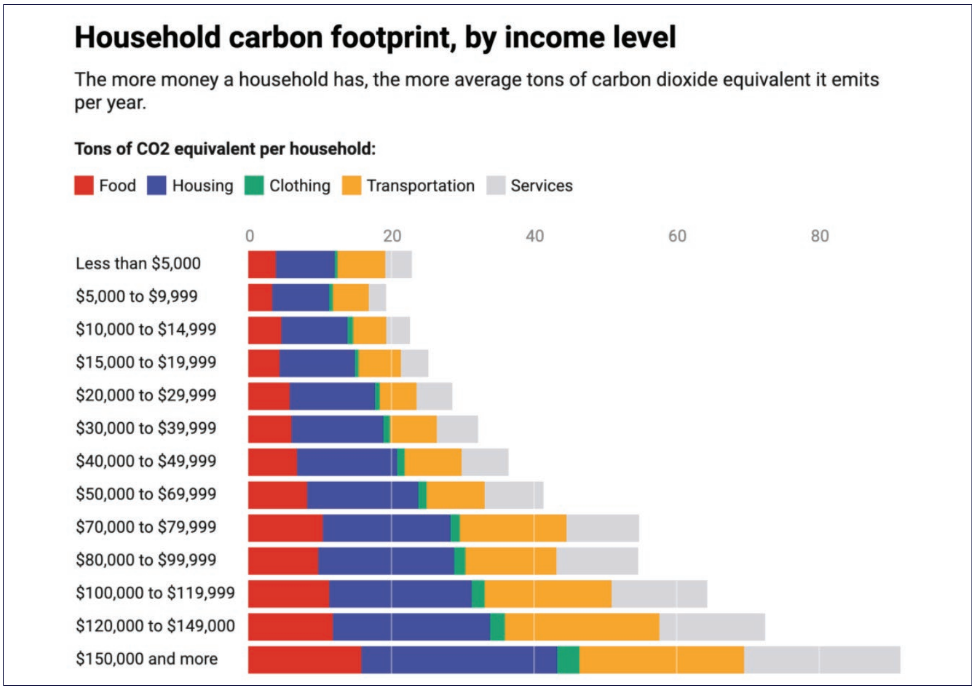
Focusing on lifestyle-based energy use allows us to view potential energy use changes on an individual or household scale. Why is this important? Lifestyle-based energy use generates lifestyle-based carbon emissions. In wealthy nations like the United States, reducing the energy necessary to support our day-to-day lives is a near-term carbon emissions reduction strategy to employ amidst the work to enact larger systemic changes that will lead to decarbonization. It is in the realm of lifestyle-based energy use that we have the most agency and can make immediate, impactful changes. Identifying ways to reduce lifestyle-based energy use will act as a carbon reduction accelerator during the period of time we need it most: now and up to the 2035 global decarbonization deadline. As Americans and as global citizens, this is the action we must take right now. At the same time, we must also engage in the political action necessary to support swift adoption of the systemic changes to ensure carbon emissions reduction across all sectors.

Reducing Lifestyle-Based Energy Use

The authors of the IPCC 1.5 report expressed "high confidence" that "behavior- and lifestyle-related measures and demand-side management have already led to emission reductions around the world and can enable significant future reductions."[44] The IPCC states "human actions are relevant at different levels, from international, national, and sub-national actors, to NGO, firm-level actors, and communities, households, and individual actions."[45]

Here we focus on what the 100 gj/a target means in the context of lifestyle-based energy use. Lifestyle-based energy use manifests directly at the individual, household, and community levels and impacts indirectly the entire global economic landscape. It is the total energy used across three areas: residential housing, transportation, and goods and food. Residential housing includes HVAC, lighting, electronics, food storage, and cooking. Transportation includes vehicle travel and air travel. Goods include construction materials as well as all of our "stuff," from clothing and furniture, to networked devices, equipment, and toys. Food is a significant aspect of lifestyle-based energy use that can be addressed by adopting a low-carbon diet, which can largely be achieved by following the advice of Michael Pollan, "Eat food, not too much, mostly plants."[46] If we can determine the amount of energy needed to support our current lifestyle based upon our individual levels of wealth and consumption, then we can agree on our collective task to make the individual, household, and community changes necessary to achieve the 100 gj/a per capita target.

Figure 5. Household Carbon Footprint, by Income Level[47]



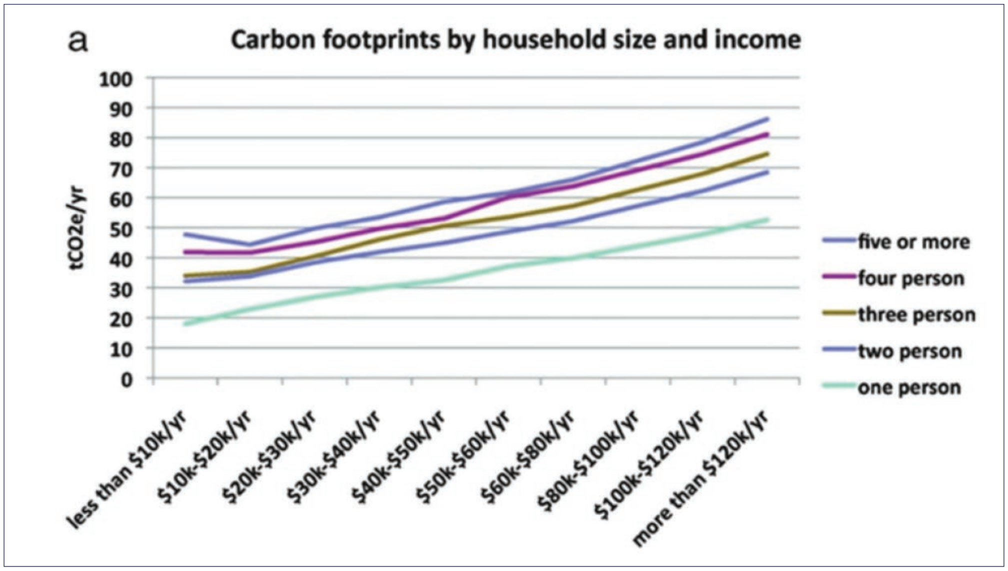
44. https://www.ipcc.ch/sr15/
45. https://www.ipcc.ch/sr15/chapter/glossary/
46. Pollan, Michael. (2008).
47. https://www.pbs.org/newshour/science/5-charts-show-how-your-household-drives-up-global-greenhouse-gas-emissions

Spotlight: Housing

In the United States, the super-sized way of life wealthy Americans enjoy shares an equally super-sized appetite for resources and carbon emissions. Larger homes are the primary reason that wealthier Americans have per capita carbon footprints roughly 25 percent higher than those of lower-income residents. In especially affluent areas, emissions can be 15 times higher.[48] The average floor area per capita (FAC) for the world's wealthiest 10 percent living in America is 42 percent higher than for members of the global middle class in America.[49] We can better understand this aspect of the American lifestyle by comparing the FAC average in the United States to the average in Europe. On average, Americans live with 42 percent more FAC than Europeans. Factors to consider in the emissions related to FAC include HVAC which is linked to regional climate variances as well as lighting, equipment, and appliances.

A shift toward smaller, energy efficient dwellings in the United States is key to locking in lower energy demand as new housing stock is built. For existing residential dwellings, efficiency measures and investment in EnergyStar-rated appliances are two widely recognized methods for reducing housing-related lifestyle-based carbon emissions. Making heat pumps the "new normal" for HVAC systems has been identified as a major carbon reduction solution and should be prioritized in existing building retrofits and new building installations.

Figure 6. Carbon Footprints by Household Size and Income[50]



48. Goldstein, B., Gounaridi, D., and Newell, J. P. (2020).
49. https://osf.io/gxm39/
50. Druckman and Jackson. (2016).

Spotlight: Transportation

In the United States, light-duty vehicles (cars and light trucks) are responsible for 55 percent of transportation energy use, commercial trucks for 24 percent, and airplanes for 9 percent.[51] Our reliance on light-duty vehicles generates the lion's share of our transportation sector emissions, a whopping 59 percent.[52]

While telecommuting has exploded in recent years, prior to the COVID-19 pandemic, more than 85 percent of Americans commuted to work in cars.[53] Also pre-pandemic, the roughly 50 percent of Americans who travel by air were responsible for 24 percent of global aviation emissions. Shockingly, the 12 percent of Americans who make more than six round trips by air a year were responsible for two-thirds of aviation emissions.[55]

Reduction in transportation has been a widely noted side effect of COVID-19. The shift to telecommuting has revealed the possibilities of a lower-carbon approach to office work while virtual conferences and staycations have supplanted carbon-intensive trips to exotic destinations. A full transition to electric vehicles is increasingly becoming more realistic as the technologies come to scale, costs come down, and financing opportunities come on line. Electric vehicles, which only represent 2 percent of the current U.S. fleet, will be the norm in a decarbonized world. In the meantime, continuing to reduce our reliance on automobile transportation and air travel will be key to trimming our transportation-related lifestyle-based energy use.

MATERIALS USE AND WASTE

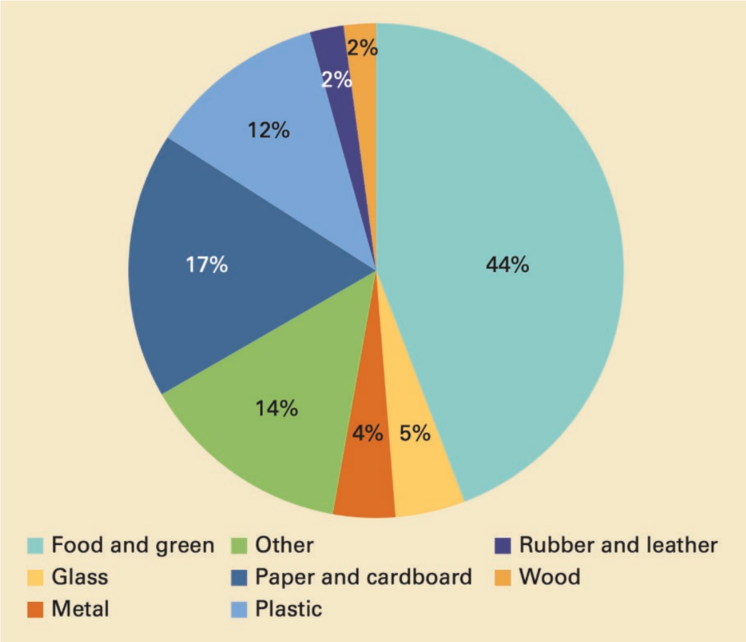
The World's Waste

The World Bank has reported that global waste generation will outpace population growth by more than double by 2050.[55] Embedded within that dire prediction is the resource extraction and carbon emissions that result from the current modes of material use. In those modes, single-use packaging is the norm, reuse systems are few, composting is rare, recycling is limited and sometimes harmful, and landfilling and incineration, where resources are destroyed, are the dominant management approaches.

