Master Plan Part 3

Sustainable Energy for All of Earth

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Executive Summary

On March 1, 2023, Tesla presented Master Plan Part 3 – a proposed path to reach a sustainable global energy economy through end-use electrification and sustainable electricity generation and storage. This paper outlines the assumptions, sources and calculations behind that proposal. Input and conversation are welcome.

The analysis has three main components:

Electricity Demand		Electricity Supply		Material Feasibility & Investment
Forecast the electricity demand of a fully electrified economy that meets global energy needs without fossil fuels.	➡	Construct a least-cost portfolio of electricity generation and storage resources that satisfies hourly electricity demand.	➡	Determine the feasibility of material needs for the electric economy and manufacturing investment necessary to enable it.

Figure 1: Process overview

This paper finds a sustainable energy economy is technically feasible and requires less investment and less material extraction than continuing today's unsustainable energy economy. While many prior studies have come to a similar conclusion, this study seeks to push the thinking forward related to material intensity, manufacturing capacity, and manufacturing investment required for a transition across all energy sectors worldwide.

240 TWh Storage	**30** TW Renewable Power	**$10T** Manufacturing Investment	**1/2** The Energy Required
0.21% Land Area Required	**10%** 2022 World GDP	**ZERO** Insurmountable Resource Challenges	

Figure 2: Estimated Resources & Investments Required for Master Plan 3

The Current Energy Economy is Wasteful

According to the International Energy Agency (IEA) 2019 World Energy Balances, the global primary energy supply is 165 PWh/year, and total fossil fuel supply is 134PWh/year[1ab]. 37% (61PWh) is consumed before making it to the end consumer. This includes the fossil fuel industries' self-consumption during extraction/refining, and transformation losses during electricity generation. Another 27% (44PWh) is lost by inefficient end-uses such as internal combustion engine vehicles and natural gas furnaces. In total, only 36% (59PWh) of the primary energy supply produces useful work or heat for the economy. Analysis from Lawrence Livermore National Lab shows similar levels of inefficiency for the global and US energy supply[2,3].

Today's Energy Economy (PWh/year)

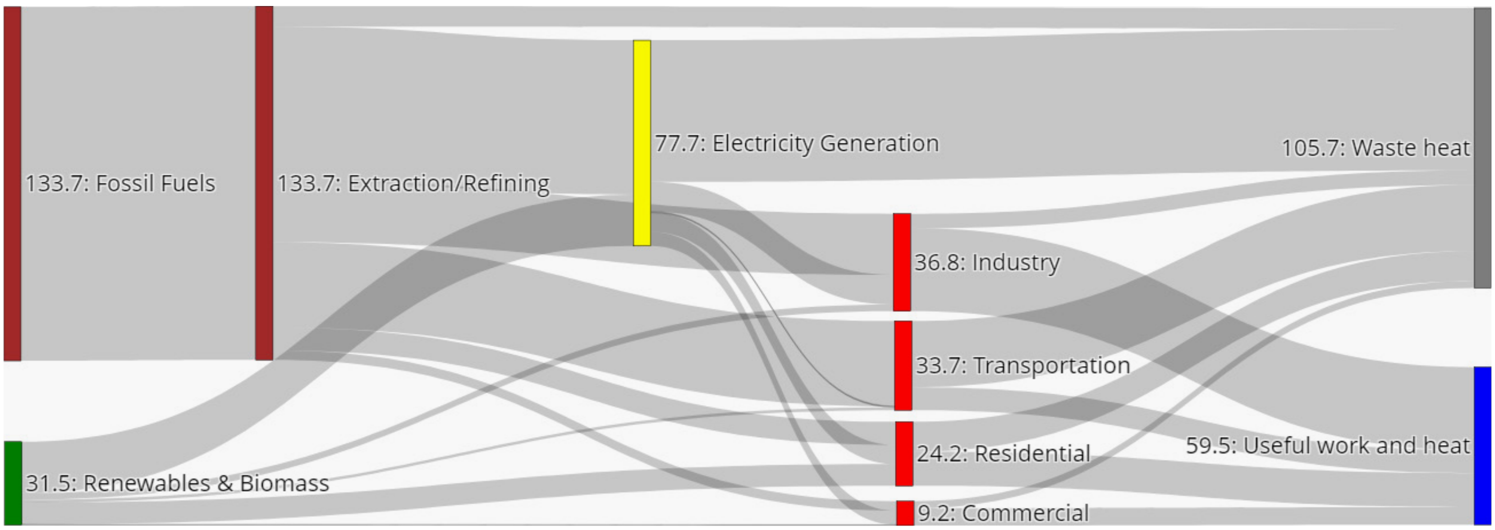

Figure 3: Global Energy Flow by Sector, IEA & Tesla analysis

a The 2021 and 2022 IEA World Energy Balances were not complete at the time of this work, and the 2020 dataset showed a decrease in energy consumption from 2019, which likely was pandemic-related and inconsistent with energy consumption trends.

b Excluded certain fuel supplies used for non-energy purposes, such as fossil fuels used in plastics manufacturing.

The Plan to Eliminate Fossil Fuels

In an electrified economy with sustainably generated energy, most of the upstream losses associated with mining, refining and burning fuels to create electricity are eliminated, as are the downstream losses associated with non-electric end-uses. Some industrial processes will require more energy input (producing green hydrogen for example), and some mining and refining activity needs to increase (related to metals for batteries, solar panels, wind turbines, etc.)

The following 6 steps show the actions needed to fully electrify the economy and eliminate fossil fuel use. The 6 steps detail the electricity demand assumptions for the sustainable energy economy and leads to the electricity demand curve that is modeled.

Modeling was done on the US energy economy using high-fidelity data available from the Energy Information Administration (EIA) from 2019-2022[c], and results were scaled to estimate actions needed for the global economy using a 6x scaling factor based on the 2019 energy consumption scalar between the U.S. and the world, according to IEA Energy Balances. This is a significant simplification and could be an area for improvement in future analyses, as global energy demands are different from the U.S. in their composition and expected to increase over time. This analysis was conducted on the U.S. due to availability of high-fidelity hourly data.

This plan considers onshore/offshore wind, solar, existing nuclear and hydro as sustainable electricity generation sources, and considers existing biomass as sustainable although it will likely be phased out over time. Additionally, this plan does not address sequestering carbon dioxide emitted over the past century of fossil fuel combustion, beyond the direct air capture required for synthetic fuel generation; any future implementation of such technologies would likely increase global energy demand.

01 Repower the Existing Grid with Renewables

The existing US hourly electricity demand is modeled as an inflexible baseline demand taken from the EIA[4]. Four US sub-regions (Texas, Pacific, Midwest, Eastern) are modeled to account for regional variations in demand, renewable resource availability, weather, and grid transmission constraints. This existing electrical demand is the baseline load that must be supported by sustainable generation and storage.

Globally, 65PWh/year of primary energy is supplied to the electricity sector, including 46PWh/year of fossil fuels; however only 26PWh/year of electricity is produced, due to inefficiencies transforming fossil fuels into electricity[d]. If the grid were instead renewably powered, only 26PWh/year of sustainable generation would be required.

02 Switch to Electric Vehicles

Electric vehicles are approximately 4x more efficient than internal combustion engine vehicles due to higher powertrain efficiency, regenerative braking capability, and optimized platform design. This ratio holds true across passenger vehicles, light-duty trucks, and Class 8 semis as shown in the Table 1.

Vehicle Class	ICE Vehicle Avg[5]	Electric Vehicles	Efficiency Ratio
Passenger Car	24.2 MPG	115 MPGe (292 Wh.mi)[e]	4.8X
Light Truck/Van	17.5 MPG	75 MPGe (450 Wh.mi)[f]	4.3X
Class 8 Truck	5.3 MPG (diesel)	22 MPGe (1.7 kWh.mi)[f]	4.2X

Table 1: Electric vs Internal Combustion Vehicle Efficiency

c US hourly time series data used as model inputs are available at https://www.eia.gov/opendata/browser/ for download.
d Embedded in the 26 PWh/year is 3.5 PWh/year of useful heat, mostly produced in co-generation power stations, which generate heat and power electricity.
e Tesla's global fleet average energy efficiency including Model 3, Y, S and X
f Tesla's internal estimate based on industry knowledge

As a specific example, Tesla's Model 3 energy consumption is 131MPGe vs. a Toyota Corolla with 34MPG[6,7], or 3.9x lower, and the ratio increases when accounting for upstream losses such as the energy consumption related extracting and refining fuel (See Figure 4).

