GLOBAL LIFE CYCLE CARBON EMISSIONS – ESTIMATES AND OUTLOOK

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Global Life Cycle Carbon Emissions – Estimates and Outlook

1. Introduction. "Energy payback" was a hot topic In the early days of solar energy. How long would it take a solar panel to pay back the electricity used to make its solar cells?[i] We understand now that the electricity will be "paid back" within a few months of initial operation. Even so, longer than necessary "carbon payback" periods for solar PV and other clean energy technologies will mean slower and less complete decarbonization.

The World Green Buildings Council and seventy national councils are engaged in quantifying GHG emissions attributable to a building and its lifetime operation. "Operating carbon" emissions of a building are equivalent amounts of CO2 (CO2-eq) emissions resulting from estimated fossil fuel use required for building operation. We can quantify GHG emissions released during manufacturing, transportation, construction and also during end of life phases of building materials and equipment. You will find them referred to as "life cycle carbon," "embodied carbon," [ii] or "embedded carbon." "Upfront carbon," which will be responsible for half of the entire carbon footprint of new construction between now and 2050[iii], refers to emissions that occur before a building product arrives at a construction site.

Life cycle carbon concerns extend beyond the buildings sector. During the energy transition, we will use fossil fuels to produce and deploy a variety of new energy technologies. This will affect the new technologies' life cycle carbon emissions. Ideally, we would choose to use only zero carbon energy to manufacture, install and operate additional zero operating carbon technologies. But supplies of zero carbon energy do not meet demand, progress would be slow, and our carbon debt would only increase. At the other extreme, we could launch crash decarbonization programs, the cost of which might undermine the economic foundations of global energy supply. As we navigate between extremes, life cycle carbon threatens to consume our remaining carbon budget. What sources of life cycle carbon matter most?

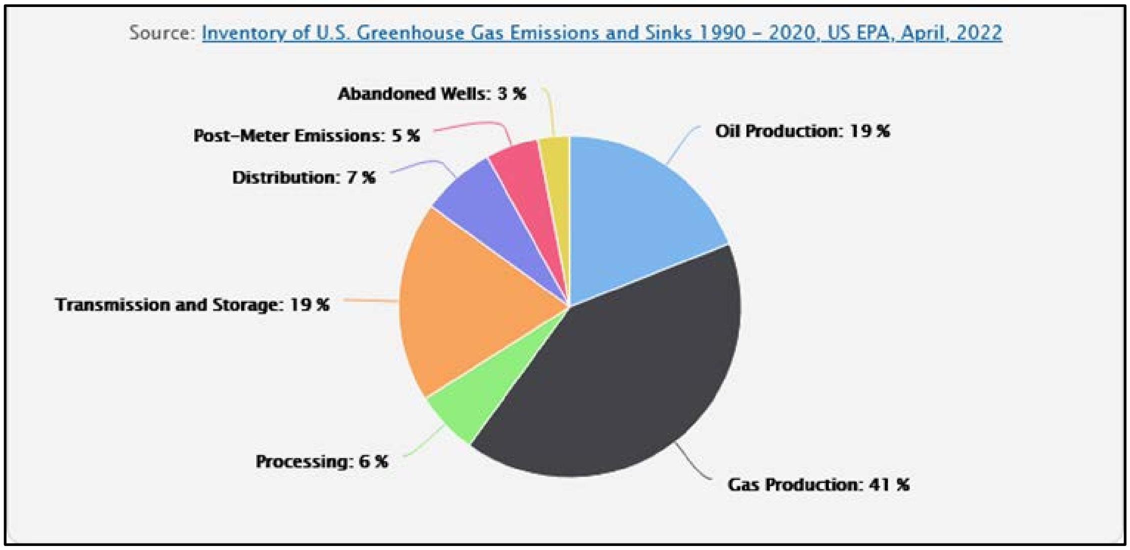

Figure 1. 2020 Oil and Gas Methane Emissions by Segment (~211 million metric tons CO2-eq)[iv]

Fugitive Methane Emissions. Methane is a potent greenhouse gas emitted in multiple ways and responsible for more than 15% of the current global atmospheric GHG inventory. Not all methane from geologic formations, aka "natural" gas, makes it from the gas well to the building or power plant. Figure 1 shows categories of oil and gas methane emissions in the US. A portion of the gas brought up from underground escapes. The US EPA estimates that methane leaks account for as little as 1.4 percent of total production, resulting in about three and a third percent of annual US energy related GHG emissions.[v] Estimates based on direct measurement of methane plumes in the Permian basin suggest leakage amounts seven times higher.[vi]

Industries avoid such "fugitive emissions" if avoidance is cheaper than increasing production. It is their economic impact that matters to producers, not their climate impact. Mitigation would require market interventions which so far have not been politically possible in the US. Fugitive methane emissions illustrate how life cycle carbon can spiral out of control if policy and regulatory attention on energy sector GHG emissions focuses only on "operating" carbon, i.e., emissions from power plants.

2. Renewable Electrification.

What other trade-offs between life cycle carbon and operating carbon will the energy transition entail? Substitution of materials, equipment and low carbon fuels for high carbon fuels is underway in industrial countries and in some economic sectors. Life cycle carbon emissions accompanying substitution are additive to historical and on-going emissions.

Renewable electrification is a key substitution strategy intended to bring operating carbon under control. So, we will need the best possible metrics for life cycle carbon in solar PV systems, in wind power plants, in batteries that store solar and wind electricity, in vehicle batteries charged with renewable electricity, in heat pumps that use renewable electricity for refrigeration, cooling or heating, and in the high global warming potential (GWP) gases[vii] that make renewable electricity enabled heat pumping possible.

Global annual energy-related carbon dioxide emissions rose to 36.3 and 36.8 billion metric tons of CO2-eq in 2021 and 2022.[viii] Life cycle emissions attributable to renewable energy supply and use are of interest because they are increasing rapidly.

Life cycle renewable energy emissions are harder to estimate than life cycle methane emissions because they depend on manufacturing processes, material consumption and energy use, and because relevant data is often proprietary. Life cycle carbon accounting in support of the global energy transition will be important to legislators, regulators, building code writers, architects, energy managers and grid operators as will better information on environmental and economic impacts of mining and manufacturing necessary to low carbon fuel production.

Economically recoverable quantities of certain key materials are hard to forecast. What technology and strategy adjustments may become important? To what extent will life cycle carbon emissions off-set the effect of substituting renewable energy for fossil fuel use? What might cause life cycle carbon emissions to escalate or exceed current estimates? What policies and strategies minimize life cycle carbon emissions? The following sections present preliminary answers.

<u>3. Renewable Electricity Generation.</u> Figure 2 quantifies and compares life cycle emissions of solar, wind and other electricity sources. Solar and wind power are driving early stage decarbonization of the global electricity sector. [ix] What will be the trajectory of life cycle carbon emissions as global solar and wind power fleets expand in future decades?