An examination of municipal solid waste – those materials discarded from homes, businesses, schools and other institutions as seen in Figure 7 – reveals that, like energy use, waste generation

51. https://www.eia.gov/energyexplained/use-of-energy/transportation-in-depth.php
52. https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions
53. https://www.worldwildlife.org/magazine/issues/summer-2017/articles/reducing-the-impact-of-commuting
54. https://www.nytimes.com/interactive/2019/10/17/climate/flying-shame-emissions.html
55. http://hdl.handle.net/10986/30317

Figure 7. Global Waste Composition



Source: worldbank.org

tracks with global wealth disparity. Figure 8 shows average global per capita waste generation is about 1.6 pounds per day (lbs/day). Average per capita waste generation in the world's wealthiest nations is about 3.5 lbs/day. Pushing up the wealthy nations average, the United States comes in at roughly 4.9 lbs/day per person. Meanwhile, the average waste generation of a resident of one of the world's poorest nations in Africa, Asia, and Latin America is closer to .9 lbs/day.[56]

Figure 8. Comparing Per Capita Waste Generation – 2016

Average amount of waste generated per capita in pounds per day (lbs/day)

Per Capita Grouping	lbs/day
United States	4.9
Wealthy Nations	3.5
Global average	1.6
Poor Nations	0.9

source: worldbank.org

56. ibid.

Inequities in Waste

Despite these numbers, due to the global scale of material flows, a disproportionate amount of pollution resulting from materials management is often felt by poor residents in wealthy nations and poor nations alike. The unrelenting flow of wasted goods and materials from communities in wealthy nations often manifests as a stream of trucks dumping materials at facilities in overburdened, low-income communities of color where diesel exhaust darkens the sky and, in the worst of circumstances, toxic emissions from incinerator smokestacks exacerbate asthma and cause cancer.[57] Activists in communities including Baltimore, MD, Chester, PA, Minneapolis, MN, Long Beach, CA, and many others are fighting to shutter incinerators and replace them with Zero Waste solutions that are a benefit rather than a burden to their communities.

The search for places to recycle materials like plastics, textiles, and electronics has brought about the rise of waste colonialism, where wealthy nations export those hard-to-recycle materials to poorer nations where no recycling infrastructure exists. The results are devastating to people and the environment.

As we seek climate justice, we must also consider the injustices inherent in the current system of wasting and strive to adopt equitable, effective systems that not only benefit the climate, but value and support people and environments everywhere.

A Systems View of "Waste" in the United States

What we commonly call "waste" is the residual materials of consumption. Those materials aren't inherently waste, which is a concept generally used to denote something unwanted, lacking worth or value. In fact, all materials have an inherent value. Through the lens of carbon emissions, that value can be seen as embodied carbon, or the energy used to turn that material from a tree or a tank of ethane gas into a greeting card or a to-go bag that somehow gets to us, we use, and then discard. From that perspective, recycling materials makes sense. After all, if by recycling we can reduce the embodied carbon in the manufacture of new products by utilizing the embodied carbon in discarded products, we reduce carbon emissions. It works if an item we "recycle" is truly recycled. That premise is widely accepted and tools such as the U.S. Environmental Protection Agency (EPA) Waste Reduction Model (WaRM) can be used to calculate the emissions reductions from recycling and other waste reduction measures such as source reduction, reuse, and composting. In fact, if 90 percent of discards to landfills and incinerators in the United States were reduced, reused, recycled, and composted, the emissions reduction would be equivalent to removing 24 percent of cars from the road.[58] That amounts to roughly 5 percent of total CO2e emissions in the United States.[59]

57. https://www.cbf.org/news-media/newsroom/2017/maryland/cbf-study-baltimore-incinerator-causes-55-million-in-health-problems-per-year.html

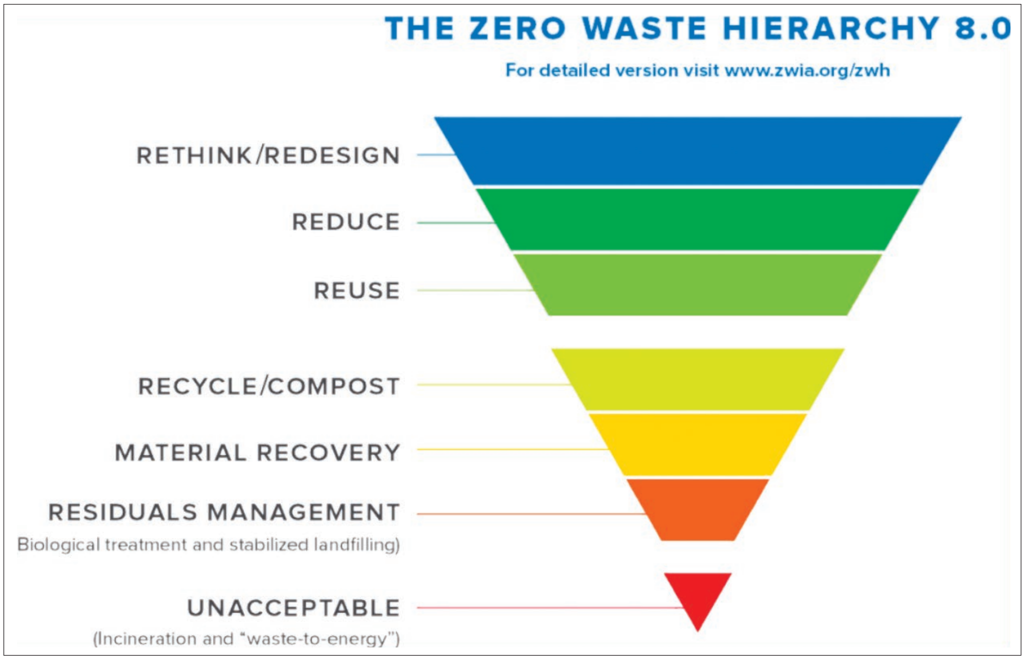
58. U.S. EPA Waste Reduction Model (WARM) & U.S Vehicle Registration Statistics

59. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

However, if we consider these materials as part of a larger system of consumption, we get a drastically different picture. Evaluated from a systems perspective, the provision of goods and food account for 50 percent of total CO2e emissions in the United States.[60] The bottom line is that if we consume less stuff, we reduce emissions across the entire system. This suggests that the faster we can learn to use less and reuse more, the faster we can take advantage of this powerful system multiplier to cut emissions.

Recycling, as has been noted, can play a part if done right and done ethically. And recent data from the EPA reveals that the emissions reductions from cutting food loss and keeping wasted food out of landfills are essential to tackling the climate crisis.[61] However, as shown in Figure 9, we must also focus our efforts on the top of the Zero Waste hierarchy to rethink and redesign our systems of stuff, reduce where possible, and adopt systems of reuse that ends our reliance on single-use plastic packaging, ends our fascination with fast fashion, and keeps valuable building materials from going to waste. We also need widespread adoption of an ethic of repair that extends the lives of our increasingly ubiquitous electronic devices and reduces the emissions and harm associated with the production of electronics.

Figure 9. The Zero Waste Hierarchy



60. U.S. EPA. (2009). Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices. https://archive.epa.gov/greenbuilding/web/pdf/ghg_land_and_materials_management.pdf

61. https://www.epa.gov/newsreleases/epa-releases-new-food-waste-reports

Spotlight: Food and Compostable Organics

A decade ago, the Food and Agriculture Organization of the United Nations reported that if food loss and waste was a country, it would be the third highest emitter of greenhouse gasses after the U.S. and China.[62] A new EPA report released in October 2023 states, "although food waste comprises 24 percent of the MSW [municipal solid waste] stream, it constitutes an estimated 58 percent of annual landfill methane emissions."[62] That is significant because landfills are the third largest anthropogenic generator of methane emissions in the United States[64] and methane is a greenhouse gas that is 80 times as powerful as CO2 during its first 20 years in the atmosphere.[65] The EPA estimates up to 40 percent of the United States' food supply is never eaten resulting in food waste being the single most common material landfilled and incinerated in the United States.[66] Project Drawdown includes reducing food waste within its top five priority actions.[67]

The EPA's new Wasted Food Scale (Figure 10) underscores the importance of preventing food waste, donating edible food, redirecting food to animals, and composting.[68] While food is made to be eaten, the added benefits of composting wasted food include increasing soil carbon storage and avoiding synthetic fertilizer use by using finished compost as a soil amendment.[69]

Figure 10. EPA's Wasted Food Scale

62. http://www.fao.org/nr/sustainability/food-loss-and-waste
63. https://www.epa.gov/system/files/documents/2023-10/food-waste-landfill-methane-10-8-23-final_508-compliant.pdf
64. https://www.iea.org/reports/methane-tracker-2021/methane-and-climate-change
65. https://www.edf.org/climate/methane-crucial-opportunity-climate-fight
66. https://www.epa.gov/sustainable-management-food/united-states-2030-food-loss-and-waste-reduction-goal#footnote1
67. https://drawdown.org/solutions/reduced-food-waste/technical-summary
68. https://www.epa.gov/sustainable-management-food/wasted-food-scale
69. https://www.epa.gov/sites/default/files/2020-12/documents/warm_organic_materials_v15_10-29-2020.pdf

Spotlight: Plastic

The problems of plastic, which sixty years ago was touted as a miracle material, are increasingly at the forefront of the news. Plastic pollution is ubiquitous. It is now found everywhere on the planet, in the human brain,[70] and in mother's milk.[71] By 2050, there is predicted to be more plastic in the world's oceans than fish (by weight).[72] Updated in 2021, the Canadian Environmental Protection Act (CEPA) now lists plastic as a toxic substance.[73]

Besides the day-to-day harm to the health of people living in fenceline communities along the United States Gulf Coast petrochemical industry corridor where many single-use plastics are produced, explosions at plants that manufacture plastics have become common in recent years exacerbating health risks. In February 2023, a train derailment in East Palestine, Ohio released toxic vinyl chloride – the key ingredient in PVC, a common type of plastic – into air, land, and water causing a grave environmental and public health disaster. Despite those high costs of plastic production, sixty percent of the plastic produced is intended for single-use.[74] The lifecycle emissions of plastics are estimated to account for 3.3 percent of total global emissions.[75]

The true nature of the global plastic trade is just now coming to light through the efforts of NGOs such as the World Wildlife Fund. A report released in November 2023 highlights the structural inequities of the global plastic value chain in the absence of global regulations.[76] Organizations like GAIA (Global Alliance for Incinerator Alternatives), Break Free from Plastic, Beyond Plastic, Plastic-Free Future, People Over Plastic, and Upstream are some of the many leaders of the global movement to address these inequities, reveal externalized costs, and to end reliance on and expand alternatives to single-use plastic. Also in November 2023, the third session of the Intergovernmental Negotiating Committee on Plastic Pollution convened with the aim to develop an international legally binding instrument that addresses the full life cycle of plastic, including its production, design, and disposal.[77] A clean energy future can't truly be clean unless we solve the problems of plastic.