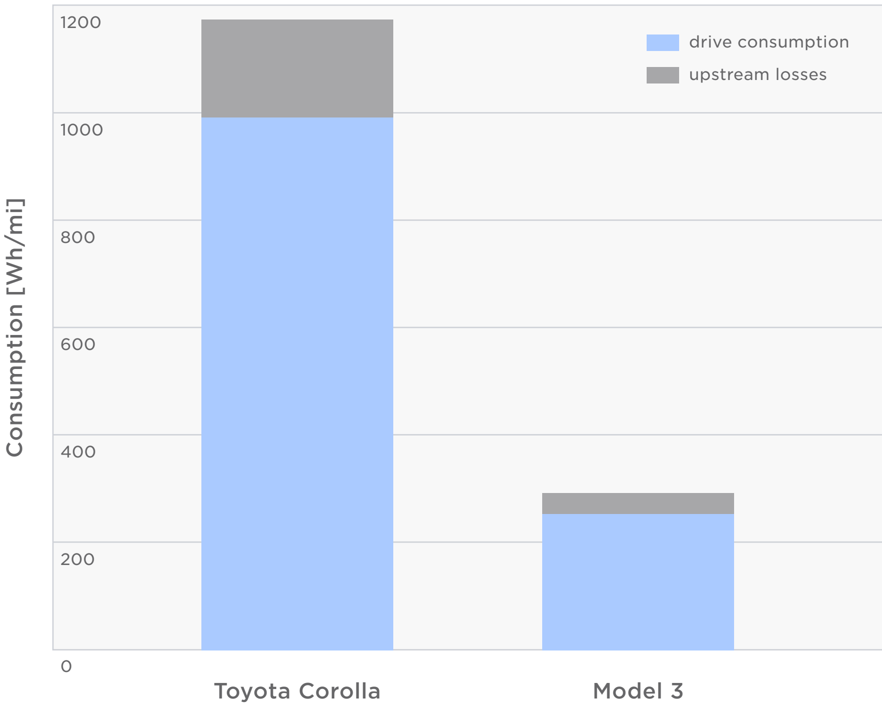

Figure 4: Comparison Tesla Model 3 vs. Toyota Corolla

To establish the electricity demand of an electrified transportation sector, historical monthly US transportation petroleum usage, excluding aviation and ocean shipping, for each sub-region is scaled by the EV efficiency factor above (4x)[8]. Tesla's hour by hour vehicle fleet charging behavior, split between inflexible and flexible portions, is assumed as the EV charging load curve in the 100% electrified transportation sector. Supercharging, commercial vehicle charging, and vehicles with <50% state of charge are considered inflexible demand. Home and workplace AC charging are flexible demand and modeled with a 72-hour energy conservation constraint, modeling the fact that most drivers have flexibility to charge when renewable resources are abundant. On average, Tesla drivers charge once every 1.7 days from 60% SOC to 90% SOC, so EVs have sufficient range relative to typical daily mileage to optimize their charging around renewable power availability provided there is charging infrastructure at both homes and workplaces.

Global electrification of the transportation sector eliminates 28 PWh/year of fossil fuel use and, applying the 4x EV efficiency factor, creates ~7 PWh/year of additional electrical demand.

03 Switch to Heat Pumps in Residential, Business & Industry

Heat pumps move heat from source to sink via the compression/expansion of an intermediate refrigerant[9]. With the appropriate selection of refrigerants, heat pump technology applies to space heating, water heating and laundry driers in residential and commercial buildings, in addition to many industrial processes.

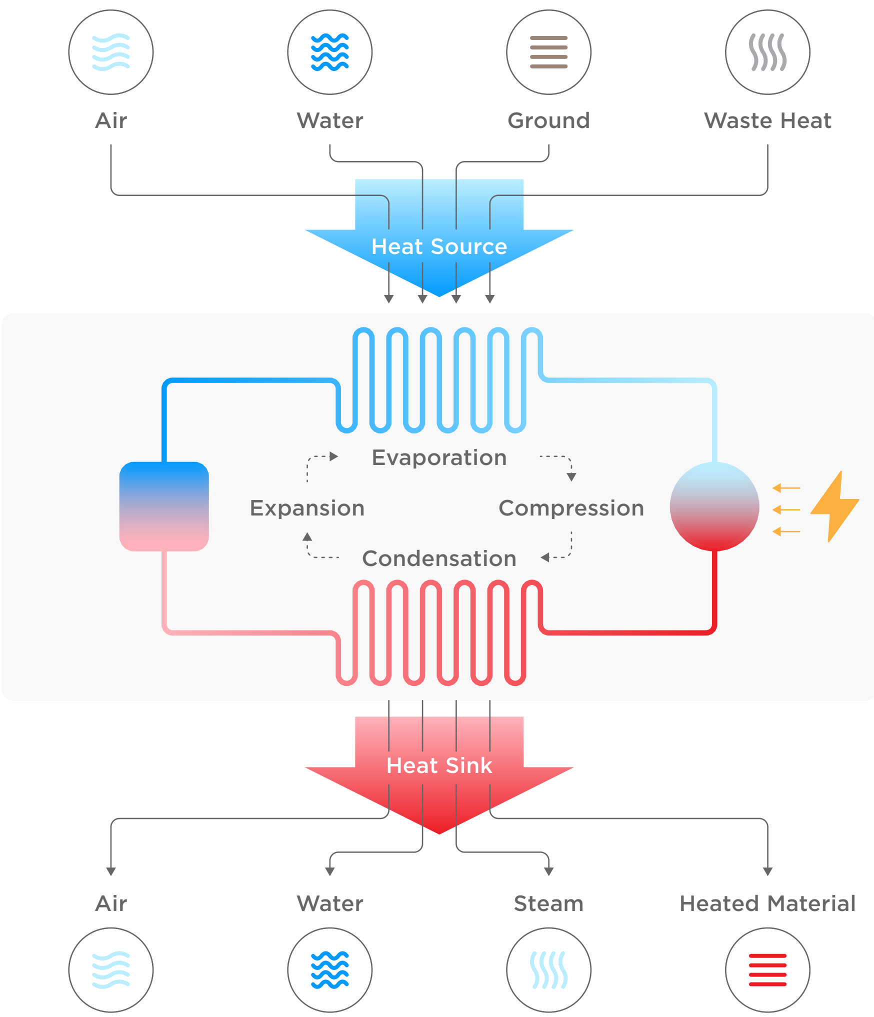

Figure 5: How Heat Pumps Work[10]

Air source heat pumps are the most suitable technology for retrofitting gas furnaces in existing homes, and can deliver 2.8 units of heat per unit of energy consumed based on a heating seasonal performance factor (HSPF) of 9.5 Btu/Wh, a typical efficiency rating for heat-pumps today[11]. Gas furnaces create heat by burning natural gas. They have an annual fuel utilization efficiency (AFUE) of ~90%[12]. Therefore, heat pumps use ~3x less energy than gas furnaces (2.8/0.9).