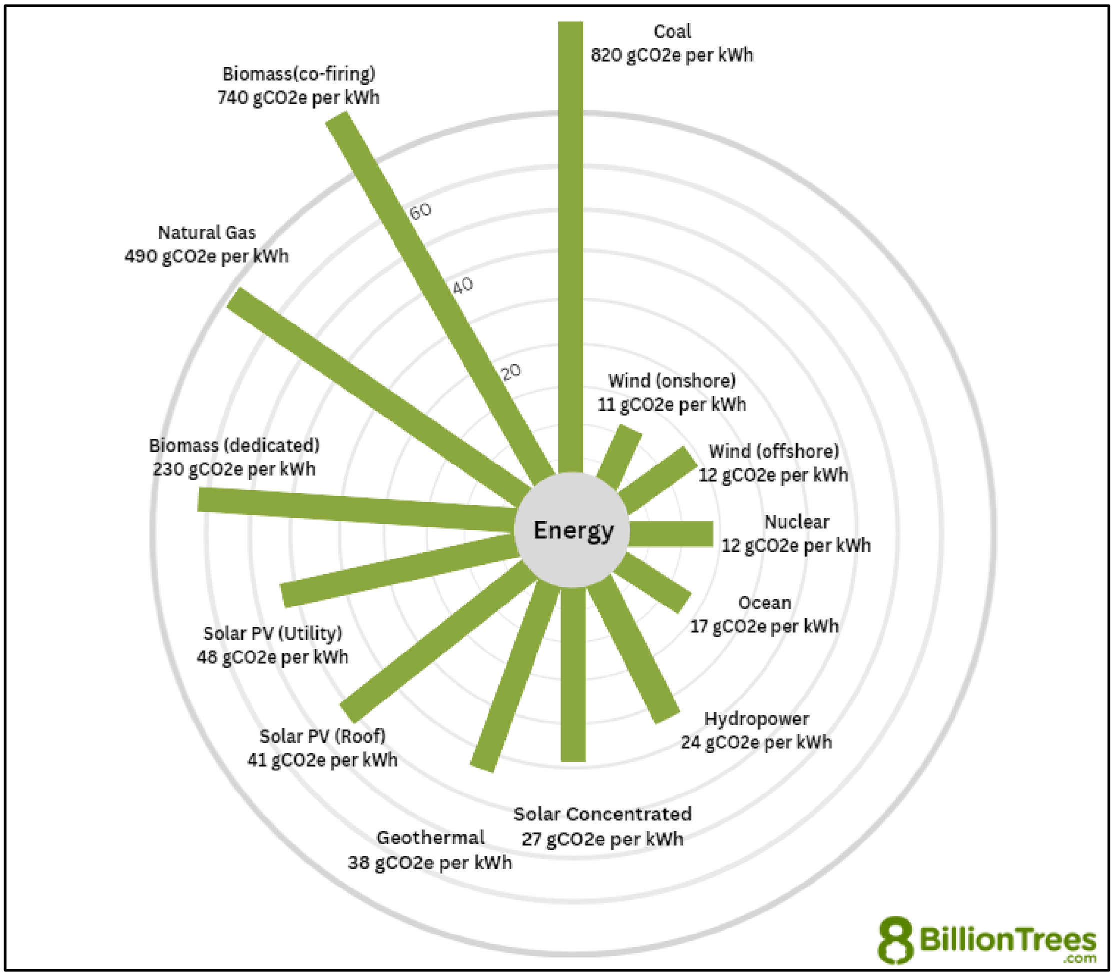

Figure 2. Life Cycle Carbon Emissions by Energy Source

2021 global solar and wind electricity production amounts were 1021 Terawatt hours (TWh)[x] and 1870 TWh[xi] respectively. If these amounts increase to four thousand TWh and five thousand TWh[xii] as forecast, resulting life cycle carbon emissions between 2020 and 2029 will be more than **six billion (metric) tons of CO2-eq**, or about 15 percent of current annual global energy related GHG emissions.

Relative proportions of solar and wind are shifting toward solar, which has four to five times wind's life cycle-emissions per kWh. Offshore wind, which may predominate, has 10 to 20 percent higher life cycle emissions than onshore wind, while rooftop solar PV has 10 to 20 percent lower life cycle emissions than "utility scale" solar PV.

Life cycle carbon emissions will continue as additional wind and solar capacity expands between 2030 and 2050. Wind and solar PV manufacturing will be less dependent on high carbon electricity in the decades beyond 2030, and both wind and solar life cycle emissions will slowly decline based on efficiency and technology improvements. Wind and solar power plants have an expected operating life of twenty to thirty years. Creating a circular global renewable economy by recycling, reusing, remanufacturing or repurposing components and materials can minimize additional life cycle carbon emissions created when new systems replace the old.[xiii] Designing renewable power plants for longer operating lives will also reduce long term life cycle carbon emissions.

Utility scale battery life cycle carbon emissions will increase faster than solar and wind life cycle emissions because the need for longer term storage increases as solar and wind power begin to dominate utility generation portfolios and because batteries have shorter operating lives than power plants. Pairing stationary batteries with rooftop solar for energy resilience purposes and pairing batteries with EV charging stations will increase overall battery life cycle emissions. Overall battery life cycle carbon emissions are off-set to the extent that electric vehicle batteries and rooftop solar paired batteries serve the additional purpose of storing and returning renewable electricity to local grids.

4. Electric Vehicle Batteries. Figure 3 forecasts global electric vehicle battery demand in 2030 that exceeds demand for stationary battery storage and consumer electronics by an order of magnitude.[xiv] Vehicle battery capacities now range between 30 and 200 kWh per vehicle and will average 100 kWh per vehicle in 2030. China, where coal is the dominant energy source, supplies around 80 percent of global EV battery demand.

According to the MIT Climate Portal, "one source of EV emissions is the creation of their (EVs') large lithium-ion batteries. The use of minerals including lithium, cobalt, and nickel, which are crucial for modern EV batteries, requires using fossil fuels to mine those materials and heat them to high temperatures. As a result, building the 80 kWh lithium-ion battery found in a Tesla Model 3 creates between 2.5 and 16 metric tons of CO2 (exactly how much depends on the energy source used to do the heating). This intensive battery manufacturing means that building a new EV can produce around 80% more emissions than building a comparable gas-powered car."[xv]

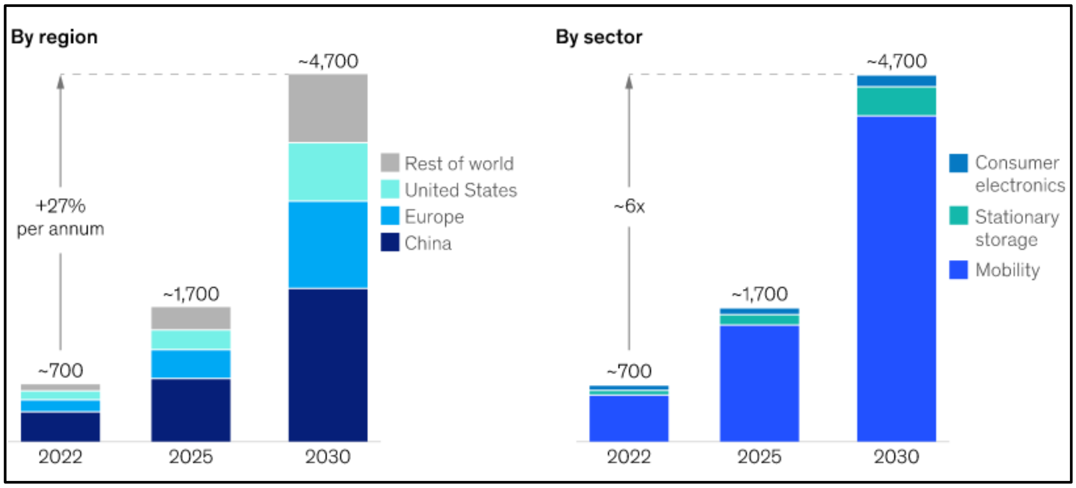

Figure 3. Annual Global Li-ion Battery Demand Forecast (GWh) – Base Case. Source: McKinsey