Spotlight: Textiles

The lengthy supply chains and energy-intensive production methods of the apparel and footwear industries account for nearly 10 percent of global carbon emissions, which is greater than the combined emissions from the aviation and shipping industries.[78] At the current rates of fast fashion-fueled consumption, the fashion industry is projected to require approximately 25 percent of the world's carbon budget by 2050.[79]

Efforts to appeal to increasingly conscious consumers have backfired for some major fast fashion clothing brands like H&M whose textile recycling program was recently revealed to be an ugly manifestation of waste colonialism.[80] Images of mountains of discarded clothing littering communities in Africa led to legal action against the company to end the greenwashing.

70. https://www.euronews.com/next/2023/08/30/microplastics-could-be-widespread-in-organs-and-impact-behaviour-new-study-suggests
71. https://www.news-medical.net/news/20230206/New-insights-into-the-release-of-microplastics-from-breastmilk-storage-bags.aspx
72. https://www3.weforum.org/docs/WEF_The_New_Plastics_Economy.pdf
73. https://www.motherjones.com/environment/2021/05/canada-declares-plastics-toxic-ban-restrictions/
74. https://wwfint.awsassets.panda.org/downloads/wwf-report---who-pays-for-plastic-pollution.pdf
75. https://ourworldindata.org/ghg-emissions-plastics
76. https://wwfint.awsassets.panda.org/downloads/wwf-report---who-pays-for-plastic-pollution.pdf
77. https://www.unep.org/inc-plastic-pollution
78. https://doi.org/10.3389/fenvs.2022.973102
78. ibid.
80. https://cosh.eco/en/articles/dundora-textielafvalberg-in-kenya

Donating gently used apparel, shopping reused, sharing and finding clothes through Buy Nothing groups, and purchasing well-made, durable, repairable garments are important actions to reduce the emissions and other harmful impacts of the textile industry.

Spotlight: Electronics

Digital devices are estimated to account for up to 5.9 percent of global carbon emissions.[81] Emissions from the production of electronics increased 53 percent between 2014 and 2020 and are predicted to increase another 46 percent by 2030.[82] As a result, e-waste is on the rise as the fastest growing solid waste stream in the world.[83] Exports of e-waste to the Global South have been widely documented as tragic instances of waste colonialism resulting in exposure to toxic chemicals for millions of women and children working in the informal waste sector.[84]

The Right to Repair movement has pulled back the curtain on the practice of planned obsolescence and challenged the value of proprietary information over the health of people and the planet. What began three decades ago in the automotive sector to allow car owners and independent mechanics to repair increasingly sophisticated and computerized vehicles has blossomed into a consumer electronics revolution. Within the past year, Minnesota, New York, and California have passed Right to Repair laws that will reduce the amount of e-waste generated by requiring electronics manufacturers to provide owners of digital devices access to repair materials like parts, tools, documentation, and software.

Over the past two decades, communities have sprouted up around the globe to support repair of electronics, household appliances, and other consumer products. Through in-person and virtual Repair Cafes and Fixit Clinics, the iFixit online network, and community based organizations like the youth-led nonprofit Community Creativity for Development (CC4D) in the Eden Rhino Camp Refugee Settlement in the west Nile region of Uganda, the repair movement has been galvanized through community-sourced how-to repair tutorials, parts, tools, and skill-sharing.

Spotlight: Building Materials

The Rocky Mountain Institute defines embodied carbon as “the millions of tons of carbon emissions released during the lifecycle of building materials, including extraction, manufacturing, transport, construction, and disposal.”[85] The embodied carbon in buildings is estimated to account for 11 percent of global emissions.[86]

Building materials when wasted result in an enormous amount of debris. In the United States, discarded building materials make up more than twice the amount of municipal solid waste generated each year, 90 percent of which is the result of the practice of demolition.[87]

81. https://doi.org/10.1016/j.cec.2022.100011
82. ibid.
83. https://www.who.int/news-room/fact-sheets/detail/electronic-waste-(e-waste)
84. https://www.who.int/news/item/15-06-2021-soaring-e-waste-affects-the-health-of-millions-of-children-who-warns
85. https://rmi.org/embodied-carbon-101/
86. https://www.aia.org/pages/6502700-roi-designing-for-reduced-embodied-carbon
87. https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials

Deconstruction is an alternative to demolition that both reduces waste and salvages the embodied carbon in building materials. It is the process of dismantling a structure to maximize the recovery of reusable and recyclable material and has been pioneered by small, local businesses over the past few decades. Communities across the United States including Portland, OR, Milwaukee, WI, and Missoula, MT have adopted ordinances and incentives to promote the practice of deconstruction and to support the local reuse economy.

A Global Movement for Zero Waste

A global movement has emerged in which municipalities, community members, businesses, and institutions are working toward a vision of Zero Waste. Initiated by grassroots activists and codified by the Zero Waste International Alliance (ZWIA), the Zero Waste movement is thriving across the globe. Advocates of Zero Waste are working to address the materials discussed above as well as many other hard-to-recycle materials with a variety of approaches that seek to reduce waste and toxicity and add value to communities.

The ZWIA definition of Zero Waste is the only definition that is peer-reviewed and internationally-accepted and its Zero Waste Declaration centers equity in its vision for a just and inclusive system resulting in a sustainable and regenerative future.[88] On December 14, 2022, the United Nations General Assembly adopted a resolution at its seventy-seventh session to proclaim March 30 as International Day of Zero Waste, to be observed annually.[89]

> *Zero Waste: The conservation of all resources by means of responsible production, consumption, reuse, and recovery of products, packaging, and materials without burning and with no discharges to land, water, or air that threaten the environment or human health."*

CONCLUSION

Consumption Matters

A 2006 study by the Carbon Trust defined consumer purchasing decisions as "the ultimate driver of carbon emissions in an economy" and attributed all carbon emissions to the delivery of products and services to meet consumer demand.[90] Whether the consumer is the United States Armed Forces, the local public school district, or you, our choices matter.

The UN Global Resources Outlook 2019 report concluded that decoupling economic growth from material consumption is essential. Without such decoupling, resource demand will more than double, greenhouse gas emissions will rise by 40 percent, and demand for land will increase by 20 percent.[91]

88. https://zwia.org/zero-waste-definition/ and https://zwia.org/zero-waste-declaration/
89. https://www.un.org/en/observances/zero-waste-day
90. Carbon Trust. (2006).
91. https://www.resourcepanel.org/reports/global-resources-outlook

Our consumption and the energy needed to drive the systems that support it are inextricably linked. At the systemic level, this awareness insists we actively advocate for a faster transition toward decarbonization, smarter urban planning that reduces the demand for concrete, and Zero Waste communities that use fewer materials and maximize reuse, recycling, and composting with a priority on local solutions. On the personal level, we can consume fewer resources and reduce consumption-based emissions by purchasing fewer new products, opting to repair instead of replace, adopting reuse habits in all aspects of our lives, walking, biking, and busing more, taking fewer flights, making dietary changes to reduce the need for animal agriculture and cutting wasted food.. We can support the systems that align with the Climate North Star such as local reuse, repair, recycling, and composting programs, walk/bike infrastructure and public transportation, and local agriculture all while adopting the emerging ethos of conscious consumerism.[92]

A New Frugality

Bearing all of the above in mind, we must focus our thinking on the role of consumption and waste and their impact on the climate in the context of our individual wealth. One way to begin is by examining how and what we consume. Is it possible to view some acts of consumption as essential and others as non-essential? We think it is. We consider modest shelter, healthy food, appropriate clothing, and sensible means of transportation as essential consumption. Those are the fundamental elements that together support our individual health and well being. Using this lens can provide insight into patterns of consumption that do not play a direct role in supporting our health and well being. Examples may include leisure travel, alcohol and tobacco consumption, miscellaneous household and recreation equipment, audio/visual equipment, and personal care products, to name a few. We may discover personal consumption choices that, when seen through this lens and when linked to the health of the climate, we find frivolous and unnecessary or possibly harmful to us.

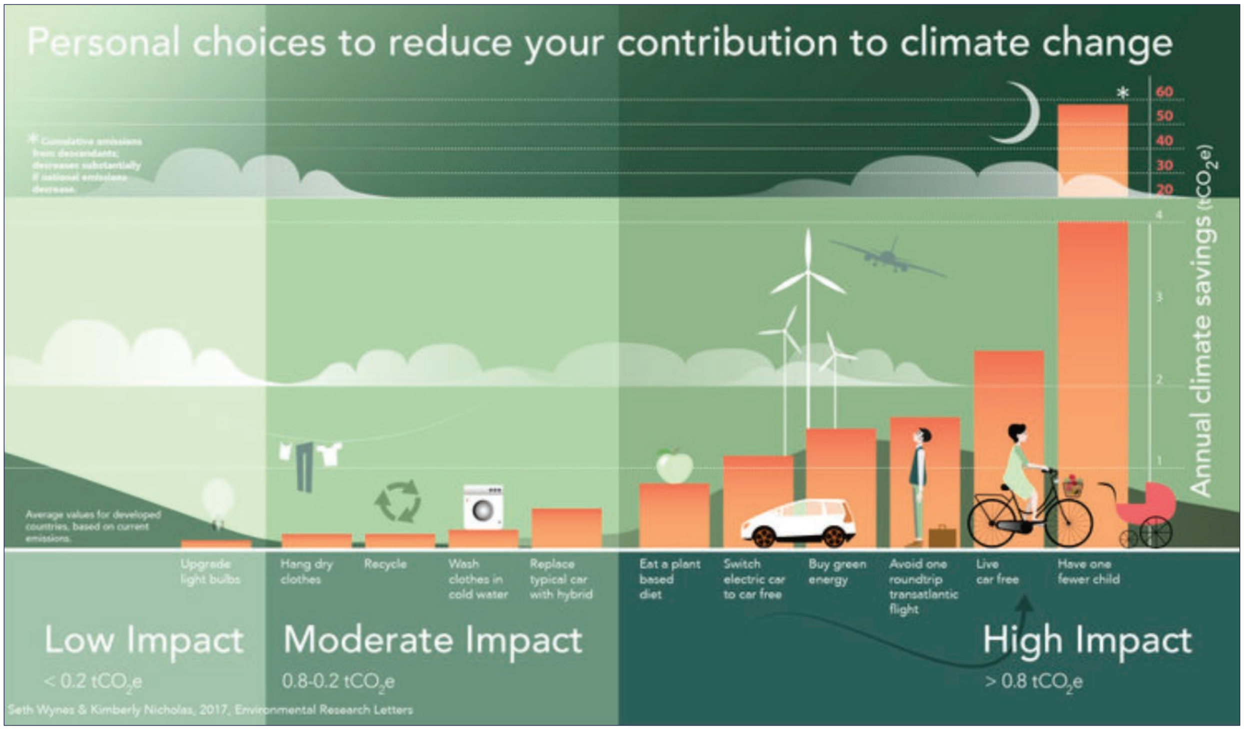
We know that consumption is linked to energy use. If we start reducing non-essential consumption, or approaching our consumption with more modesty, we can begin to celebrate a new frugality that will help to lead us away from climate disaster. We can consider this notion as we begin to assess what it is we really need to support a healthy, fulfilling life for ourselves and our loved ones.