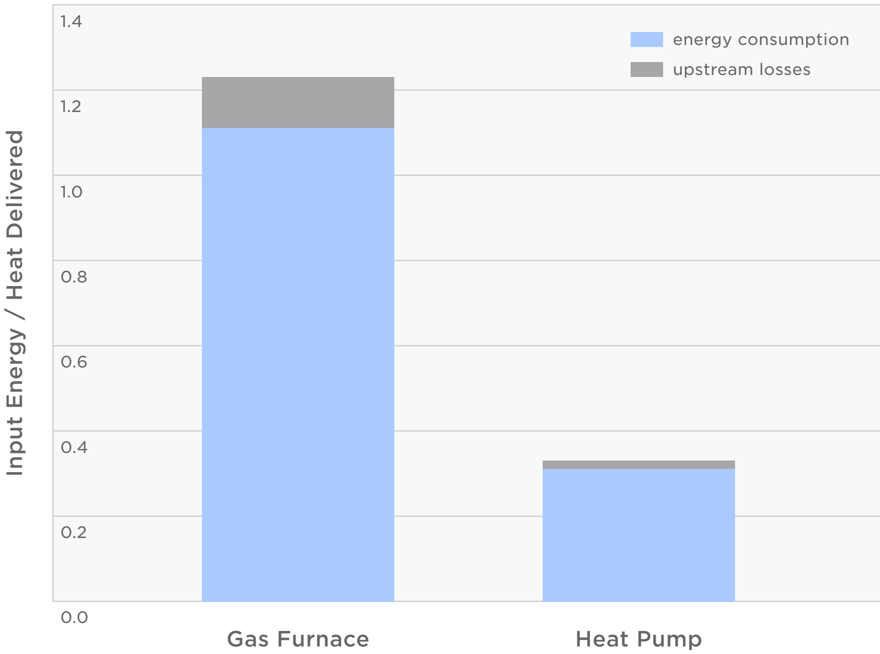

Figure 6: Efficiency improvement of space heating with heat pump vs gas furnace

Residential and Commercial Sectors

The EIA provides historical monthly US natural gas usage for the residential and commercial sectors in each sub-region[8]. The 3x heat-pump efficiency factor reduces the energy demand if all gas appliances are electrified. The hourly load factor of baseline electricity demand was applied to estimate the hourly electricity demand variation from heat pumps, effectively ascribing heating demand to those hours when homes are actively being heated or cooled. In summer, the residential/commercial demand peaks mid-afternoon when cooling loads are highest, in winter demand follows the well-known "duck-curve" which peaks in morning & evening.

Global electrification of residential and commercial appliances with heat pumps eliminates 18 PWh/year of fossil fuel and creates 6PWh/year of additional electrical demand.

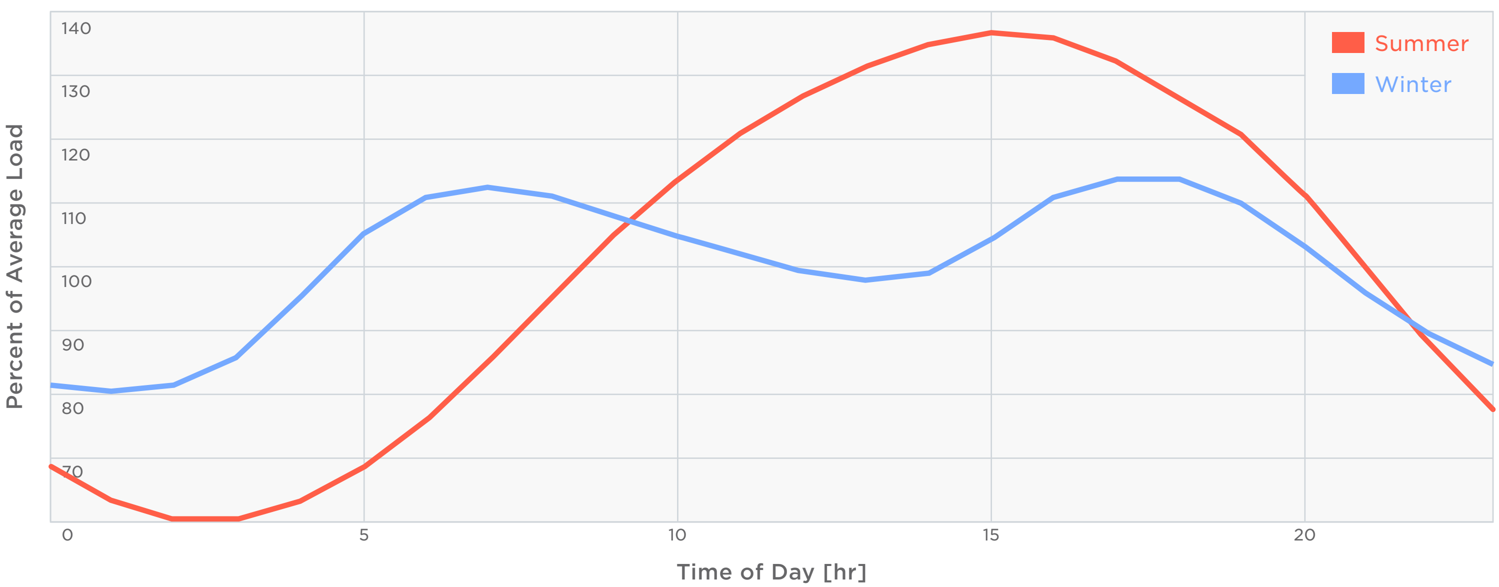

Figure 7: Residential & commercial heating & cooling load factor vs time of day

Industrial Sector

Industrial processes up to ~200C, such as food, paper, textile and wood industries can also benefit from the efficiency gains offered by heat pumps[13], although heat pump efficiency decreases with higher temperature differentials. Heat pump integration is nuanced and exact efficiencies depend heavily on the temperature of the heat source the system is drawing from (temperature rise is key in determining factor for heat pump efficiency), as such simplified assumptions for achievable COP by temperature range are used:

Temperature/Application	COP
0-60C Heat Pump	4.0
60-100C Heat Pump	3.0
100-200C Heat Pump	1.5

Table 2: Assumed Heat Pump Efficiency Improvements by Temperature

Based on the temperature make-up of industrial heat according to the IEA and the assumed heat pump efficiency by temperature in Table 2, the weighted industrial heat pump efficiency factor modeled is 2.2[14,15,16].

The EIA provides historical monthly fossil fuel usage for the industrial sector for each sub-region[8]. All industrial fossil fuel use, excluding embedded fossil fuels in products (rubber, lubricants, others) is assumed to be used for process heat. According to the IEA, 45% of process heat is below 200C, and when electrified with heat pumps requires 2.2x less input energy[16]. The added industrial heat-pump electrical demand was modeled as an inflexible, flat hourly demand.

Global electrification of industrial process heat <200C with heat pumps eliminates 12PWh/year of fossil fuels and creates 5PWh/year of additional electrical demand.

04 Electrify High Temperature Heat Delivery and Hydrogen Production

Electrify High Heat Industrial Processes

Industrial processes that require high temperatures (>200C), account for the remaining 55% of fossil fuel use and require special consideration. This includes steel, chemical, fertilizer and cement production, among others.

These high-temperature industrial processes can be serviced directly by electric resistance heating, electric arc furnaces or buffered through thermal storage to take advantage of low-cost renewable energy when it is available in excess. On-site thermal storage may be valuable to cost effectively accelerate industrial electrification (e.g., directly using the thermal storage media and radiative heating elements)[17,18].