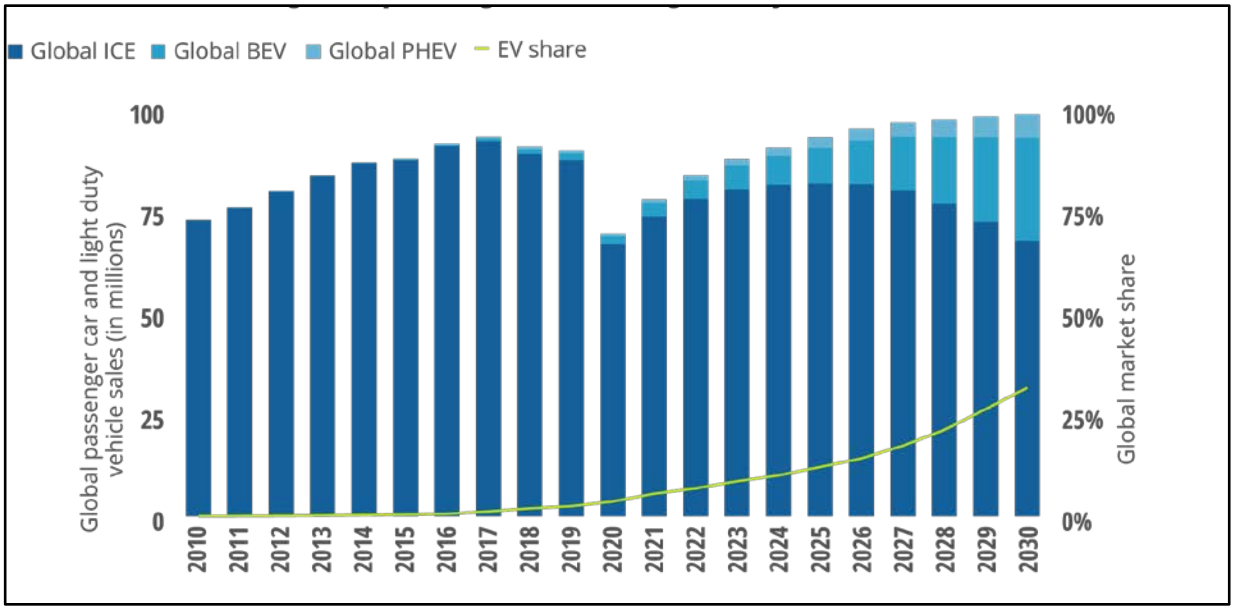

Figure 4. Outlook for Annual Global Passenger-car and Light -duty Vehicle Sales, to 2030. Source: Deloitte Insights

Ten metric tons of CO2 per vehicle is a ballpark estimate of included GHG emissions attributable to EV battery manufacturing between now and 2050.[xvi] This estimate assumes significant decarbonization of China's electricity supply in the next decade, and/or increased manufacturing in countries relying more on renewables and natural gas.

Figure 4 shows that global annual sales of passenger and light duty vehicles are in the range of one hundred million vehicles per year and that the EV share of new vehicles will increase. The global automotive industry will do its best to sustain or even increase its current $4 trillion annual sales revenues. At ten metric tons of life cycle carbon per vehicle, this will result in at least **ten billion tons of CO2-eq** life cycle carbon emissions released in making the EVs on global roadways in 2030. We can expect comparable amounts per decade unless a circular automotive materials economy functions at the global level as well or better than the recycling process for lead acid batteries in the US.

Some automakers once argued that this hefty carbon debt would remain un. Investigations and modeling by Independent research teams in the US and Europe rebutted this claim. A consensus emerged that, in general, an EV pays its carbon debt during its initial twenty thousand miles, less where charging electricity is fully decarbonized, much more where electricity generation depends on mining and burning coal. Only in a small percentage of cases is it never repaid.

There is a devil in the details of operating temperature and battery age. Battery University advises that "lithium ion battery self-discharge increases with age, cycling and elevated temperature. Discard a battery if the self-discharge reaches 30 percent in 24 hours....The self-discharge of all battery chemistries increases at higher temperature, and the rate typically doubles with every °C (18°F)."

Not only is battery round trip efficiency less than 100 percent in utility scale applications, but lithium-ion battery self-discharge rates will be higher in equatorial and sub-tropical areas, influencing the mix of EVs and hybrid vehicles in these areas. Until vehicle to grid (V2G) experience accumulates and suggests otherwise, we can assume EV round trip efficiencies will be comparable to utility scale battery round trip efficiencies that range around eighty percent. Note that solar and wind generation capacities and life cycle carbon estimates should be based on kWh delivered for charging, not kWh actually resulting in propulsion.

When compared to the current **six hundred billion tons of CO2-eq** per decade of on-going global GHG emissions[xvii] global life cycle EV emissions through 2030 are certainly a price worth paying to accelerate the transition to maximum substitution of EVs for fully fuel dependent vehicles. That said, the global automotive industry must take steps to minimize them.

A circular global automotive materials economy requires environmentally responsible sourcing of battery minerals[xviii] and higher average vehicle utilization factors. In the meantime, climate policy makers must recognize that batteries in under-utilized vehicles take many years to repay their carbon debt and so become part of the climate action problem, not part of its solution. The same concern applies to large lithium-ion batteries used only to back up continuous power sources. Rarely used, they serve no decarbonization purpose but still result in life cycle carbon emissions.

5. Stationary Renewable Electricity Storage. While the automotive transition is easy to track and forecast, the stationary battery market, once focused on uninterruptible power supplies, now encompasses a growing diversity of existing or rapidly emerging applications and industries. Utilities, grid electricity customers and public charging station owners[xix] will all own significant shares of total installed battery capacity.

Rapid expansion of bulk solar and wind power generation capacity coupled with retirements of fossil generation capacity, for example in California[xx], requires rapid and proportional expansion of battery storage capacity to meet grid reliability and generation capacity, aka “resource adequacy” requirements imposed by energy regulators. California’s electricity retailers are now purchasing amounts of solar electricity that require significant and proportionate amounts of battery storage to satisfy their “resource adequacy” (generation capacity) obligations.

In California, where the renewable share of an electricity retailer’s generation portfolio meets a high percentage of electricity demand, battery storage capacity is expanding at the rate of 2 kWh of battery capacity for each 1 kW of solar power generation capacity.[xxi] Battery storage proportions will increase as dispatchable sources of fossil generation are retired by their owners. If global installed wind and solar capacity in 2030 reaches 4000 GW, consistent with current forecasts[xxii], and assuming 5-10 kWh of battery capacity per kW of production capacity is necessary to match production to demand, global life cycle carbon emissions will increase by **2-4 billion tons of CO2-eq** by 2030.[xxiii]

Life cycle carbon for more decentralized stationary battery deployment, paired with rooftop solar and integrated with EV charging stations, is harder to forecast. An increasing portion of solar PV capacity will be on rooftops. Rooftop solar installations increasingly include battery storage to maximize the economic and energy resilience benefits of on-site solar PV.[xxiv] Use of vehicle batteries to shift rooftop solar production to match grid electricity demand or for energy security purposes may partially off-set demand for utility scale battery storage and thus reduce battery storage life cycle carbon emissions.