As noted earlier, reducing lifestyle-based energy use will act as a carbon reduction accelerator as we work toward the 2035 global decarbonization deadline. This is the period of time where our day-to-day choices matter most. The good news is there is an abundance of choices we can make to reduce carbon emissions in our lives. No matter where you are on your personal journey of decarbonization, dear reader, there is something you can do. Start small by washing clothes in cold water or eating one meatless meal a week. Try composting. Or go big by making your next vehicle an EV or, better yet, choosing to go car-free and bike, walk, or bus. If you are a homeowner and have the resources to do so, install an electric heat pump to heat and cool your home powered by rooftop solar panels. If you

92. https://www.theconsumergoodsforum.com/blog/2021/10/04/conscious-consumerism-is-transforming-industries/

have the capacity to invest in a decarbonized future, do it. The ROI is a liveable climate, which we all know is priceless. Regardless of what you do, each and every choice each of us makes adds up. Figure 11 includes a few more of the many ideas for taking real action to save our climate.

Figure 11. Personal Choices to Reduce Your Contribution to Climate Change (Credit: earth-changers.com)



Political Engagement: a Moral Imperative

As has been discussed, lifestyle-based carbon emissions are those over which each of us has the agency to reduce through the decisions we make in our day-to-day lives. The 83 percent of Americans who are among the world's wealthiest citizens can—and must—begin evaluating our lifestyle-based energy use immediately and taking steps to reduce them and the associated carbon emissions. However, in the context of the 100-gj/a per person target, lifestyle-based energy use accounts for only about half of total energy use and therefore only about half of carbon emissions. The other half of carbon emissions are due to the energy demands of commerce and industry and the systems that support our consumption habits. Instead of just standing by and hoping that politicians and industry will make the systemic changes necessary to avoid climate disaster, it is our civic duty to compel them to do so.

As the devastation of the climate crisis continues to render our forests to ash, our lakes to deserts, and our islands to memories, there must come a moment when we ask ourselves: How much longer can we bear to cooperate with the current system? What can we do to compel society to adopt proven climate change solutions before it is too late? What are we willing to do—how many Netflix nights are we willing to sacrifice—to secure a liveable climate? Considering the stakes, political engagement becomes a moral imperative. We must support each other to elevate one another into the social space of activism so that our collective voices can amplify our message and multiply our impact.

A Very Personal Choice

The shifts in personal behavior described here will challenge us. The cultural headwinds are strong. The momentum of our consumption and waste generation is supported by decades of practice and promotion from all sectors of society. The entrenched power that supports our reliance on fossil fuels is mighty.

However, it is through our personal choices—from cultivating frugality, to choosing what we buy, to deciding how we spend our free time—that we can flex our power. Person by person, household by household, community by community, we can shift toward the Climate North Star and save our future. Whether we solve the climate crisis or succumb to it is up to us. It is ultimately a personal choice and the most exciting challenge we will ever face.

Figure 12. Lifestyle-Based Energy Use Reduction Targets (in USD per adult)*

POPULATION CATEGORY	ANNUAL INCOME	REDUCTION REQUIREMENT
Global One Percent	$173,500+	80-99% reduction by 2035
Wealthiest 10 Percent	$52,100 to $173,499	50-80% reduction by 2035
Middle 40 Percent	$9,400 to $52,099	20-50% reduction by 2035
Poorest 50 Percent	under $9,400	no reduction; can increase energy use until 2035

*based on income data from World Inequality Report 2022

CITATIONS

Chancel, Lucas, and Piketty, Thomas. (2015). Carbon and inequality: from Kyoto to Paris Trends in the global inequality of carbon emissions (1998-2013) & prospects for an equitable adaptation fund. Paris School of Economics.

Carbon Trust. (2006). https://www.carbontrust.com/resources/the-carbon-emissions-generated-in-all-that-we-consume

Davis, S.J., and K. Caldeira. (2010). Consumption-based accounting of CO2 emissions.

PNAS March 23, 2010 107 (12) 5687-5692; https://doi.org/10.1073/pnas.0906974107

Druckman, A., and T. Jackson. (2010). The bare necessities: How much household carbon do we really need? Ecological Economics 69, 1794-1804. [from Sager working paper]

Druckman, Angela & Jackson, Tim. (2016). Understanding Households as Drivers of Carbon Emissions. 10.1007/978-3-319-20571-7_9.

Goldstein, B., Gounaridi, D., and Newell, J. P. (2020). The carbon footprint of household energy use in the United States. Proceedings of the National Academy of Sciences.

Kaza, Silpa; Yao, Lisa C.; Bhada-Tata, Perinaz; Van Woerden, Frank. 2018. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development;. © Washington, DC: World Bank. http://hdl.handle.net/10986/30317 License: CC BY 3.0 IGO.

Peters, G. P., Davis, S. J., and Andrew, R. (2012). A synthesis of carbon in international trade, Biogeosciences, 9, 3247–3276, https://doi.org/10.5194/bg-9-3247-2012

Pollan, Michael. (2008). In defense of food : an eater's manifesto. New York :Penguin Press.

Sager, Lutz. (2017). Income inequality and carbon consumption: evidence from environmental Engel curves. GRI Working Papers 285, Grantham Research Institute on Climate Change and the Environment. [Published as Sager, Lutz (2019). Income inequality and carbon consumption: Evidence from Environmental Engel curves. Energy Economics, Elsevier, vol. 84(S1).]

Weber, C., and H. Matthews. (2008). Quantifying the global and distributional aspects of American household carbon footprint. Ecological Economics 66, 379-391. [from Sager working paper]

Climate North Star Synthesis Impacts

SCOTT DENNING

CLIMATE NORTH STAR IMPACT ON CARBON EMISSIONS, ATMOSPHERIC CO_2 LEVELS, GLOBAL TEMPERATURE AND SEA LEVEL RISE

The Climate North Star (CNS) scenarios outlined in previous sections envision exactly the kind of action called for by climate scientists. We call for rapid decarbonization of energy and a global transformation of forest and agricultural land management to focus on carbon sequestration.

As explained above, we call for emissions from fossil fuel combustion to fall from 9.9 GtC/yr in 2019 to zero in 2035. Furthermore, we call for elimination of carbon emissions from deforestation and forest degradation, avoiding about 97 GtC in land-use emissions over the next 75 years. Forest carbon management would consist of an ambitious program of carbon sequestration by afforestation (120 GtC), reforestation (55 GtC), and proforestation (42 GtC). Forest management would therefore sequester a total of 217 GtC in forests by 2100. Finally, we recommend changes in agricultural practices which sequester carbon via improved soil and crop management. These practices are estimated to sequester a net of 24 GtC over 100 years.

Here we estimate the trajectory of future climate change and sea level rise that would result from implementation of our emission scenarios beginning immediately after 2022.

ASSUMPTIONS

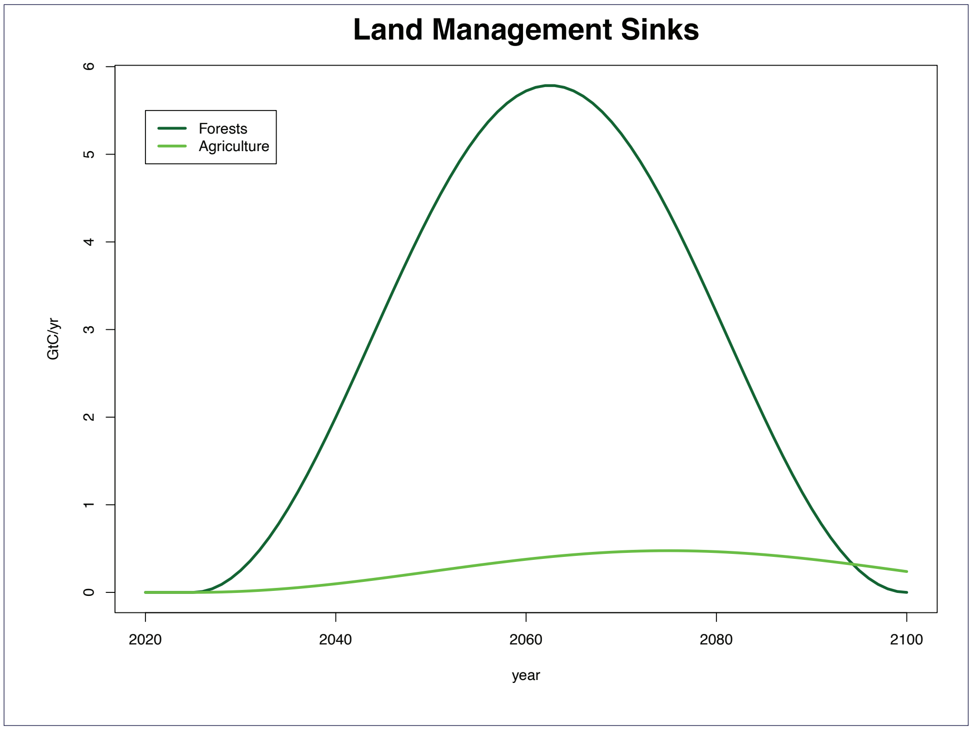
FOSSIL FUEL EMISSIONS

We use fossil fuel emissions from the 2021 Global Carbon Budget (Friedlingstein et al 2021), updated to 2022 using estimates from Liu et al (2022). We then use a linear ramp of emissions to zero in 2035. All non-CO2 greenhouse gases are included in that number (as CO2 equivalents using the appropriate Global Warming Potentials).