Identify the optimal thermal storage media by temperature/application

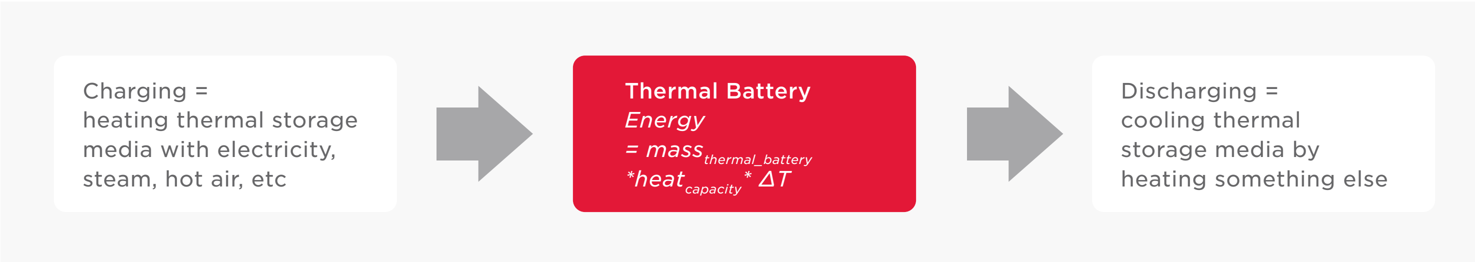

Figure 8: Thermal Storage Overview

Delivering Heat to High Temperature Processes

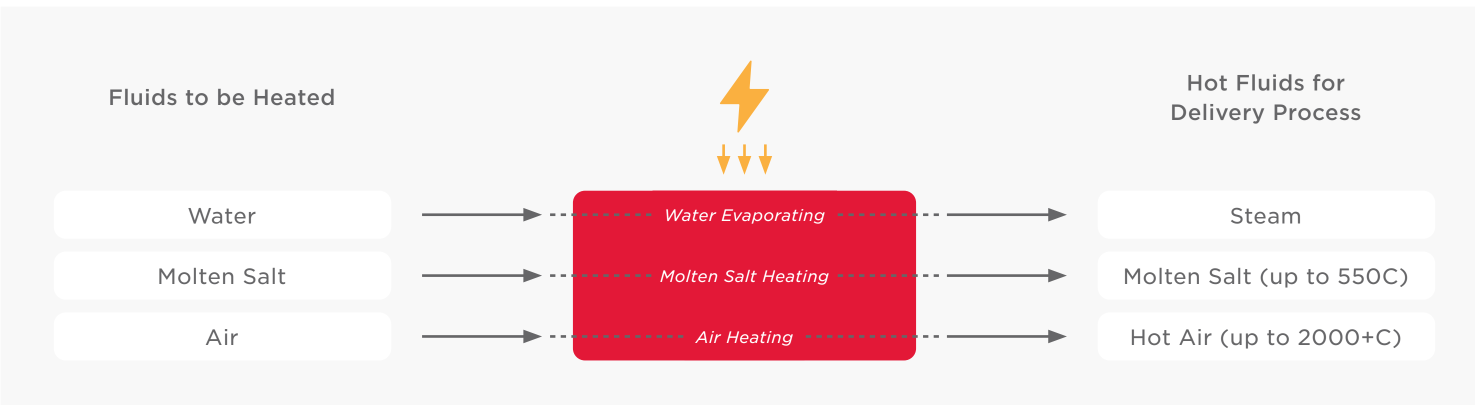

Figure 9A: Thermal Storage - Heat Delivery to Process via Heat Transfer Fluids

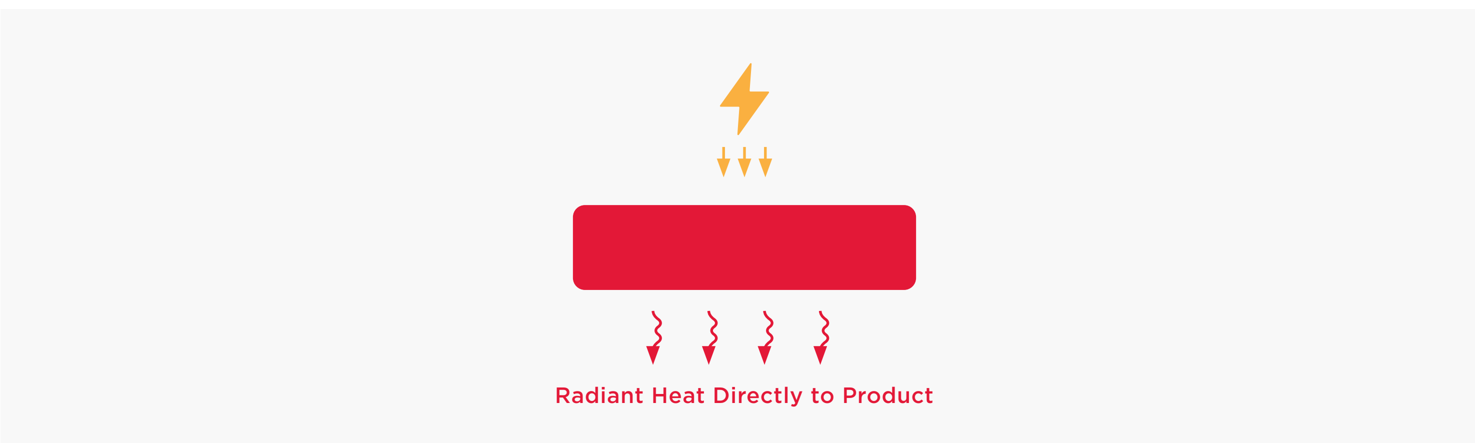

Figure 9B: Thermal Storage - Heat Delivery to Process via Direct Radiant Heating

Electric resistance heating, and electric arc furnaces, have similar efficiency to blast furnace heating, therefore will require a similar amount of renewable primary energy input. These high-temperature processes are modeled as an inflexible, flat demand.

Thermal storage is modeled as an energy buffer for high-temperature process heat in the industrial sector, with a round trip thermal efficiency of 95%. In regions with high solar installed capacity, thermal storage will tend to charge midday and discharge during the nights to meet continuous 24/7 industrial thermal needs. Figure 9 shows possible heat carriers and illustrates that several materials are candidates for providing process heat >1500C.

Global electrification of industrial process heat >200C eliminates 9PWh/year of fossil fuel fuels and creates 9PWh/year of additional electrical demand, as equal heat delivery efficiency is assumed.

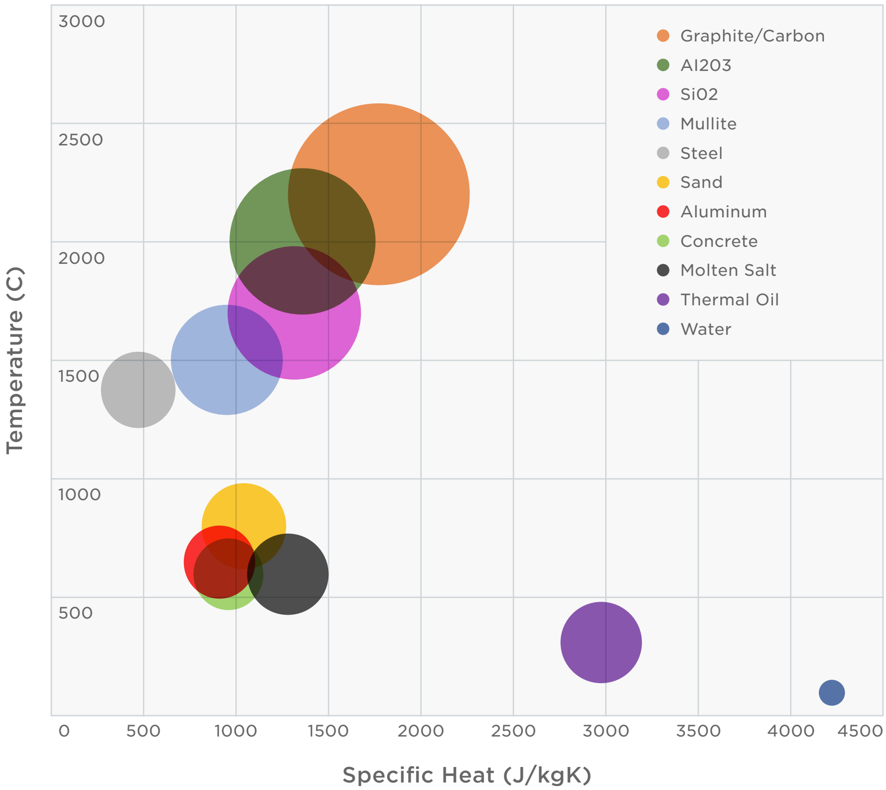

Figure 10: Thermal Storage - Heat Storage Media

Note: Bubble diameters represent specific heat over usable range.

Sustainably Produce Hydrogen for Steel and Fertilizer
Today hydrogen is produced from coal, oil and natural gas, and is used in the refining of fossil fuels (notably diesel) and in various industrial applications (including steel and fertilizer production).

Green hydrogen can be produced via the electrolysis of water (high energy intensity, no carbon containing products consumed/produced) or via methane pyrolysis (lower energy intensity, produces a solid carbon-black byproduct that could be converted into useful carbon-based products)[g].

To conservatively estimate electricity demand for green hydrogen, the assumption is:

- No hydrogen will be needed for fossil fuel refining going forward
- Steel production will be converted to the Direct Reduced Iron process, requiring hydrogen as an input. Hydrogen demand to reduce iron ore (assumed to be Fe_3O_4) is based on the following reduction reaction:

  Reduction by H_2
  - $Fe_3O_4 + H_2 = 3FeO + H_2O$
  - $FeO + H_2 = Fe + H_2O$

- All global hydrogen production will come from electrolysis

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g Sustainable steel production may also be performed through molten oxide electrolysis, which requires heat and electricity, but does not require hydrogen as a reducing agent, and may be less energy intensive, but this benefit is beyond the scope of the analysis[19].