Vehicle charging stations may include battery storage to minimize grid demand charges[xxv] and to maximize charging equipment utilization. "Fast chargers make for an incredibly "peaky" load on the grid, which means demand charges can reach 90 percent of total electricity costs at charging stations."[xxvi]

So called "second use" battery cells reclaimed from during decommissioning of battery projects can meet a portion of the future needs for local stationary battery storage. However, plans for large scale battery recycling in the US now focus on reclaiming cadmium, nickel and lithium for use in manufacturing new vehicle batteries, not on supplying cells for second use batteries.[xxvii]

Because national policies may continue to incentivize rapid deployment, there is potential for battery deployment to involve redundancies that result in under-utilized battery capacity and greater than necessary life cycle carbon emissions. Potential redundancies and potential missed opportunities suggest a need for more robust renewable integration and decarbonization strategies that account for life cycle life cycle carbon.

(Preceding sections covered upfront carbon for both EV and stationary batteries. A later section discusses battery losses in more detail.)

6. Refrigerants. Heat pump use is pervasive in the US and increasing in other industrial countries. Every US home has one heat pump; most have at least two, one in a refrigerator, another one or more in air conditioners. Vehicles typically have heat pump enabled air conditioners.

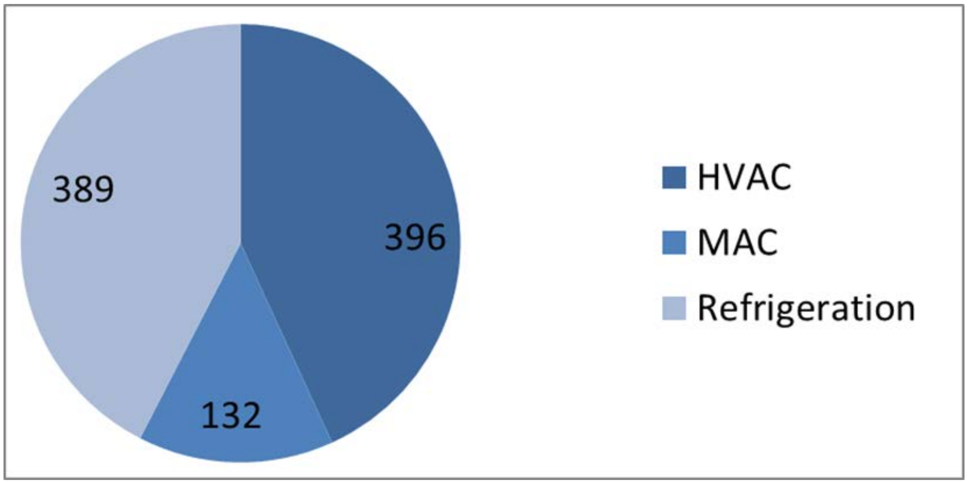

Figure 5. Global Vapor Compression Use of Refrigerants, in kilotons. Source: NREL[xxviii]

Figure 5 shows the relative size of major global heat pump markets, including heating ventilation and air conditioning (HVAC), mobile air conditioning (MAC), and refrigeration. Heat pumps contain refrigerants, gases that vaporize when heated and condense when cooled. Without significantly increasing the amounts of refrigerant required per unit of cooling capacity, a refrigeration system can be reconfigured to pump heat into and out of a building using the same compressor. In colder regions, peak heat demand exceeds air conditioning demand and requires greater compressor capacity and more refrigerant.

Refrigerants entering the atmosphere that caused the notorious “ozone hole” classified as “ozone depleting substances.”

Hydrofluorocarbons (HFCs) are potent greenhouse gases that substitute for ozone-depleting substances phased out under the Montreal Protocol. Per molecule, HFCs can be thousands of times more potent GHGs than CO2[xxix]. Regulators classify them as high global warming potential (high GWP) gases.[xxx]

Between 2020 and 2030, HFCs released from discarded cooling equipment will contribute about 4% of total global energy related greenhouse gas emissions – **fifteen billion tons of CO2-eq**.[xxxi] Figure 6 shows annual emissions increasing as markets for refrigeration and air conditioning expand. Where the market for space cooling has saturated, annual percentages are even higher. For example, in spite of California’s mild climate, high GWP gases that refrigerants create when they evaporate account for about five and half percent of California’s total annual GHG emissions.[xxxii]

HFC gas usage is accelerating globally as new markets for heat pumps (water heating, for example) take root and expand, and as residential air conditioning becomes more prevalent in hot, high population areas of the world.[xxxiii] Significant growth in HFC use in developing countries will occur because of population growth, rapid urbanization, electrification and changing consumer patterns. According to the Climate and Clean Air Coalition, “Atmospheric observations show that the volume of HFCs in the atmosphere is increasing rapidly, about 10-15% per year. The increased use of refrigerants will also result in increased energy consumption and related greenhouse gas emissions. Absent remedial measures,, The Climate and Clean Air Coalition estimates that HFCs will amount to 9-19% of total GHG