AGRICULTURE AND FORESTRY

Deforestation and other land-use emissions are assumed to decline on a linear ramp from the current 0.88 GtC/yr (Friedlingstein et al 2022) to zero in 2030. From 2025 to 2100, global agriculture and forests are assumed to sequester carbon due to management changes described in previous sections above. During this period, carbon sinks accelerate as forests and soils grow and soils accumulate more and more carbon. We assume that the time trajectory of these land management sinks rises and then falls gradually as indicated in Figure 1. Carbon sequestration reaches a maximum rate in the 2060s and then declines as forest maturation and decomposition once again balance growth.

Figure 1: Time trajectory of Climate North Star Land Management Carbon Sinks due to improved forest and agricultural practices



RESULTS

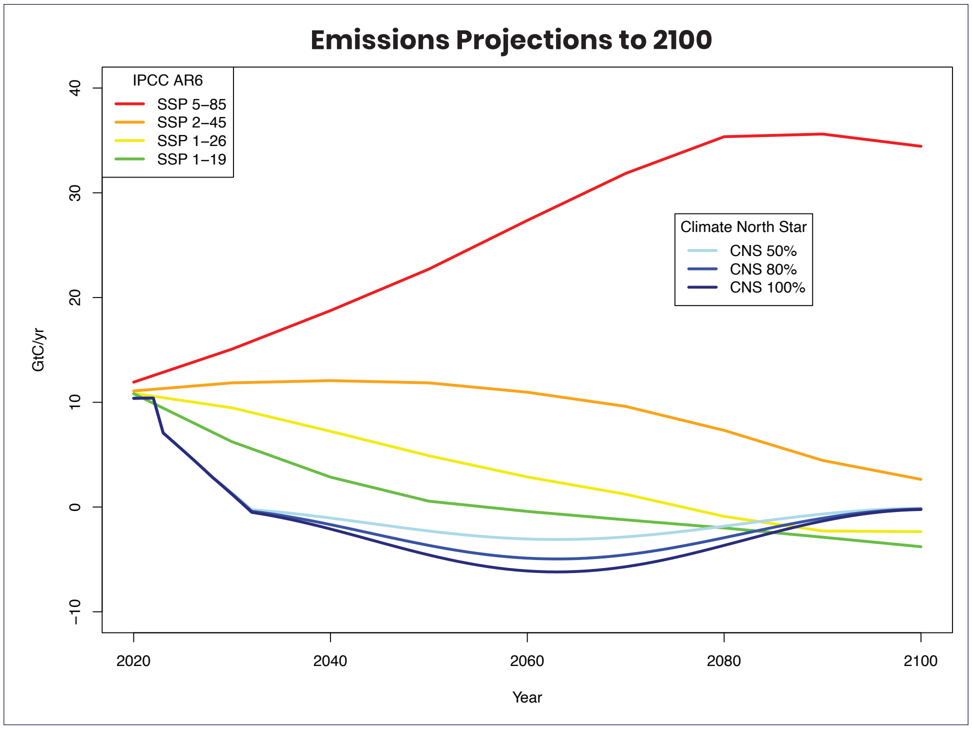
TOTAL CARBON EMISSIONS

Combining emissions from both fossil fuels and land use with our projections of sequestration by forest and agricultural management, the total Climate North Star carbon emissions are compared in Figure 2 with several emission scenarios used in the Climate Model Intercomparison Project version 6 (CMIP6) by the Intergovernmental Panel on Climate Change (IPCC) as described in the recently released Sixth Assessment Report (AR6, 2022). For CMIP6, social scientists developed emission scenarios called Shared Socioeconomic Pathways (SSPs) using Integrated Assessment Models which considered population, demographics, trade, technology, and policy (Gidden et al, 2019). The SSP scenarios are labeled with two numbers: the first denotes warming (Celsius) and the second denotes radiative climate forcing (Watts per square meter), both in 2100 relative to preindustrial conditions. For example, SSP1-26 projects emissions consistent with 1 Celsius of warming resulting from 2.6 Watts per square meter of radiative forcing in 2100. By contrast SSP5-85 includes emissions consistent with 5 Celsius of warming and 8.5 Watts per square meter of radiative forcing in 2100. The CMIP6 scenarios which limit warming to less than 1.5 Celsius achieve this by including large amounts of highly problematic industrial carbon capture and storage (CCS) technologies to draw down CO_2 concentrations.

The CNS scenario envisions substantially lower CO_2 emissions over the next several decades than even the most aggressive scenario considered by IPCC (SSP-1-19). Our scenario achieves zero emissions in 2035, followed by negative emissions through 2100. The IPCC AR6 scenarios rely on increasing deployments of biomass energy with CCS (BECCS) throughout the century whereas the CNS scenario achieves larger amounts of negative emissions in the 2020s and 2030s through land management for carbon sequestration. As these forest and agricultural soil carbon sinks mature in the late 21st Century, the CNS sinks saturate, and the artificial sinks envisioned by IPCC authors overtake them in the 2080s.

We consider three CNS emissions scenarios: one in which all recommendations described in the previous chapters are adopted (labeled CNS 100%), and two others in which only 80% and 50% of the recommended changes occur (labeled CNS 80% and CNS 50%). Positive emissions from fossil fuel combustion, deforestation, and agriculture are rapidly ramped down to zero in all three CNS scenarios, but the CNS land management sinks diverge after 2035.

Figure 2: Total Carbon Emissions in Climate North Star and selected IPCC SSP scenarios



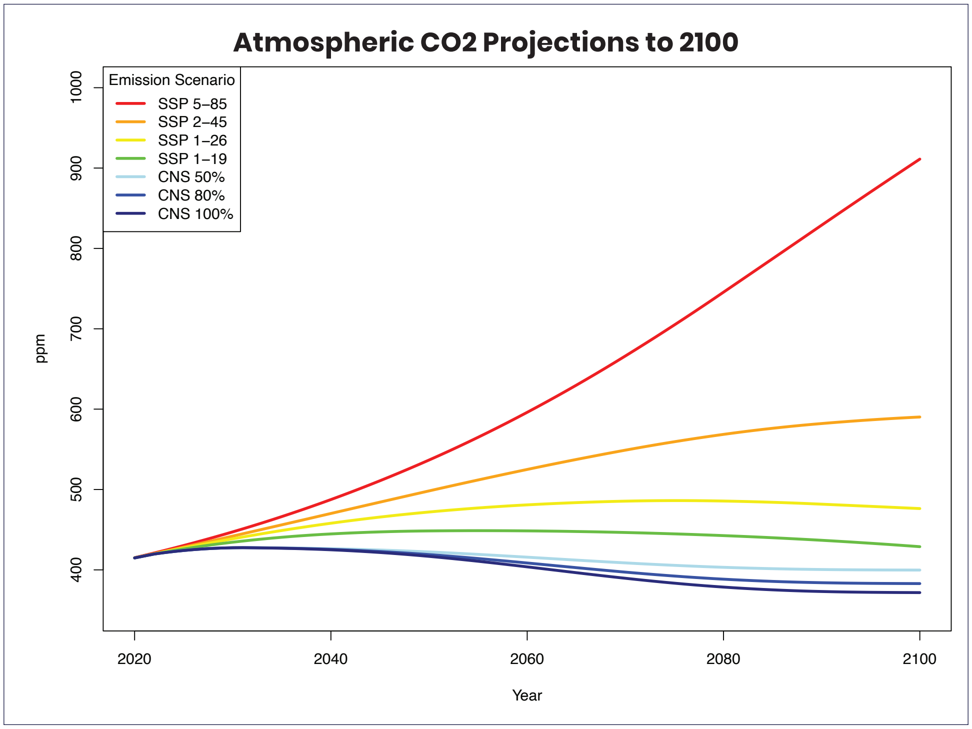
NATURAL CARBON SINKS

Carbon sinks in the oceans and land ecosystems have sequestered about 50% of net CO_2 emissions since the beginning of the modern instrument record in the 1950s (Denning, 2022). It has been surprising to many carbon cycle scientists that the net uptake of carbon by these sink processes has scaled almost perfectly with CO_2 emissions for many decades even as emissions have quadrupled.

As a baseline, we assume that the sinks will continue to offset exactly half of global CO_2 emissions for the rest of this century. Note that this assumption means that negative emissions will also be offset by a factor of 50% as previously sequestered carbon "leaks back out" of storage pools in plants, soils, and seawater.

We assume that carbon sinks are independent of both CO_2 and temperature – that is, we assume no carbon-climate feedback.

Figure 3: Projected CO_2 concentration in the atmosphere for each emission scenario plotted in Fig 2. SSP scenarios use the Shared Socioeconomic Pathways of IPCC CMIP6.



ATMOSPHERIC CO_2

Each GtC of net carbon emissions is diluted into the mass of the global atmosphere to produce 0.47 ppmv net change in CO_2 concentration (Denning 2017). Using this scaling and assuming that natural carbon cycles in the ocean and biosphere continue to absorb 50% of emissions, we project atmospheric CO_2 concentrations for each emission scenario described above (Figure 3).

Projected CO_2 concentration in all the CNS scenarios is less than even the most aggressive CMIP6 scenarios in every year. Projected CO_2 peaks by 2030 (428 ppm) in all CNS scenarios but peaks in the mid 21st Century (449 ppm) under SSP-1-19 and around 2075 (486 ppm) for SSP-1-26. In 2100, projected CO_2 ranges from 911 ppm under SSP5-85 down to 372 ppm under CNS 100%. In the higher SSP scenarios, atmospheric CO_2 concentrations are projected to continue rising well beyond 2100.

GLOBAL MEAN SURFACE TEMPERATURE

We estimate global mean surface air temperature using the Transient Climate Response to (cumulative) Emissions (TCRE; MacDougall, 2016). The logarithmic (saturating) response of radiative climate forcing by greenhouse gasses is very closely compensated by the increasing sensitivity of atmospheric CO_2 to emissions as natural sinks saturate. This fortuitous cancellation is observed in virtually all comprehensive Earth System Models which simultaneously project biogeochemical sinks, greenhouse gas concentrations and warming (Matthews et al, 2021). Furthermore, the time lags associated with thermal inertia in the surface ocean are compensated by changing atmospheric conditions so that temperature changes are well predicted by contemporaneous emissions.

According to the TCRE framework, the change in global mean surface air temperature relative to preindustrial conditions can be simply calculated from

$$\Delta T = TCRE\, \Sigma E$$

where ΔT is in Celsius (or equivalently Kelvin), ΣE is the cumulative global fossil fuel emissions since $\Delta T = 0$ (1750), and TCRE is about 2.0 Celsius per 1000 GtC of cumulative emissions. Based on the Global Carbon Budget (Friedlingstein et al, 2022), cumulative historical emissions from 1750 to 2020 were ΣE_{2020} = 675 GtC.