These simplified assumptions for industrial demand, result in a global demand of 150Mt/yr of green hydrogen, and sourcing this from electrolysis requires an estimated ~7.2PWh/year of sustainably generated electricity[h,20,21].

The electrical demand for hydrogen production is modeled as a flexible load with annual production constraints, with hydrogen storage potential modeled in the form of underground gas storage facilities (like natural gas is stored today) with maximum resource constraints. Underground gas storage facilities used today for natural gas storage can be retrofitted for hydrogen storage; the modeled U.S. hydrogen storage requires ~30% of existing U.S. underground gas storage facilities[22,23]. Note that some storage facilities, such as salt caverns, are not evenly geographically dispersed which may present challenges, and there may be better alternative storage solutions.

Global sustainable green hydrogen eliminates 6 PWh/year of fossil fuel energy use, and 2 PWh/year of non-energy use[i,24]. The fossil fuels are replaced by 7PWh/year of additional electrical demand.

05 Sustainably Fuel Planes & Boats

Both continental and intercontinental ocean shipping can be electrified by optimizing design speed and routes to enable smaller batteries with more frequent charge stops on long routes. According to the IEA, ocean shipping consumes 3.2PWh/year globally. By applying an estimated 1.5x electrification efficiency advantage, a fully-electrified global shipping fleet will consume 2.1PWh/year of electricity[25].

Short distance flights can also be electrified through optimized aircraft design and flight trajectory at today's battery energy densities[26]. Longer distance flights, estimated as 80% of air travel energy consumption (85B gallons/year of jet fuel globally), can be powered by synthetic fuels generated from excess renewable electricity leveraging the Fischer-Tropsch process, which uses a mixture of carbon monoxide (CO) and hydrogen (H2) to synthesize a wide variety of liquid hydrocarbons, and has been demonstrated as a viable pathway for synthetic jet fuel synthesis[27]. This requires an additional 5PWh/year of electricity, with:

- H_2 generated from electrolysis[21]
- CO_2 captured via direct air capture[28, 29]
- CO produced via electrolysis of CO_2

Carbon and hydrogen for synthetic fuels may also be sourced from biomass. More efficient and cost-effective methods for synthetic fuel generation may become available in time, and higher energy density batteries will enable longer-distance aircraft to be electrified thus decreasing the need for synthetic fuels.

The electrical demand for synthetic fuel production was modeled as a flexible demand with an annual energy constraint. Storage of synthetic fuel is possible with conventional fuel storage technologies, a 1:1 volume ratio is assumed. The electrical demand for ocean shipping was modeled as a constant hourly demand.

Global sustainable synthetic fuel and electricity for boats and planes eliminates 7PWh/year of fossil fuels, and creates 7PWh/year of additional global electrical demand.

06 Manufacture the Sustainable Energy Economy

Additional electricity is required to build the generation and storage portfolio - solar panels, wind turbines and batteries - required for the sustainable energy economy. This electricity demand was modeled as an incremental, inflexible, flat hourly demand in the industrial sector. More details can be found in the Appendix: Build the Sustainable Energy Economy - Energy Intensity.

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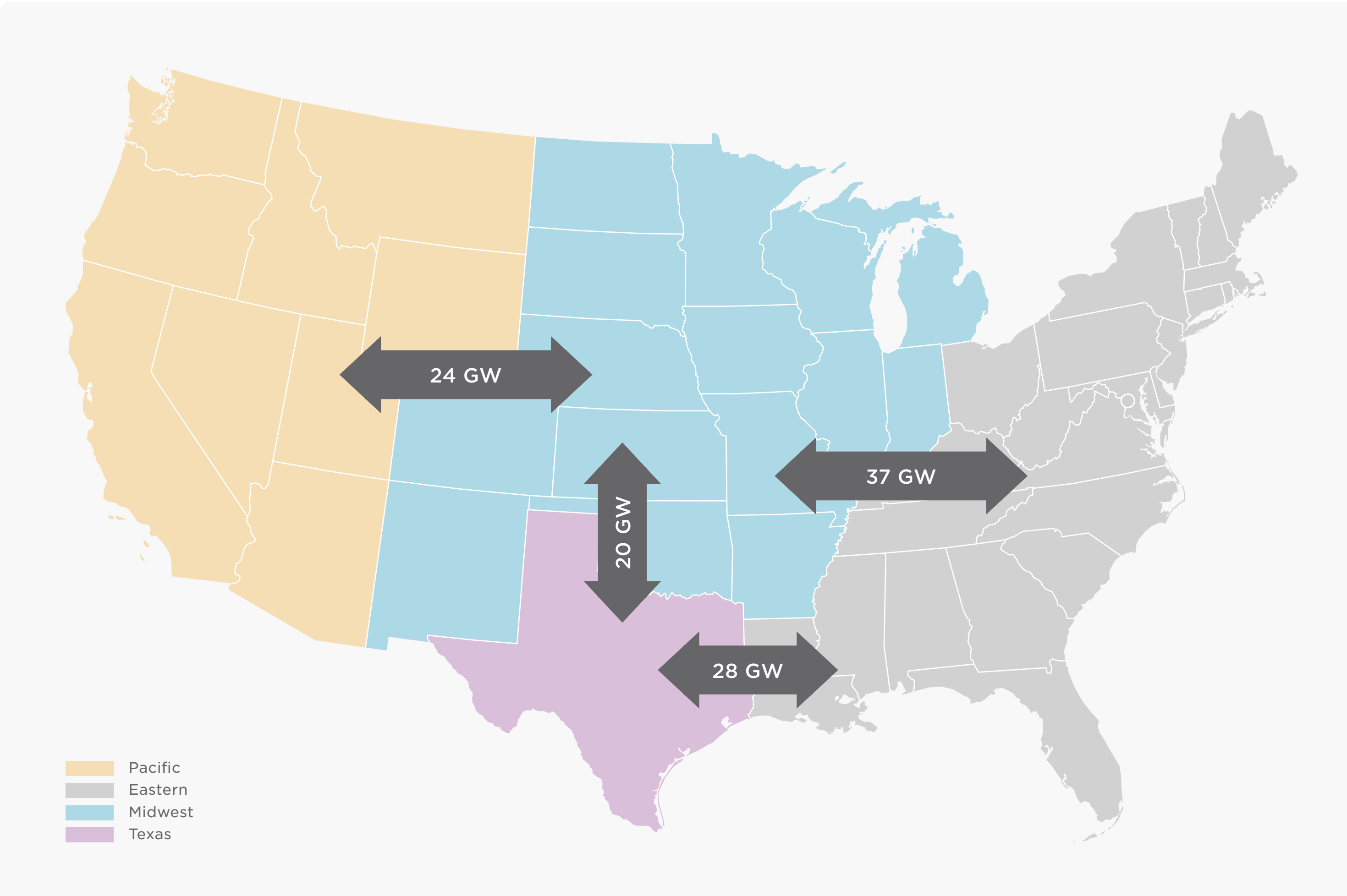
h Adjusted current demand for hydrogen, removing demand related to oil refining, as that will not be required. Assumed all of the hydrogen produced from coal and natural gas today is replaced. Then, the energy required to produce the hydrogen from coal and natural gas, compared to electrolysis, is calculated.

i According to the IEA, 85% of natural gas non-energy consumption is consumed by fertilizer and methanol production

Modeling the Fully Sustainable Energy Economy

These 6 steps create a U.S. electrical demand to be fulfilled with sustainable generation and storage. To do so, the generation and storage portfolio is established using an hourly cost-optimal integrated capacity expansion and dispatch model[j]. The model is split between four sub-regions of the US with transmission constraints modeled between regions and run over four weather-years (2019-2022) to capture a range of weather conditions[k]. Interregional transmission limits are estimated based on the current line capacity ratings on major transmission paths published by North American Electricity Reliability Council (NERC) Regional Entities (SERC[30], WECC[31], ERCOT[32]). Figure 11 shows the fully electrified economy energy demand for the full US.