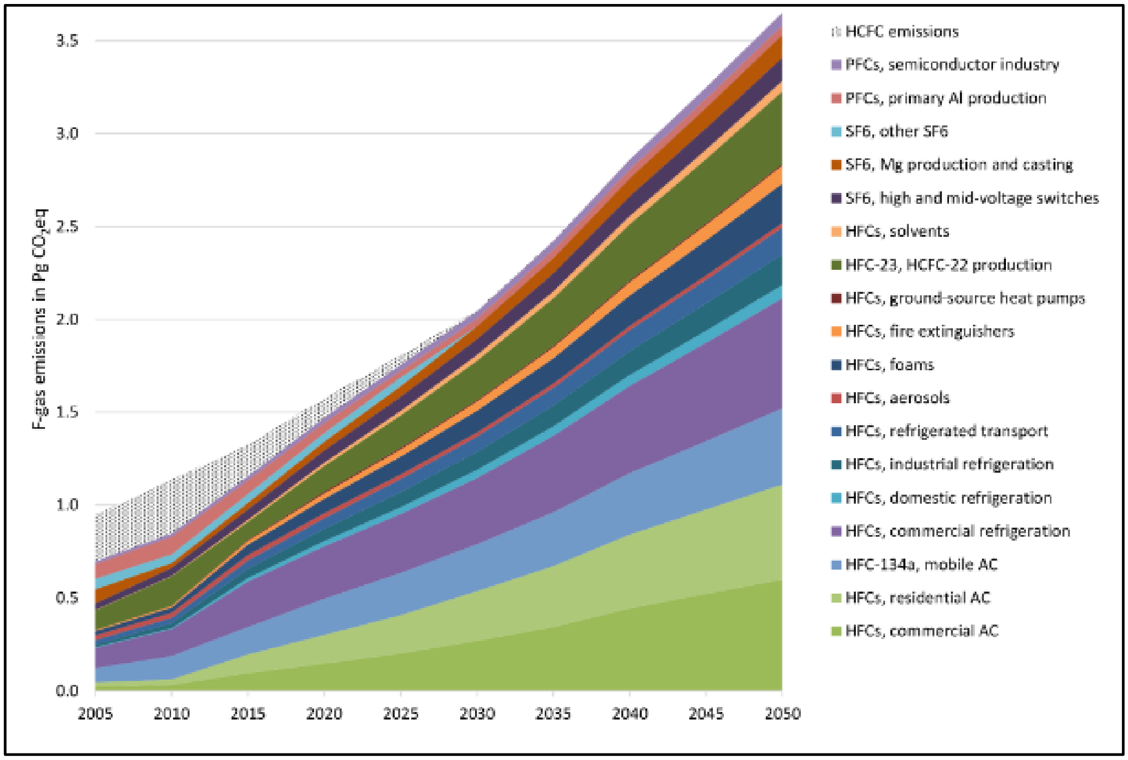

Figure 6. Baseline Emissions of Fluorinated Gases by Source Sector[xxxiv]

emissions by 2050."[xxxv] The IEA sees leaked refrigerants as potentially resulting in as much as **one hundred billion tons of CO2-eq** emissions between 2020 and 2050.[xxxvi]

High GWP refrigerants that are either reclaimed or end up in the atmosphere, and HFCs have atmospheric residence times exceeding two hundred years.[xxxvii] So, the share of future GHG emissions attributable to high GWP refrigerant inventories in existing and new equipment depends on reclamation programs. Reclamation experience to date is not encouraging. Annual refrigerant reclamation in the US is five percent of annual production[xxxviii], and the percentage is declining.[xxxix]

In the US, state waste management agencies actively regulate waste collection and recycling. They can take steps to reward refrigerant reclamation. In parallel, the US should develop a more coherent vision for a circular energy materials and equipment economy that encompasses of reclamation of high GWP materials[xl] and recovers, reuses and repurposes renewable electricity generation and storage equipment.

<u>7. Renewable Electricity Storage and Transport Losses.</u> The power sector will need to produce, transport and store massive amounts of renewable electricity[xli] to enable affordable reductions in overall power generation emissions. Storage losses not only increase life cycle carbon emissions attributable to stationary batteries but require significantly more annual renewable electricity generation because, as mentioned earlier, storage "round trip efficiencies" are much less than 100 percent. Current forecasts of required renewable electricity production may be underestimates if they do not account for losses of stored renewable electricity.

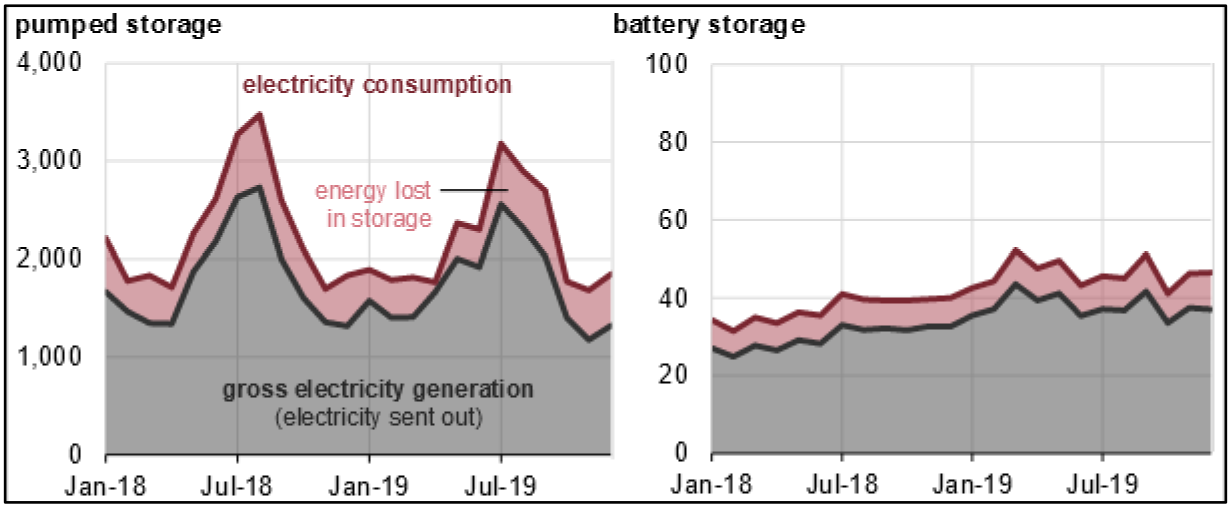

Figure 7. Monthly Round trip Efficiency of Pumped Storage and Battery Storage in the US, GWh[xlii]

Because of losses in transporting and storing renewable electricity, substitution of renewable electricity produced for electricity consumed will not be one for one. It will be more like 1.2 to 1.3 for one. The U.S. Energy Information Administration (EIA) estimates that annual electricity transmission and distribution (T&D) losses averaged about 5% of the electricity transmitted and distributed in the United States in 2017 through 2021.[xliii] Losses are higher in most if not all other countries, and in important cases like India, three times higher.[xliv] In the US there is substantial variation from state to state and even greater variation from country to country. The global average is around 8%.

"Round trip" storage losses take an even bigger bite, just as they do in the case of EV batteries. Figure 7 shows that twenty percent of stored bulk electricity in the US is unused, or "lost," due to pumping losses, initial battery self-discharge and higher rates of self-discharge at elevated ambient temperatures.[xlv]

Assuming storage of a portion of daily renewable electricity production, we can estimate resulting losses. Assuming capacity to store four hours of daytime solar production for use at night and to store four hours of wind production for use during higher demand hours, and assuming nominal electricity transport losses, the incremental life cycle carbon impact globally between 2020 and 2030 would be **4 billions of tons of CO2-eq**. Because future losses will scale with wind and solar production they will be significantly higher in future decades.

8. Renewable Heat and Fuels. Just as renewable electricity now reduces fossil fuel use, so renewable heat and renewable fuels will increasingly substitute for fossil heat and fossil fuels. Life cycle emissions attributable to renewable heat and fuels are of concern in cases where industry requires vast quantities of new materials and equipment. Three cases merit assessment. First, substitution of solar heat for fossil heat is underway and expected to continue. Four hundred million solar water heating systems worldwide. Second, the US and Brazil blend ethanol with gasoline in large quantities and proportions.