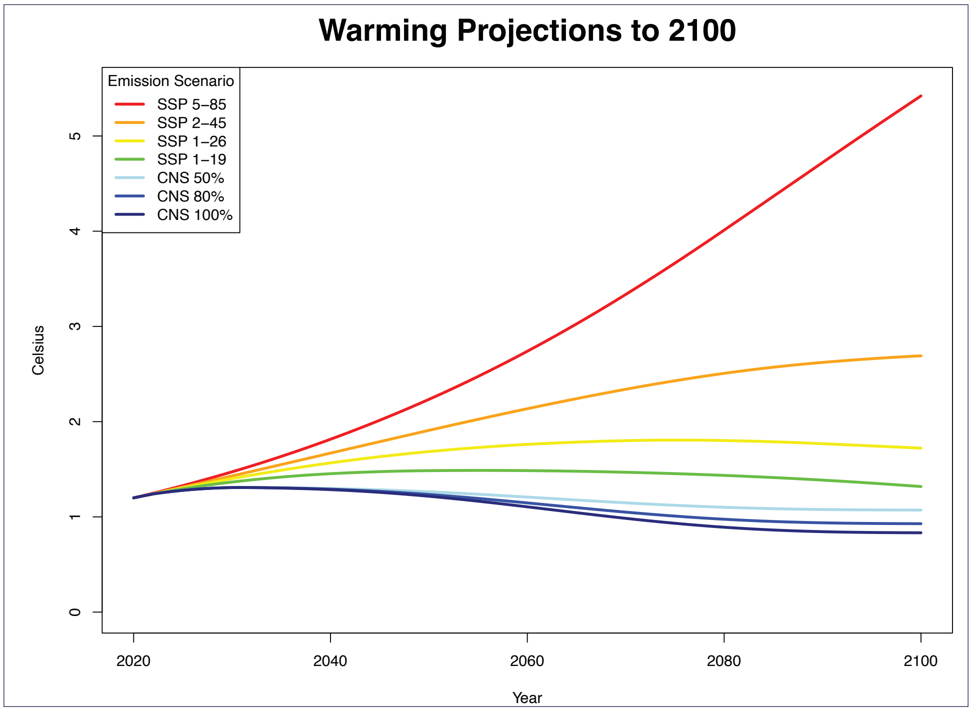
There are three key science and policy implications of the TCRE framework:

1. Every kg of carbon ever burned anywhere contributes the same amount of warming;
2. Warming stops when carbon burning stops; and
3. Cooling in response to negative emissions is identical to warming for positive emissions.

We projected global warming through the end of the 21st Century for all the emission scenarios shown above and present the results in Figure 4. As expected, the IPCC CMIP6 scenarios range from extreme warming (more than 5 C and rising fast in 2100 for SSP5-85) to successful limitation of warming to less than 1.5 C above preindustrial (around 1.3 C and falling for SSP1-19).

The CNS scenarios project less warming than even the most aggressive emission cuts envisioned in CMIP6 even though the artificial negative emissions in SSP1-19 are greater than the land management sinks in CNS 100% by 2100. That's due to the early aggressive cuts in CNS 100 and emphasizes the benefits of early action to prevent warming rather than overshooting and attempting to clean up our mess later. Warming in all three CNS scenarios peaks about 2030 (at 1.3 Celsius) and falls to 1.0, 0.9, and 0.8 C by 2100.

Figure 4: Projected change in global mean surface air temperature (relative to 1750) for Climate North Star and selected IPCC SSP scenarios



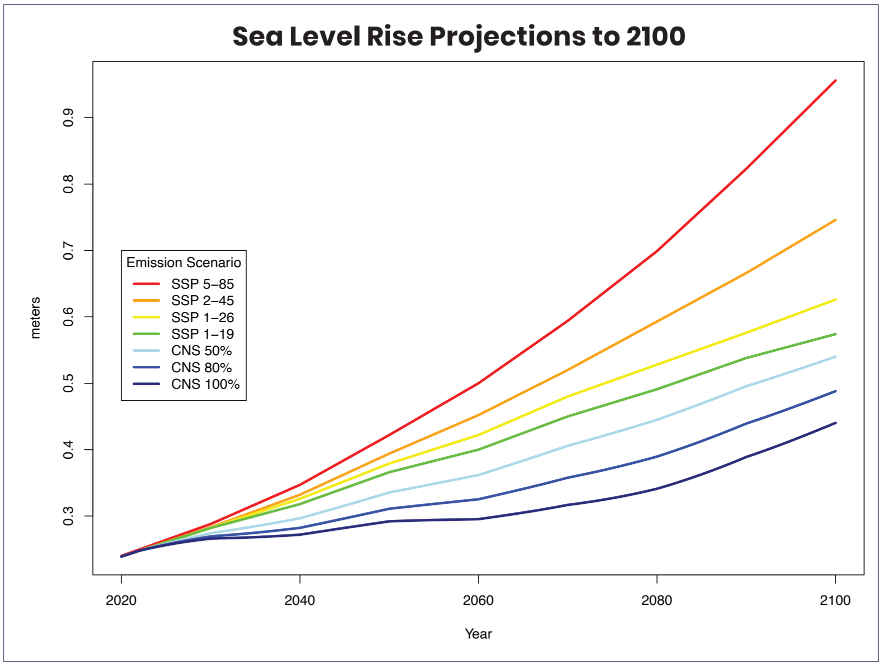
SEA LEVEL RISE

Sea level rise is extremely difficult to predict because over decades and centuries it is dominated by the three-dimensional behavior of flowing ice within continental ice sheets in Greenland and Antarctica. This has consistently been a problem with climate assessments such as IPCC and the US National Climate Assessment.

We use CMIP6 simulations of sea level rise (SLR) projected to 2100 in IPCC AR6 using the emission scenarios presented above and adjust them for the reduced emissions in the CNS scenarios. We adjusted the AR6 numbers to a baseline of global mean sea level in 1880 using data compiled by the US Environmental Protection Agency (US EPA, 2021). Median estimates of sea level in 2100 in CMIP6 ranges from 0.57 m in the SSP1-19 scenario to 0.96 m under SSP5-85, relative to a baseline in 1880 (Fox-Kemper et al 2022; Garner et al 2022a,b). The response of SLR to global mean surface air temperature in the full Earth System Models used in CMIP6 is complex, with time lags of decades to perhaps centuries because the polar ice sheets respond slowly to warming. Even though climate is projected to be slowly cooling in 2100 under SSP1-19, sea level is projected to continue rising.

We used multiple linear regression of SLR against both time and warming in the lowest two CMIP6 scenarios to isolate the warming response separate from the time trend. We obtained a temperature coefficient of 0.275 m per degree C from this linear model and applied this coefficient to each of the CNS scenarios by simply adjusting the projected SLR in SSP1-19 downward according to the reduced warming in each scenario. This approach preserves the time trend of the lowest CMIP6 scenario but accounts for the cooler projected climate.

Figure 5: Projected change in global mean sea level relative to 1850 for Climate North Star and selected IPCC SSP scenarios



Our calculations show substantially less SLR under the CNS scenarios than even the most aggressive CMIP6 scenarios. Under SSP1-19, SLR is projected to be 0.57 m in 2100 while the CNS 100% scenario projects SLR of just 0.44 m above 1880 conditions by the end of the century.

Over the very long run atmospheric CO_2, temperatures, and sea levels will fall once more as the deep ocean equilibrates and rock weathering returns the Earth system to balance. The larger the total historical release of fossil carbon by combustion, the longer this is projected to take. Recovery to preindustrial conditions is likely to take a few centuries for the CNS and lowest IPCC SSP scenarios, versus many millennia for the higher SSP scenarios (Archer et al 2009).

Projecting sea levels over these longer time scales is notoriously difficult because the behavior of ice sheets in Greenland and Antarctica is subject to huge uncertainties and tipping points. The rate of melting of these ice sheets depends less on current temperatures than it does on historical warming since the industrial revolution. Nevertheless, the sooner CO2 emissions cease, and temperatures stabilize and decline, the less likely is a catastrophic collapse of the ice sheets. In the long run, adopting aggressive emissions targets as proposed here can be seen as insurance against the worst possible outcomes of rising seas.

Archer, D. et al. (2009), Atmospheric Lifetime of Fossil Fuel Carbon Dioxide, Annu. Rev. Earth Planet. Sci., 37, 117–134, doi:10.1146/annurev.earth.031208.100206.

Denning, A. S., 2017. Combustion to Concentration to Warming: What Do Climate Targets Mean for Emissions? Climate Change and the Global Carbon Cycle. In Encyclopedia of the Anthropocene, Elsevier. 11pp.

Denning, A. S., 2022. Where Has all the Carbon Gone? Ann. Rev. Earth Planet. Sci., 50, https://doi.org/10.1146/annurev-earth-032320-092010

Fox-Kemper, B., H. T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S. S. Drijfhout, T. L. Edwards, N. R. Golledge, M. Hemer, R. E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I. S. Nurhati, L. Ruiz, J-B. Sallée, A. B. A. Slangen, Y. Yu, 2022, Ocean, Cryosphere and Sea Level Change. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In press.

Friedlingstein P O'Sullivan M Jones MW Andrew RM Hauck J et al, 2021. Global Carbon Budget 2020. Earth Syst. Sci. Data, 12: 3269–3340.

Garner, G. G., R. E. Kopp, T. Hermans, A. B. A. Slangen, G. Koubbe, M. Turilli, S. Jha, T. L. Edwards, A. Levermann, S. Nowikci, M. D. Palmer, C. Smith, in prep. Framework for Assessing Changes To Sea-level (FACTS). Geoscientific Model Development.

Garner, G. G., T. Hermans, R. E. Kopp, A. B. A. Slangen, T. L. Edwards, A. Levermann, S. Nowikci, M. D. Palmer, C. Smith, B. Fox-Kemper, H. T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S. S. Drijfhout, T. L. Edwards, N. R. Golledge, M. Hemer, R. E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I. S. Nurhati, L. Ruiz, J-B. Sallée, Y. Yu, L. Hua, T. Palmer, B. Pearson, 2021. IPCC AR6 Sea-Level Rise Projections. Version 20210809. PO.DAAC, CA, USA. Dataset accessed [2022-05-23] at https://podaac.jpl.nasa.gov/announcements/2021-08-09-Sea-level-projections-from-the-IPCC-6th-Assessment-Report

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press.

Liu Z Deng Z Davis S J Giron C and Ciais P, 2022. Monitoring global carbon emissions in 2021. Nature Reviews, 3: 217-219.

MacDougall A H, 2016. The transient response to cumulative CO2 emissions: a review. Curr Clim. Change Rep. 2: 39–47. DOI 10.1007/s40641-015-0030-6.