Modeled Regions and Grid Interconnections



Map 1: US Modeled Regions and Interconnections

j Convex optimization models that can determine optimal capacity expansion and resource dispatch are widely used within the industry. For instance, by utilities or system operators to plan their systems (e.g., generation and grid investments required to meet their expected load), or to assess the impact of specific energy policies on the energy system. This model builds the least-cost generation and storage portfolio to meet demand every hour of the four-year period analyzed and dispatches that portfolio every hour to meet demand. The capacity expansion and dispatch decisions are optimized in one step, which ensures the portfolio is optimal over the period analyzed, storage value is fully reflected and the impact of weather variability modeled. Other analyses typically model capacity expansion and portfolio dispatch as two separate steps. The capacity expansion decisions are made first (e.g. how much generation and storage is estimated to be the least-cost portfolio over the time horizon), followed by separate dispatch modeling of the portfolio mix (e.g. how much generation and storage should be dispatched in each hour to meet demand with sufficient operating reserves). The two-stage approach produces pseudo-optimal results, but allows more computationally intensive models at each stage.

k The model is constrained to meet a 15% operating reserve margin every hour to ensure this generation and storage portfolio is robust to a range of weather and system conditions beyond those explicitely modeled.

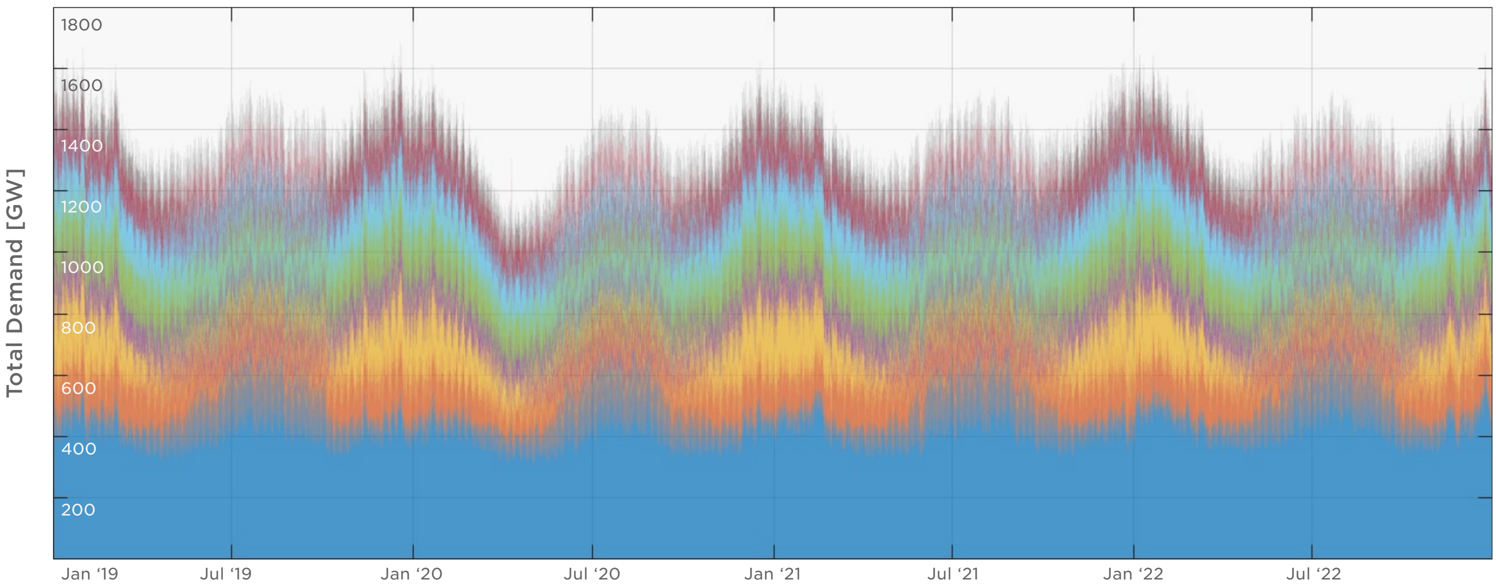


Figure 11: US Fully Electrified Hourly Demand

Wind and solar resources for each region are modeled with their respective hourly capacity factor (i.e., how much electricity is produced hourly per MW of installed capacity), its interconnection cost and the maximum capacity available for the model to build. The wind and solar hourly capacity factors specific to each region were estimated using historical wind/solar generation taken from EIA in each region, thus capturing differences in resource potential due to regional weather patterns[l,m]. Capacity factors were scaled to represent forward looking trends based on the recent Princeton Net-Zero America study[33]. Figure 11 shows the hourly capacity factor for wind & solar versus time for the full US. Table 3 shows the average capacity factor and demand for each region of the US.

l EIA does not report offshore wind production for the period analyzed given the limited existing offshore wind installed capacity. The offshore wind generation profile was estimated by scaling the historical onshore wind generation profile to the offshore wind capacity factor estimated by the Princeton Net-Zero America study.

m Each region is modeled with two onshore wind and two solar resources with different capacity factor, interconnection cost and maximum potential. This accounts for the fact that the most economic sites are typically built first and subsequent projects typically have lower capacity factors and/or higher interconnection cost as they may be farther located from demand centers requiring more transmission or in locations with higher cost land.

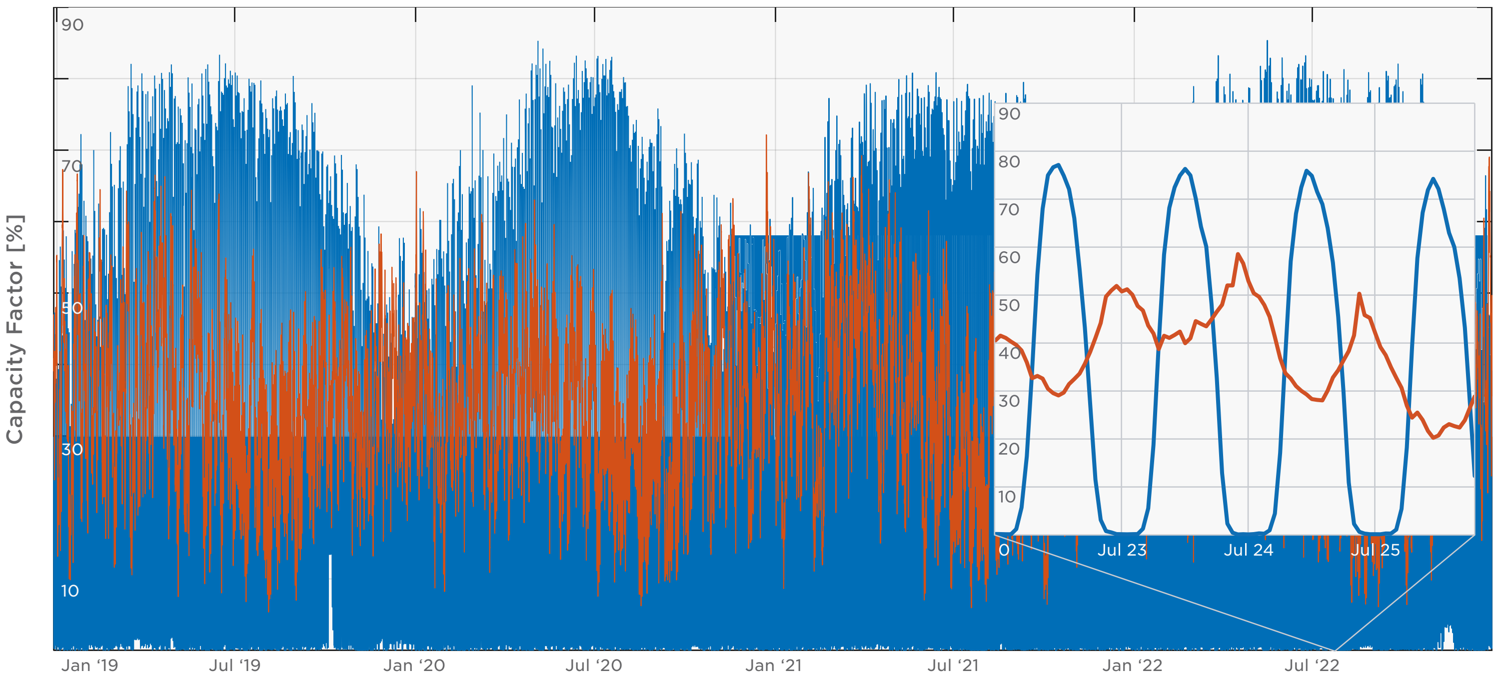


Figure 12: US Historical Hourly Renewable Capacity Factor

Region	Wind CF	Solar CF	Demand [PWh/yr]
East	29%	22%	4.6
Midwest	40%	27%	3.6
Pacific	36%	27%	1.9
Texas	37%	23%	1.6
Full U.S.	34%	24%	11.6

Table 3: Wind and solar average historical capacity factor, and fully electrified economy demand by region

The model builds generation and storage based on resource-specific cost and performance attributes, and a global objective of minimizing the levelized cost of energy[n]. The model assumes increased inter-regional transmission capacities[o].