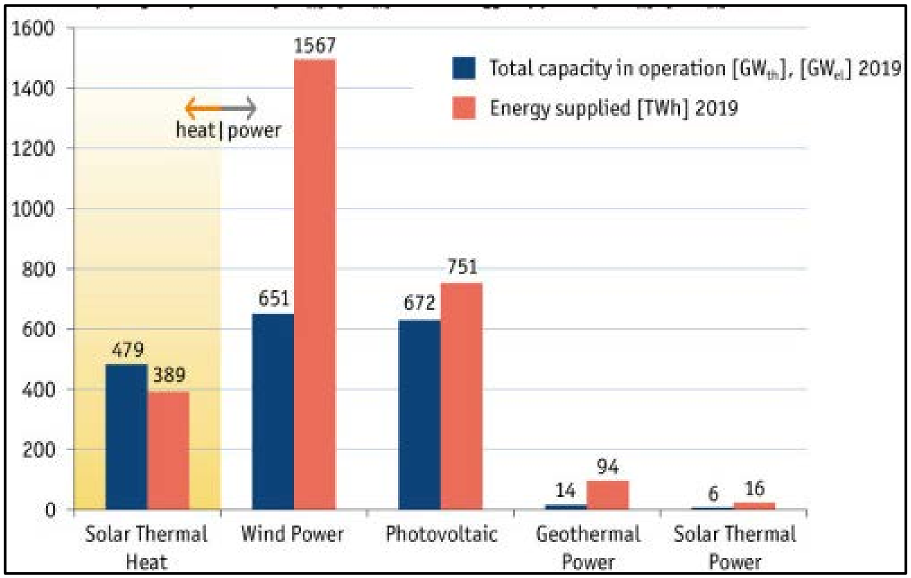

Figure 8. Global Capacity in Operation and Energy Supplied, 2019[xlvi]

Third, (long-envisioned) substitution of renewable hydrogen for natural gas and petroleum in the transportation sector and use as a seasonal electricity storage medium is now receiving significant policy support in the US and other industrial countries.

Heat is the world's largest energy end use, accounting for almost half of global final energy consumption in 2021, significantly more than electricity (20%) and transport (30%). Industrial processes account for fifty one percent of overall heating energy use. Building energy uses, mostly for space heating and water heating, but also for cooking account for forty six percent.[xlvii] Figure 8 shows the 2019 solar thermal heat contribution to global energy supply compared to contributions from renewable electricity sources.

Significant solar thermal heat use preceded significant wind and solar electricity use. Applications in the buildings sector are opportune but there are reasons solar thermal market growth is slower than solar PV growth in the US. PV equipment now lends itself to plug-and-play panel and grid connections and saves grid electricity costs that have been increasing, while solar water heating retrofits require more specialized skill sets and save retail natural gas costs that have been at historic lows. Also, PV panel ratings enable indexing of subsidies to energy commodity values and enable retailers to offer relatively accurate forecasts of economic performance, while solar water heating economic performance is more complex because it depends on usage as well as production factors.

Electrification of the buildings and industrial sectors requires both massive investment in energy usage retrofits and additional renewable electricity beyond the amounts necessary to decarbonize current grid electricity usage. As natural gas prices increase, solar heat use for water, space and industrial heating will become more economically advantageous. Its low life cycle carbon will make it an important complement to renewable electrification.

8.1 Low Temperature Solar and Geothermal Heat. In most parts of the world solar heat can reduce the amounts and costs of electricity or natural gas used to heat water and living spaces. In agricultural areas it can reduce the amounts and costs of fuels used for crop drying. The market for solar water heating is strong in some countries, though not in the US. The fact that, ideally, solar water heating requires a backup source capable of meeting full daily demand for extended periods reduces its appeal.

However, the opportunity to use solar heat to reduce natural gas consumption and GHG emissions without foregoing reliability and resilience benefits of natural gas will be appealing in countries that have mature and technically well supported natural gas distribution industries. These countries can substitute a combination of solar heat and renewable natural gas (RNG) for natural gas. RNG produced from animal waste and other organic waste with geological natural gas to deliver a blended fuel having lower GHG emissions.

Heat pump efficiency is inversely related to the temperature difference between outdoor and indoor air. So, heat pumps can raise solar and "geothermal," aka ground source, heat to higher temperatures more efficiently on average than heat from ambient outdoor air. Solar-assisted and "geothermal" heat pumps reduce electricity use and related GHG emissions by a factor of two to four.

Integration of solar heat and solar electricity collection is also possible and beneficial from a GHG emissions perspective. Hybrid systems are attracting interest among residential and commercial housing owners around the world. Hybrid PV-thermal (PVt) systems[xlviii] that use solar PV panels to both absorb heat and generate electricity maximize the decarbonization effectiveness of solar PV by producing two units of heat for every unit of electricity produced.

Using solar panels to preheat air for space heating also lowers PV cell temperatures and thereby increases their efficiency. Uncovered PV thermal (PVt) collectors paired with heat pumps[xlix] are an attractive solution for single-family homes or commercial buildings because they deliver cost savings, lower GHG emissions and lower life cycle carbon emissions per unit of energy delivered. Life cycle emissions reductions from solar water and space heating and crop drying will be important in future decades, though between 2020 and 2030 they will contribute less than **a tenth of a billion tons of CO2-eq** unless adoption accelerates**.**

8.2 High Temperature Solar Heat. Where the ratio of direct to diffuse solar radiation is high, "direct solar radiation"[l] mirrors focus, or "concentrate," sunlight to generate steam or hot air for use in electricity production or industrial processes. High temperature solar heat stored in molten nitrate salt generates steam for power generation or "process heat" for medium to high temperature industrial processes.

Life cycle emissions of high temperature solar heat used to produce electricity, labeled "Solar Concentrated" in Figure 1, are lower than life cycle emissions for solar PV. In the best " direct" solar resource areas, the ability to store high temperature heat efficiently and at low cost can avoid the need for long term battery storage and avoid its high costs and life cycle emissions. High temperature storage can also support economically efficient, uninterrupted, and low life cycle carbon operation of industrial processes.

8.3 Renewable Fuel - Bio-ethanol. Substitution of bio-ethanol for gasoline results in a reduction in direct GHG emissions that more than off-sets life cycle carbon emissions resulting from bio-ethanol production. The United States and Brazil produce more bio-ethanol than all other countries combined. Bio-ethanol use for global transportation may decline as EVs substitute for IC engine vehicles in the US and as the US adopts less carbon intensive and more regenerative agricultural practices.

8.4 Renewable Hydrogen Vehicle Fuel. Renewable hydrogen produced using renewable electricity is a potential substitute for natural gas and for effective but still relatively inefficient[li] long term storage of renewable electricity. Energy-intensive, high temperature industrial production processes, for example in the glass, food and ceramic sectors, are candidates for substitution of renewable hydrogen for natural gas. However, neither industrial experience at scale nor experience-based life cycle carbon estimates are available.

Renewable hydrogen will make it possible for fuel cell electric vehicles (FCEVs) to replace fossil fueled vehicles. Hydrogen fueled trucks and buses will have a near term role paving the way for renewable hydrogen fueling of personal vehicles in the longer term. FCEV development and pilot manufacturing and commercialization is underway in Asia. California is investing in fueling infrastructure. Again, experience-based life cycle carbon estimates are not available.

electrolyzers powered by renewable electricity produce renewable hydrogen. Losses are a significant lifecycle carbon concern. Ignoring losses in converting renewable electricity to renewable hydrogen, EVs relying on renewable electricity and hydrogen fuel cell electric vehicles FCEVs relying on renewable hydrogen have comparable life cycle carbon footprints. [lii] However, converting renewable electricity to hydrogen at a power plant site and then using a fuel cell to convert it back to electricity in a vehicle requires roughly twice as much renewable electricity per mile of vehicle travel than using renewable electricity directly in an EV.[liii]

9. Life Cycle Carbon Emissions Estimates and Actions.

9.1. Life Cycle Emissions in the Current Decade. Substitution of materials, equipment and low carbon fuels for high carbon fuels is underway. Progress varies from country to country and between economic sectors. Substitution of manufactured equipment for fuels adds "life cycle carbon" to on-going GHG emissions. To what extent do GHGs emitted in creating low carbon energy economies retard overall decarbonization progress? Table 1 shows estimated global energy equipment life cycle GHG ("carbon") emissions during the decade beginning in 2020 for key energy technologies that enable energy sector decarbonization. Life cycle carbon emissions for these technologies for the years 2020 through 2029 add up to a minimum of thirty-five billion metric tons of CO2-eq, or a year's worth of current global energy related GHG emissions. Overall life cycle carbon emissions will continue to increase after 2029 at least until renewable energy is the dominant energy source worldwide.