Matthews H. D. Tokarska K. B. Rogelj, J. Smith C. J. MacDougall A. H. et al, 2021. Nature Communications 2: 7. https://doi.org/10.1038/s43247-020-00064-9

US EPA, 2021. Digital data on mean global sea level, downloaded 2022-05-23 from https://www.epa.gov/sites/default/files/2021-04/sea-level_fig-1.csv

continued from page 19...

Most importantly I am inserting this into the paper you're reading so that every single person working to advance the Climate North Star (CNS) proposal cannot look back and say "I didn't know any better."

For decades, scientists have been talking about the need to reduce carbon dioxide emissions and other planet-warming greenhouse gasses because of the future harm they could cause. At the same time, communities located closest to the pollution of those gasses – and living with the harms they already cause on a daily basis – have been organizing to stop them at the source. Unfortunately, throughout this time, there have often been disconnects between these two groups, and the mainstream environmental organizations that often act as proxies for the findings of climate and environmental scientists. Throughout this tumultuous history, this rift has manifested in anything ranging from a lack of consultation with impacted communities while developing conservation projects, all the way to advancing local, regional, and even global policies that, while calculated to be politically expedient in attempts to "save" the environment, actually perpetuate harm to people and allow for continued pollution. This was apparent in the celebrations coming from the mainstream environmental movement about the Inflation Reduction Act, which stayed relatively quiet about billions of dollars in subsidies and incentives promised to the fossil fuel industry and other technologies that either continue harm, are unproven, or both – things like industrial carbon capture and storage.[1]

Given the fact that mainstream environmentalism and academia – including organizations and universities founded by profound white supremacists – have well-documented histories entrenched in white "supremacy," colonization, patriarchy, and extractive capitalism, it comes as no surprise that these groups have a difficult time working with and being trusted by the Black, Indigenous, People of Color (BIPOC) and low-income communities who have been most impacted by the issues they are trying to solve.

The Environmental Justice movement's origins come from the 1982 Warren County protest against the placing of a toxic landfill in a majority Black and low-income area in rural North Carolina, where "[o]ld-time civil rights organizers...converged on the area, using old- time protest tactics to make their point"[2]. This moment was the genesis for the 1987 report Toxic Wastes and Race, a groundbreaking study from the United Church of Christ Commission for Racial Justice, that found "race to be the most potent variable in predicting where commercial hazardous waste facilities were located in the U.S."[3]. Seeing Civil Rights leaders at this protest makes sense since fourteen years earlier the movement, including Martin Luther King Jr., was working with Black sanitation workers in Memphis who were exposed to hazardous conditions while making less money.

Seventy years before that, the United State's saw the beginning of it's conservation movement – the bedrock of modern day environmentalism – with founders who openly advocated for the forced sterilization of BIPOC folks, removal of Native Americans from their traditional lands to create National

1. The world's first CO2 pipeline explosion in Yazoo County Mississippi in 2020 – hospitalizing 49 people – is a somber reminder of what will happen more often if the federal government, mainstream environmentalist, and fossil fuel companies get what they want with large scale carbon capture and sequestration (CCS) that some predict would increase the current CO2 pipeline system from 5,000 miles to rival the country's 2.6 million mile petroleum pipeline network. - Zegart, Dan. 2021, August 26. The Gassing of Satartia. Huff Post. https://www.huffpost.com/entry/gassing-satartia-mississippi-co2-pipeline_n_60ddea9fe4b0ddef8b0ddc8f?utm_campaign=Hot%20News&utm_medium=email&_hsmi=153322060&_hsenc=p2ANqtz-_0PgWu1PXbMIW 1k44UGeww vwQjS2_5mDuuhSIoiw6dgmJk4CV1pYckMTED5h-RYoqqFT8BPpwy1IhmKb2uCNX66bZ2hw&utm_content=153322060&utm_source=hs_email

2. 1982, October 12. Dumping on the Poor. The Washington Post. https://www.washingtonpost.com/archive/politics/1982/10/12/dumping-on-the-poor/bb5c9b8c-528a-45b0-bd10-874da288cd59/

3. Bullard et al. 2007. Toxic Wastes and Race at Twenty, pg. X. https://www.ejnet.org/ej/twart.pdf

Parks, and actively excluded BIPOC people from their membership and activities. As an editorial stated in the Washington Post about the Warren County protest, "we can celebrate the marriage of civil rights activism with environmental concerns," continuing on to reflect that, "it is good to see a broadening of the traditionally white, upper-middle-class environmental movement"[4].

These complex and intertwined histories have forced the Environmental Justice movement to hold governments, polluters, and mainstream environmental organizations all accountable for their harmful, extractive practices. While harm perpetrated by governments and polluters is well understood and reiterating it here won't serve our purpose, unfortunately the issues caused by mainstream environmentalism in frontline communities is much less known. Fortunately for those hoping to learn from the past, communities working to advance Environmental Justice have a long practice of public accountability through publishing open letters dating back to 1990. That's when the SWOP Letter was published, with one hundred signers, who pointed out "in the name of eliminating environmental hazards at any cost, across the country industrial and other economic activities which employ us are being shut down, curtailed or prevented while our survival needs and cultures are ignored. We suffer from the end results of these actions, but are never full participants in the decision-making which leads to them."[5,6]

This decades-long struggle of communities on the frontlines of extractive industry to practice self-determination and be supported in advancing their solutions to the problems they face is critically important in considering Climate Justice today; and put in no uncertain terms in the 2009 article *Carbon Fundamentalism vs Climate Justice* by Gopal Dayaneni, who wrote that "without a holistic, integrated approach to the ecological crisis that is grounded in science but predicated on justice and equity, we will simply shift the problem around, make it worse, and further compromise our survival."[7]

In other words, unless our work to address the climate crisis also actively dismantles the power structures, institutions, and cultural norms that got us here in the first place, it will actively perpetuate those very things.

One foundational intellectual abstraction that has helped to get us where we are today, is the scientific and academic attempt at approaching these issues objectively. To be sure, it is tempting to try to turn societal problems into equations, based on quantitative factors; if only we could reduce the amount of greenhouse gasses in the atmosphere then we will solve the problem. But, as the scholar Gloria E. Anzaldúa drills down on the flaw of objectivity in her book *Borderlands/La Frontera: The New Mestiza*: "In trying to become "objective," Western culture made "objects" of things and people when it distanced itself from them, thereby losing "touch" with them. This dichotomy is the root of all violence." And unsurprisingly, we have seen those who are trying to save the world perpetuate violence upon BIPOC and low-income communities time and time again.

I have been asked to consider whether or not the proposal of this paper – that of a maximum speed carbon transition combined with a maximum speed carbon drawdown from transformed agriculture and forestry practices – is consistent with Climate Justice principles. The only reasonable answer I've been able to come to is, it remains to be seen.

4. 1982, October 12. Dumping on the Poor. The Washington Post. https://www.washingtonpost.com/archive/politics/1982/10/12/dumping-on-the-poor/bb5c9b8c-528a-45b0-bd10-874da288cd59/
5. 1990, March 16. SWOP Letter. https://www.ejnet.org/ej/swop.pdf
6. A collection of these letters can be found at: https://climatejusticealliance.org/greens/
7. 2009. Dayaneni. Race, Poverty, and the Environment, pg. 9. https://movementgeneration.org/wp-content/uploads/2014/03/RPE_CarbonFundamentalism_2009.pdf

I'm sure that sentiment will be considered optimistic by many because current efforts at *industrial* carbon capture and sequestration (CCS) through so-called "nature-based solutions" involving agriculture and forestry are simply incompatible with Climate Justice[8]. To expound on this later, I will discuss some of the central principles of the Climate Justice movement and where it stands today. In the meantime, here are a few key points to consider: 1) CS methods alone do not guarantee a reduction of greenhouse gas emissions or extraction of fossil fuels at their source, thereby allowing for continued harm in Frontline communities; 2) the methodologies are being developed in academic and corporate settings with little to no input or guidance, let alone leadership, from those who stand to be most impacted; 3) the methodologies are often tied to carbon offset schemes that perpetuate the extraction and burning of fossils fuels, and prop up the idea that nature can be commodified; 4) at the scale they are most often proposed, they would bolster and further entrench – rather than challenge and dismantle – industrialized, corporate agriculture and forestry that are part of what got us here in the first place.

Reconciling all of this will be an uphill struggle for those who wish to see the ideas laid out in CNS come to fruition.

Setting that contradiction aside, simply put, if the ideas set forth in this paper are adopted by the mainstream and are approached in the same way other attempts to save the planet have been over the last century – with white "supremacy" as its foundation, objectivity its guiding light, and manifest destiny at its core – it is guaranteed that the approach will not be consistent with Climate Justice principles. If, however, the authors of this paper, those of you reading it who represent the scientific consensus on these issues, the people excited to turn these concepts into policies, and other folks who have historically supported mainstream environmentalism (with or without consciously knowing about its negative impacts) are willing to put in the work and dedicate yourselves to approaching this in a way that is in alignment with, informed by, and accountable to the communities who have been most impacted by the issues causing the crises we face, then there's a *chance* we'll be able to look back and say "damn, it looks like we finally got it right."

We'll be looking back at a time when frontline communities were finally empowered and supported in determining their futures by the mainstream. When they had access to adequate financial resources and political power to see all of the bold solutions they were already creating lead us into the future. A time when those with critical scientific knowledge and others with the financial and social capital to make significant change happen, relinquished control of it in service of the people in their own communities who have borne the brunt of extractive industry. A time when people started to recognize that the root causes of the climate crisis – white "supremacy," patriarchy, colonization, and capitalism – are also the root causes of every injustice we face as a people, and every harm inflicted on our natural surroundings. When the people entrenched in mainstream environmentalism finally put all of those EDI workshops and webinars to the test and joined the truly intersectional, trans-local movements that were already getting stuff done.

Then we all worked together and tore down antiquated structures that didn't actually serve us while actively building resilient new communities that serve us all.

8. This should not be confused with practices already happening or being proposed in Frontline communities that reconcile multiple environmental, social, and economic problems while bolstering natural systems such as agroecology and the rematriation of land to indigenous stewardship.

Making sure any work to "save the world" is done with a Climate Justice approach – that is, it's led and driven by people directly and historically impacted by the causes of climate change – is going to take a lot of work, but at this point there is simply no other way. Not only is it the right thing to do from a moral and ethical standpoint, but it is also the most logical and efficacious.