To provide reliable year-round power, it is economically optimal to deploy excess solar and wind capacity, which leads to curtailment. Curtailment will happen when (1) solar and/or wind generation is higher than the electricity demand in a region, (2) storage is full and (3) there is no available transmission capacity to transmit the excess generation to other regions. There is an economic tradeoff between building excess renewable generation capacity, building grid storage, or expanding transmission capability. That tradeoff may evolve as grid storage technologies mature, but with the assumptions modeled, the optimal generation and storage portfolio resulted in 32% curtailment.

n Costs considered in the objective function: levelized capex of new generation and storage with a 5% discount rate, fixed and variable operational and maintenance (O&M) costs.

o 37 GW of transmission capacity is modeled between the Midwest and the East, 28 GW between Texas and the East, 24 GW between Pacific and the Midwest and 20 GW between Texas and the Midwest. This corresponds to ~3% of the modeled combined regional peak load. E.g., the peak load of the combined East and Midwest regions was ~1.2 TW, and the transmission capacity between Midwest and the East modeled as 37 GW. Currently, the transmission capacity is <1% of the combined regional peak loads (with transmission to/from Texas the lowest). Higher transmission capacities generally reduce the total generation and storage buildout, but there is an economic tradeoff between building more transmission and building more generation plus storage.

For context, curtailment already exists in markets with high renewable energy penetration. In 2020, 19% of the wind generation in Scotland was curtailed, and in 2022, 6% of solar generation in California (CAISO) was curtailed due to operational constraints, such as thermal generators' inability to ramp down below their minimum operating level, or local congestion on the transmission system[34,35].

The sustainable energy economy will have an abundance of inexpensive energy for consumers able to use it during periods of excess, which will impact how and when energy is used.

In Figure 12 below, hourly dispatch is depicted across a sample of fall days, showing the role of each generation and storage resource in balancing supply and demand, as well as the concentration of economic curtailment in the middle of the day when solar is abundant.

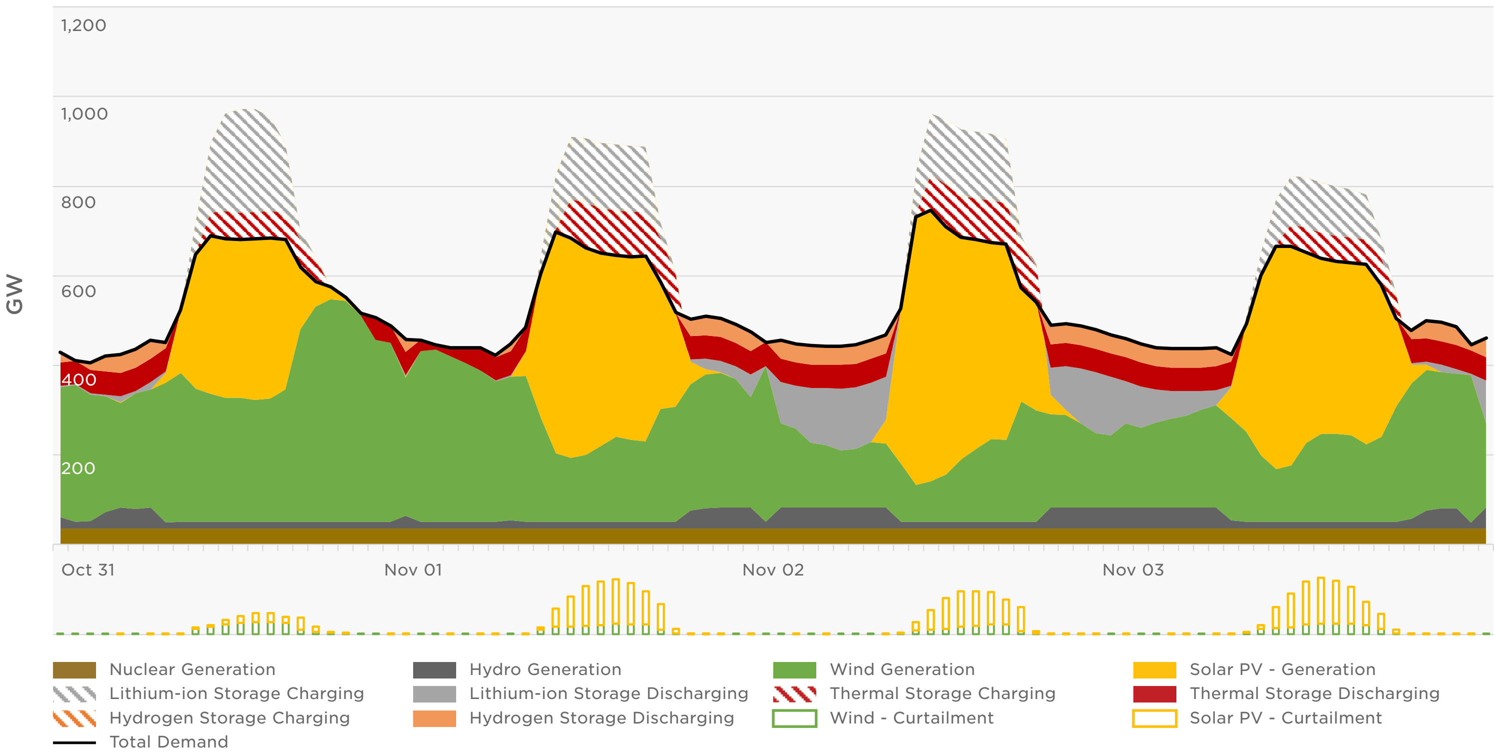


Figure 13: Hourly generation in 2019 in US Eastern region (excluding imports/exports)