Table 1. Estimated Global Renewable and Refrigerant Equipment Life Cycle GHG (Carbon) Emissions (2020-2029) (billions of tons of CO2-eq)

Renewable Electricity Generation	**6**
Electric Vehicle Battery Storage	**>10**
Renewable Electricity Storage and Transport Losses	**4**
Refrigerants	**15**
Solar Water and Space Heat	**0.1**
High Temperature Solar Heat	**<< 0.1**
Renewable Vehicle Fuel - Bio-ethanol and Bio-diesel	**< 0.1**
Renewable Vehicle Fuel - Hydrogen	**<< 0.1**
Renewable Hydrogen Energy Storage	**<< 0.1**
Total	**>35**

9.2. Life Cycle Carbon Emissions in Future Decades. Humanity can mitigate and minimize life cycle carbon emissions despite the fact they are an unavoidable byproduct of decarbonization investments. Sources of life cycle carbon emissions are diverse and depend on deployment rates. Life cycle emissions from renewable electricity generation and EV battery storage deployment will increase and then recede when and if demand for new equipment recedes. Life cycle carbon emissions forecast accuracy will improve as experience accumulates. With Table 1 as a baseline, the next step will be to evaluate best and worst case scenarios.

9.3. Near Term Life Cycle Carbon Minimization. Life cycle carbon emissions will account for a significantly larger share of total GHG emissions in future decades. Minimizing rates of life cycle carbon emissions increases will require action to reduce overall energy intensity, focus on major sources, plan for greater circularity, increase equipment longevity and begin explicitly accounting for and forecasting life cycle carbon emissions as a sub-set of overall energy related emissions.

9.3.1. Energy Intensity. We can reduce energy intensity by adopting policies that reward both energy efficiency and energy conservation. Energy efficiency relies on the intelligence of the energy consuming system and its integration with supply. Heat pumps, for example, can operate more efficiently and be smaller when solar and geothermal heat reduces the temperature gap between heat source and heat sink. There are also ways to lower the gap in cooling applications, for example by relying on the thermal mass of a building to stabilize its temperature so that cooling operations shift away from the hottest parts of the day.

Energy conservation, on the other hand, requires using more pervasive human intelligence to avoid using energy unnecessarily, for example, heating and cooling unused spaces, producing and purchasing vehicles that are oversized relative to their primary intended use, and reducing leakage and losses in energy transport systems. More effective integration of heat storage with solar sources and heat pumps, closer attention to integration of renewable heat and renewable hydrogen with renewable electricity, more efficient renewable hydrogen production, and longer lithium ion battery lifetime will require closer technical and policy attention as the energy transition continues.

9.3.2. Major Sources. Table 1 shows that life cycle carbon emissions attributable to leakage of electrification refrigerants and lithium ion battery production are already dominant and increasing. Policies focused on high GWP emissions could, for example, reward recovery of high GWP refrigerants, substitution of lower GWP refrigerants. Policies focused on electric vehicle substitution for gasoline and diesel fueled vehicles could, for example, prioritize high usage vehicles until EV substitution is farther along.

9.3.3. Planning for Circularity. Planning for circularity would emphasize recycling, reusing, remanufacturing and repurposing materials and equipment and thus reduce life cycle emissions of replacement equipment and systems. A circular renewable electrification economy would encompass solar, wind and stationary battery storage as well as efficient electricity usage equipment. A circular global electric vehicle economy requires environmentally responsible sourcing of battery minerals and high vehicle utilization factors. There is ample information to support national planning for circularity in these cases. National planning processes could inform state planning and state planning could in turn inform city and county planning.

9.3.4. Increase Equipment Longevity. Other than fugitive natural gas emissions that may decline, and electricity storage and transport losses that may increase, life cycle emissions in other Table 1 categories in future decades will stabilize at levels determined by replacement cycles, residual fossil fuel use, and circularity. Replacement cycles are less than a decade for EV battery storage, a decade and a half for refrigeration and HVAC equipment, and two or more decades for renewable electricity generation. Battery storage longevity is a major concern, both because new batteries add life cycle carbon and because battery round trip efficiency falls off rapidly toward the end of a battery's life, increasing the effect of losses on other sources of life cycle carbon.[liv]

9.3.5. Explicitly account for life cycle carbon emissions in GHG inventories and forecasts. Life cycle carbon is already increasing the cost of global decarbonization while retarding progress. At this time, it is an important but not accurately forecastable side-effect of life saving decarbonization medicine. Explicit and complete accounting will motivate both improved accuracy and better informed policy attention.

End Notes:

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[i] The silicon in solar cells is manufactured through a reduction process in which the silica is heated with a carbon material and the oxygen is removed, leaving behind purer, metallurgical-grade silicon. From there, the grade must be further purified into polysilicon, the solar-grade purity of which is 99.999 percent. Source: https://www.letsgosolar.com/faq/how-are-solar-panels-made/

[ii] "Embodied" carbon is the sum of greenhouse gas emissions released during the following life cycle stages: raw material extraction, transportation, manufacturing, construction, maintenance, renovation, and end-of-life for a product or system. Source: https://se2050.org/resources-overview/embodied-carbon/what-is-embodied-carbon/

[iii] Ref: https://worldgbc.org/article/bringing-embodied-carbon-upfront/. The World Green Buildings Council estimates that "carbon emissions released before the built asset is used", the portion of embodied carbon referred to as 'upfront carbon', will be responsible for half of the entire carbon footprint of new (building} construction between now and 2050, threatening to consume a large part of our remaining global carbon budget."

[iv] https://www.epa.gov/natural-gas-star-program/estimates-methane-emissions-segment-united-states

[v] Figure 1 shows that about 78% of 2020 oil and gas methane emissions in 2020 were attributable to natural gas.