First, it's pretty clear that the approach we've been taking to solve the climate crisis isn't working. We've seen this work unfold in various ways over the years, but it almost always follows the same model. Scientific consensus states that a certain thing needs to be done to avoid the worst case scenario for climate change. The board and executive leadership of mainstream environmental organizations – or worse yet, entirely new ones that are formed to fix the problem – decide that this should be a top priority and create new programmatic focus areas to ensure that the gravity of the situation is disseminated into every community across the world. In order to maintain the power these groups have accumulated, they get really good at navigating the political and economic milieu they occupy. To keep the people with money and power happy, they maintain centrist, neoliberal, and technocratic agendas that lack teeth and are more politically expedient than scientifically founded. With budgets in the hundreds of millions, they are able to develop really captivating communications campaigns that position them as the ones to trust by foundations and individuals alike, leading to them absorbing 99% of all philanthropic dollars aimed at supporting environmental and climate related work (we're talking over a billion dollars a year)[9]. Then they get staff and volunteers to work in communities to advance the agenda that was more often than not determined somewhere far away from the neighborhood this work is actually happening in. It then comes as no surprise that, for decades, these agendas have been out of touch with the actual input or desires of the people in those communities. All the while we have seen global temperatures continue to rise and no actual reduction in emissions. It's a trickle-down social justice approach to saving the world and, just like its namesake, this model is a failure that does more harm than good.

We need to recognize that all around the world communities are hard at work reducing emissions at the source *and* creating alternative community/economic structures to the industries that fueled the problems in the first place. There are plenty of examples of this in recent years. Globally there has been a trend of "developing" countries in the Global South becoming leaders in renewable energy production and investments[10], while many countries in the Global North have insufficient plans to address their contributions to the climate crisis[11]. Here in the United States we have seen Indigenous-led fights that shut down the largest coal power plant in the Western U.S. (burning coal on Navajo Nation while supplying energy to the majority White cities of Las Vegas and Phoenix), and stalled or canceled completion of tar sand pipelines (one of the most polluting fossil fuels). At the same time, a broad coalition came together and won the Portland Clean Energy Fund – a surcharge placed on big-box retailers that creates a pool of capital to be accessed by local projects that advance renewable energy upgrades, infrastructure, jobs, and more. In other parts of the country, there are non-extractive loan funds popping up that allow for local, sustainable projects to receive funding in a way that circulates capital within their community rather than letting it be pulled out by corporations. There was the grass-roots fight to stave off gentrification in the Brooklyn neighborhood of Sunset Park, which helped to stop unwanted development and instead positioned the community to get the port

9. Baptista et al. 2020. Environmental Justice and Philanthropy: Challenges and Opportunities for Alignment. https://static1.squarespace.com/static/5d14dab43967cc000179f3d2/t/5e5e7781cccebf576948d365/1583249295033/EJ+and+Philanthropy+Alignment+MW+and+GS_3.3.20_final.pdf

10. Goodwin. 2018, August 27. The Developing World is Taking Over Renewable Energy. https://sustainablebrands.com/read/cleantech/the-developing-world-is-taking-over-renewable-energy

11. 2021, August 15. "Global Update: Climate target updates slow as science demands action." Climate Action Tracker. https://climateactiontracker.org/publications/global-update-september-2021/

greenlit to host an offshore wind turbine facility, operations, and maintenance hub (and associated jobs) that is going to be key to New York reaching its goal of 70% renewable energy production by 2030, and zero emissions by 2040. While at times these fights have had support from mainstream environmental organizations, they all succeeded because they were led by the communities being impacted and the organizations directly accountable to them.

Another reason doing this work from the ground up should be a priority is that the communities hit first and worst by climate change and pollution are more likely to acknowledge the issues exist in the first place, and have a greater willingness to address them, than those displaced from the problems. According to a 2020 survey, while only 53% of white people think that climate change is a major problem, Latinx, Black, and Asian + Other respondents responded at 68%, 66%, and 74% respectively. White people are also less aware that Black and Latinx communities are at a greater risk of facing pollution, with less than 40% thinking that either population experiences more exposure than the general population[12].

Finally, if those with the most political, economic, and cultural power in this moment – the ones with direct access to political forums, to millions of dollars in assets, to gigantic social media followings, etc. – do not do work to make this change happen with frontline communities centered, they will be perpetuating the problems that got us here in the first place. Otherwise, we may see a transition to a carbon neutral economy in time to “save the planet” but the means of production and vast majority of capital will still be controlled by white people from the global north in a globalized system that sees people and planet as subservient to the economy.

This is a lot of work to be sure, but the beauty is that we already have significant guidance for how to do it in a good way.

There are core documents that lay out the principles of the Climate Justice movement, and its active and adjacent predecessor Environmental Justice, dating back to the 1990s. The 1991 *Principles of Environmental Justice* affirms sixteen agreements, ranging from the need for self-determination to demanding that pollutive practices be stopped, and articulating the innate spiritual connection humans have with Mother Earth[13]. The *Jemez Principles for Democratic Organizing* from 1996 succinctly complement these ideas:

> **Be inclusive**
>
> **Emphasis on bottom-up organizing**
>
> **Let people speak for themselves**
>
> **Work together in solidarity and mutuality**
>
> **Build just relationships among ourselves**
>
> **Commitment to self-transformation**[14]

12. Morning Consult. 2020, October 23. "Results: Differences in Adults' Concern and Perceptions of Climate Threats, Environmental Injustice." https://climateadvocacylab.org/system/files/EDF%20WEACT%20Equity%20Memo_Detroit.pdf
13. 1991. Principles of Environmental Justice. http://www.ejnet.org/ej/principles.html
14. 1996. Jemez Principles for Democratic Organizing. https://www.ejnet.org/ej/jemez.pdf

Given that these principles have existed for nearly thirty years, and they now adorn the websites of most mainstream environmental organizations, it's not that we merely need to be aware of them. We need to practice them. Remember them. Operate by them until they define our interactions. And the only way this is possible is through building deep, trusting relationships. Only then can we be held accountable to these principles, and in turn to the frontline communities already doing the work.

There is also the now frequently-referenced need for a Just Transition. While the term has become a ubiquitous component of the mainstream environmental lexicon, it cannot be ignored that this concept comes directly from labor organizing, including that of atomic workers engaging in the peace movement of the 70s who recognized that nuclear disarmament would, in turn, cost them their jobs. A transition that, while it never came to fruition, bears remarkable similarity to the need to transition from our current fossil-fuel based economy. For that reason, any suggestion of a Just Transition that does not have a focus on ensuring the well-being of workers and their communities is a co-optation of the phrase rather than a true manifestation of the work. Since the term was originally coined in the 1990s by Tony Mazzocchi, a leader of the Oil, Chemical, and Atomic Workers union, it has been incorporated as a central theme within Environmental and Climate Justice. Just Transition Principles have been developed by groups like the Just Transition Alliance, Indigenous Environmental Network, and Climate Justice Alliance. Summed up by Just Transition Alliance on their

webpage *What is Just Transition*, it is "a principle, a process and a practice. The principle of just transition is that a healthy economy and a clean environment can and should co-exist. The process for achieving this vision should be a fair one that should not cost workers or community residents their health, environment, jobs, or economic assets. Any losses should be fairly compensated. The practice of just transition means that the people who are most affected by pollution – the frontline workers and the fenceline communities – should be in the leadership of crafting policy solutions."

Beyond the roots of the movement, we can also look to what communities on the frontlines of Environmental and Climate Justice are calling for today. Quite possibly, one of the most expansive looks into the recent deliberations, desires, and dreams of these communities is the *People's Orientation to the Regenerative Economy*. In response to popular calls for a Green New Deal, it was developed by the United Frontline Table, "a coalition of 16 networks, alliances, coalitions, and their members, with the cooperation of movement support organizations." It is a tool that lays out fourteen planks that provide over eighty policy ideas, that "have been collectively strategized by community organizations and leaders from across multiple frontline and grassroots networks and alliances to ensure that regenerative economic solutions and ecological justice — under a framework that challenges capitalism, white supremacy, and hetero-patriarchy — are core to any and all policies." Five points of intervention are identified, illustrated beautifully as a woman watering a thriving plant surrounded by birds. The seeds of the plant are the narrative – the "story and vision for the world we want and know is possible." Narrative shapes the cultural reality in which we coexist and is crucially important to this work. The water is the organizing that happens on the ground in the community. It is what infuses the seeds with life to grow. It is "the vehicle that moves us from where we are, to where we want to be." It takes both narrative and organizing to see successful policy design and development – the plant. Electoral power and implementation of policy are the fruits the plant bears. Throughout all of this, the birds represent principled struggle through direct action "that create critical connections that lead to critical mass to serve as a reminder that our lawmakers and our systems of governance must always be by and for the people."[15]

The Peoples' Solutions Lens is another helpful tool that helps people to quickly determine if a proposed climate solution that advances CNS is also aligned with Climate Justice. There are four simple questions to answer: Who makes the decisions? Who benefits? What else will this impact? And, how will this build or shift power? This section should have served as an intro to the right answers to those questions, and if you still aren't sure, hopefully you know where to look[16].

> ***As you can see now, I had plenty of good reasons to be apprehensive. But now that I've shared all of this, there's only one thing left for me to say: It is not up to me if Climate North Star is consistent with the principles of Climate Justice – it's up to you.***

15. 2020, June. A People's Orientation to a Regenerative Economy, pg. 10-11. https://climatejusticealliance.org/wp-content/uploads/2020/06/ProtectRepairInvestTransformdoc24s.pdf
16: https://ittakesroots.org/peoples-solutions-lens/

POSTSCRIPT

As this passage brings into sharp relief, the climate crisis is so profoundly unfair, as the wealthy countries that triggered it are much better equipped to contend with its lethal impacts than developing countries.

"…in 2016, my family lived in Zomba, Malawi. Outside our window there was a green tree that, one morning, was suddenly covered with mangoes. For so many in the districts around Zomba that year, mango trees were a lifeline, the fruits boiled hard and green to keep the children from starving. Because that year had been climate change-dry, and the year before there were floods, and now there was hunger.

Most people around Zomba don't drive cars, or throw out plastic, or have refrigerators to run, even when there's electricity to run them. What they do have is religion. And the most religious Christians I have ever met — so few of whom had access to quality education, to climate data or weather.com — told me without pause, or conflict with their deep faith, that global warming had destroyed their crops. They did not say it with anger toward me, an American, who lives in the place that generates the pollution that sends the bad weather their way. It was just a fact of life — and death. For them, climate change wasn't a looming threat. It was a real emergency for them and their children…"

--Nathan Englander, "A Man Set Himself on Fire. We Barely Noticed,"New York Times, April 20, 2018

EPILOGUE

"This world is so beautiful I can hardly believe it exists!"
--Ralph Waldo Emerson

A healthy coral reef. NASA Global Climate Change. Photo credit: Jeremy Cohen, Penn State University.

"The care of the Earth is our most ancient and most worthy, and after all, our most pleasing responsibility..."
--Wendell Berry

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