[vi]https://pubs.acs.org/doi/10.1021/acs.est.1c06458

[vii] https://ww2.arb.ca.gov/resources/documents/high-gwp-refrigerants

[viii] Ref: https://www.iea.org/news/global-co2-emissions-rebounded-to-their-highest-level-in-history-in-2021

[ix] The amount of material per area of solar cell that determines its life cycle emissions was reduced by a factor of four as the solar PV industry grew and matured. According to the International Energy Agency, "today, electricity-intensive solar PV manufacturing is mostly powered by fossil fuels, but solar panels only need to operate for 4-8 months to offset their manufacturing emissions. This payback period compares with the average solar panel lifetime of around 25-30 years. Electricity provides 80% of the total energy used in solar PV manufacturing, with the majority consumed by production of polysilicon, ingots and wafers because they require heat at high and precise temperatures. Today, coal generates over 60% of the electricity used for global solar PV manufacturing, significantly more than coal's share in global power generation (36%). This is largely because PV production is concentrated in China – mainly in the provinces of Xinjiang and Jiangsu where coal accounts for more than 75% of the annual power supply and benefits from favorable government tariffs." Source: https://www.iea.org/reports/solar-pv-global-supply-chains/executive-summary "Under European conditions...., photovoltaic technologies show life cycle GHG emissions of about 37 g CO2 eq./kWh both for ground- and roof-mounted system – the global average is 52/53 (ground-/roof-mounted). About 40% of this climate change impact is due to the electricity consumption for solar-grade silicon refining....the two main parameters influencing the life cycle GHG emissions of poly-Si panels are electricity for manufacturing and module efficiency/normal irradiation." Source: https://upload.wikimedia.org/wikipedia/commons/4/44/CO2_Emissions_from_Electricity_Production_IPCC.png

[x] Ref: https://www.iea.org/reports/solar-pv

[xi] Ref: https://www.iea.org/reports/wind-electricity

[xii] Based on current growth rates. Cf. preceding references.

[xiii] https://www.researchgate.net/publication/366311622_Toward_a_More_Circular_Renewable_Energy_Economy

[xiv] Annual stationary battery capacity in Figure 3 may be an underestimate. As the percentage of variable renewables in generation portfolios increases battery deployment rates may increase faster than solar and wind generation capacity expands.

[xv] https://climate.mit.edu/ask-mit/are-electric-vehicles-definitely-better-climate-gas-powered-cars

[xvi] Accurate figures in the future will be between 2.5 and 16 metric tons, based on the difference between using low and high carbon energy sources.

[xvii] Ref: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf

[xviii] According to McKinsey , "the extraction and refining of raw materials, as well as cell production, can have severe environmental effects, such as land degradation, biodiversity loss, creation of hazardous waste, or contamination of water, soil, and air. Unprofessional or even illegal battery disposal can cause severe toxic pollution. This is a problem within today's lead-acid battery value chain. In addition, GHG emissions resulting from mining of battery minerals and heat used in battery manufacturing depend on the carbon footprint of the energy used in mining and manufacturing processes." Source: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular

[xix] Ref: https://www.evgo.com/press-release/evgo-balances-ev-fast-charging-with-14-battery-storage-systems-across-11-evgo-fast-charging-stations/

[xx] For example, the California Public Utilities Commission recently called for adding about 17.5 gigawatts of utility-scale solar power and 3.5 gigawatts of on-shore wind power by 2032, along with 13.6 gigawatts of battery storage, 1.7 gigawatts of offshore wind. Ref: https://www.canarymedia.com/articles/clean-energy/how-california-can-get-to-a-reliable-85-clean-grid-by-2030

[xxi] Reflects the amount of battery storage necessary to meet California's resource adequacy requirements for high renewable energy generation portfolio percentages. Cf. https://valleycleanenergy.org/power-sources/

[xxii] Cf. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/renewable-energy-development-in-a-net-zero-world

[xxiii] At a tenth of a metric ton of CO2-eq emissions per kWh of lithium ion battery storage, 4000 GW of renewable electricity capacity and 5kWh per kW of battery capacity would require 20,000 GWh of battery storage capacity, resulting in 2 GT CO2-eq.

[xxiv] For example, the California Public Utilities Commission recently considered incentivizing solar paired batteries while at the same time reducing incentives for on-site solar electricity production. Cf. https://www.researchgate.net/publication/359120138_Consequences_of_Proposed_Repurposing_of_California's_Retail_Solar_Industry#fullTextFileContent

[xxv] https://www.canarymedia.com/articles/ev-charging/fast-ev-chargers

[xxvi] Ref: https://www.canarymedia.com/articles/ev-charging/fast-ev-chargers

[xxvii] Ref: https://www.technologyreview.com/2023/01/17/1065026/evs-recycling-batteries-10-breakthrough-technologies-2023/

[xxviii] Ref: https://www.nrel.gov/docs/fy20osti/70207.pdf

[xxix] Ref: https://www.nrel.gov/docs/fy20osti/70207.pdf

[xxx] There is technical potential to substitute CO2 for high GWP gases in heat pump water heaters. Adoption potential and rates of adoption globally will depend on initial market and retailer experience, initially in Australia.

[xxxi] Estimate based on data and forecasts in https://phys.org/news/2022-09-climate-hfcs-refrigerators-air-conditioners.html

[xxxii] Source: https://ww2.arb.ca.gov/sites/default/files/classic/cc/inventory/2000-2020_ghg_inventory_trends.pdf In 2020, refrigeration and air conditioning equipment contributed 92 percent of California's ODS substitute emissions.

[xxxiii] Ref: https://www.iea.org/reports/the-future-of-cooling

[xxxiv] Ref: https://acp.copernicus.org/articles/17/2795/2017/acp-17-2795-2017.pdf

[xxxv] Ref: https://www.ccacoalition.org/en/initiatives/hfc

[xxxvi] https://trakref.com/blog/the-15-billion-ton-problem-the-u-s-refrigerant-recycling-market-fails-to-stop-leaks/

[xxxvii] Ref: https://archive.ipcc.ch/ipccreports/tar/wg1/016.htm

[xxxviii] Ref: https://trakref.com/blog/the-15-billion-ton-problem-the-u-s-refrigerant-recycling-market-fails-to-stop-leaks/

[xxxix] Perhaps in part because hydrofluorocarbons being phased out in compliance with the Kigali Amendment to the Montreal protocol have declining commercial value.

[xl] Ref: https://www.iresn.org/news/2022/12/14/toward-a-more-circular-renewable-energy-economy

[xli] More than 27500 thousand TWh. Ref: https://www.iea.org/data-and-statistics/charts/global-electricity-demand-by-scenario-2010-2030

[xlii] https://www.eia.gov/todayinenergy/detail.php?id=46756

[xliii] Ref: https://www.eia.gov/tools/faqs/faq.php?id=105&t=3

[xliv] Ref: https://www.electricalindia.in/losses-in-distribution-transmission-lines/

[xlv] https://batteryuniversity.com/article/bu-802b-what-does-elevated-self-discharge-do

[xlvi] Ref: https://www.iea-shc.org/solar-heat-worldwide-2020

[xlvii] Ref: https://www.iea.org/fuels-and-technologies/heating

[xlviii] https://www.iea-shc.org/Data/Sites/1/publications/Solar-Heat-Worldwide-2020.pdf

[xlix] Heat pumps operate at greatest efficiency when the temperature difference between heat source and heat sink is minimized.

[l] Direct solar radiation is defined as radiation which has not experienced scattering in the atmosphere, so that it is directionally fixed, coming from the disc of the Sun.

[li] Partial because round-trip efficiency is in the fifty percent range.

[lii] Ref: https://theicct.org/wp-content/uploads/2023/02/lca-ghg-emissions-hdv-fuels-europe-feb23.pdf

[liii] Relying on electrolytic hydrogen, electrolysis and fuel cell losses plus hydrogen liquefaction, transport and storage losses results in approximately 25 to 35 percent of the renewable electricity generated at the source available to move the vehicle compared to 70 to 80 percent in the EV case.

[liv] Electric vehicle mileage will be even more variable and harder to predict than gas mileage.