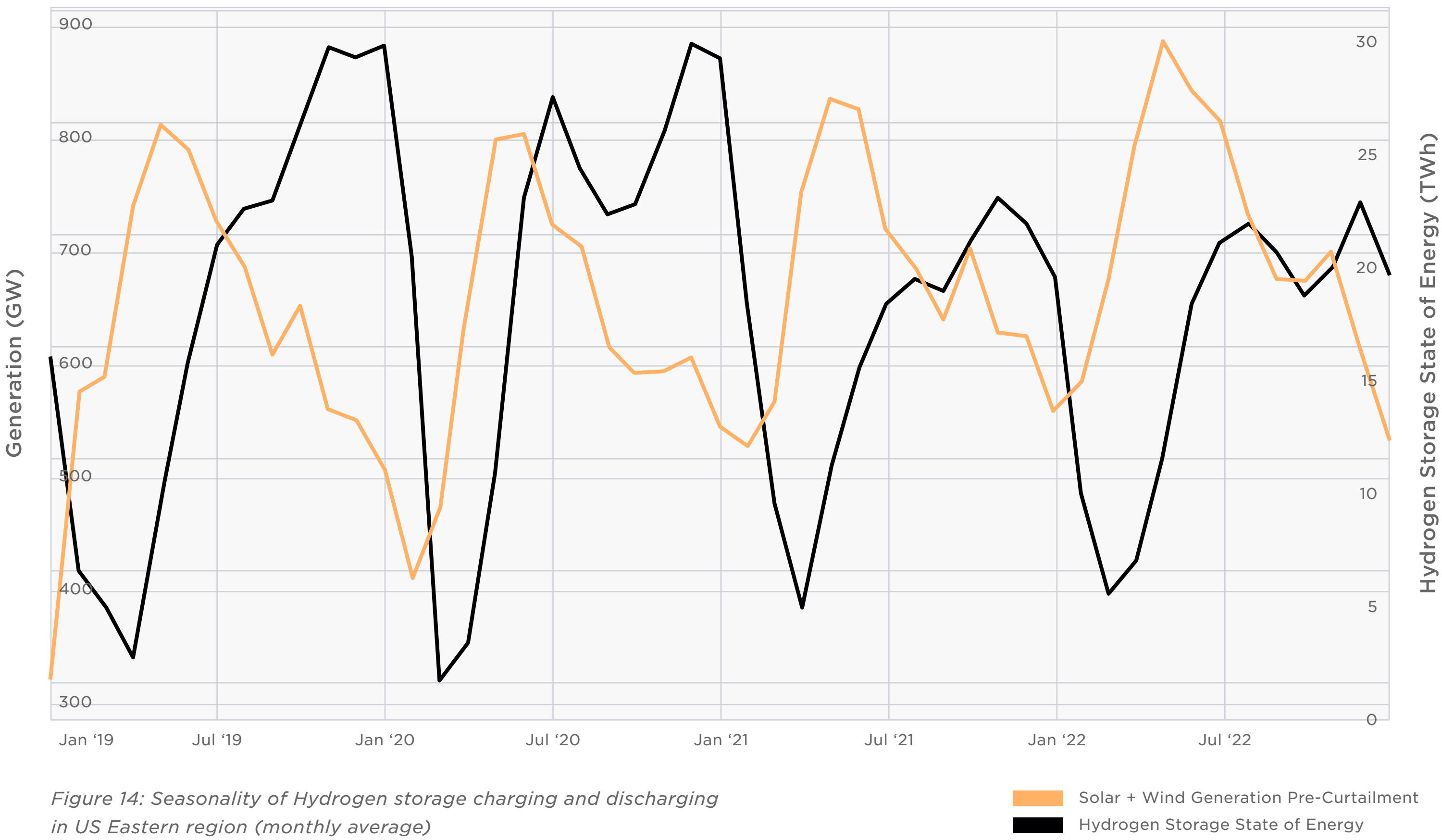


Figure 14: Seasonality of Hydrogen storage charging and discharging in US Eastern region (monthly average)

In Figure 14, hydrogen storage is generally filled during the shoulder months (spring and fall) when electricity demand is lower as heating and cooling seasons are over, and solar and wind generation is relatively high. Similarly, as excess generation declines in summer and winter months, hydrogen reservoirs decline providing inter-seasonal hydrogen storage.

Energy Storage Technologies Evaluated

For stationary applications, the energy storage technologies in Table 4 below, which are currently deployed at scale, are considered. Li-ion means $LiFePO_4$/Graphite lithium-ion batteries. A range of conservative future installed costs are listed for lithium ion given the volatility in commodities prices (especially lithium). While there are other emerging technologies such as metal-air (Fe <-> Fe_2O_3 redox couple) and Na-ion, these are not commercially deployed and therefore not considered.

Storage	Technology	2030-2040 Installed Cost[p]	O&M Cost (/kW-yr)	RTE	Annual Cycling Limit	Lifetime	Technical Potential (limitation)
Mechanical	Thermal (15h)	$78/kWh[r]	$15.00[q]	95%[r]	NA	20 years[r]	Industrial thermal loads only
-	Pumped Hydro	>$270/kWh[36]	$17.80[44]	80%[44]	NA	100 years	<26TWh (reservoir volumes)[36]
-	Seasonal Hydro (~2mo)	NA	NA	-	~5.7 (in-flow limited)	100 years	<90TWh (volume & in-flows)[37]
E-chem	Li-ion (4h-8h)	$184-$231/kWh[r]	$0.80[38]	95%[r]	365[r]	20 years[r]	-
H^2	Geological/ Salt Caverns	$19/kg of H^2 [39]	NA	98%	NA	50+ years	-

Table 4: Energy Storage Technologies Evaluated

p This includes the storage equipment cost, balance of system, interconnection and installation cost.
q Efficiency for the electricity to thermal conversion. The model does not include generating electricity from heat.

Generation Technologies Evaluated

The Table below details all the generation technologies considered in the sustainable energy economy. Installed costs were taken from studies for 2030-2040 from NREL and the Princeton Net-Zero America study.

Generation	2030-2040 Installed Cost	O&M Cost (/kW-yr)	Capacity Factor	Lifetime	Model Constraint	US Technical Potential (limitation)
Solar	$752/kW[44] + interconnection[40]	$15.97[41]	23-28%[40]	30 years[44]	Technical potential per region/resource class[40]	<153 TW (available land)[42]
Onshore Wind	$855/kW[44] + interconnection[40]	$27.57[41]	36-52%[40]	30 years[s]	Technical potential per region/resource class[40]	<11 TW (available land)[42]
Offshore Wind	$2,401/kW[44] + interconnection[40]	$76.51[44]	48-49%[40]	30 years[s]	Technical potential per region/resource class[40] Technology only available in East region	<1 TW[43,45]
Hydro	$4,200/kW[44] to $7,000/kW	$61.41[44]	NA	100 years	152 GW Exogenously Built	<152 GW (river flow rates)[46]
Nuclear	$10,500/kW[t]	$127.35[41]	Modeling Output	<80 years	No New Nuclear	NA (deployment pace)
Geothermal	$5,616/kW[44]	$99.32[44]	>95%[47]	30 years[44]	No New Build	<100 GW[u]

Table 5: Generation Technologies Evaluated

r Internal estimate.

s Assumed lifetime improvement. The NREL 2019 Cost of Wind Energy Review estimates wind cost with 25-year lifetime as reference and creates sensitivities with 30-year lifetime

t Assumed 50% higher capex than the EIA Cost and Performance Characteristics of New Generating Technologies

u Excluding Deep Enhanced Geothermal System Resources

Model Results

US Only Model Results – Meeting New Electrification Demand
For the US, the optimal generation and storage portfolio to meet the electricity demand, each hour, for the years modeled is shown in the Table below.

Electricity Generation Technology	Installed Capacity (GW)	Annual Generation[v] (TWh)	Annual Generation Curtailed[w] (TWh)
Onshore Wind	1,971	6,060	1,721
Offshore Wind	64	212	62
Solar PV	3,052	4,046	2,431
Nuclear (Existing)	99	699	Na
Hydro	152	620	Na
Total	**5,338**	**11,637**	**4,214**

Storage/Other Technologies	Installed Capacity (GW)	Installed Capacity (TWh)
8h Lithium-ion Storage	815	6.5
Industrial Thermal Storage	453	6.9
Electrolyzer	418	Na
Hydrogen Storage[x]	Na	107
Total	**1,686**	**120**

Table 6: Model Results for US only

In addition, 1.2 TWh of distributed stationary batteries are added based on incremental deployments of distributed stationary storage alongside rooftop solar at residential and commercial buildings. This includes storage deployments at 15 million single-family homes[48] with rooftop solar, industrial storage paired with 43GW[49,50] of commercial rooftop solar, and storage replacement of at least 200GW[51] of existing backup generator capacity[y]. Distributed storage deployments are exogenous to the model outputs given deployment driven by factors not fully reflected in a least-cost model framework, including end-user resiliency and self-sufficiency when storage is paired with rooftop solar.

v After accounting for curtailment.
w The model curtails wind/solar generation when the electricity supply is higher than the electricity demand and battery/thermal/hydrogen storage are full already. Curtailed wind/solar generation is generation that isn't consumed by end-uses.
x 17.8 TWh of jet fuel derived from H2 are stored with current infrastructure
y Solar and storage is deployed at less than one-third of suitable residential buildings designated by NREL. Four hours of storage is assumed for C&I deployment and for backup generator substitution.

World Model Results – Meeting New Electrification Demand

Applying the 6 steps to the world's energy flow would displace all 125PWh/year of fossil fuels used for energy use and replace them with 66PWh/year of sustainably generated electricity[z]. An additional 4PWh/year of new industry is needed to manufacture the required batteries, solar panels and wind turbines (assumptions can be found in Appendix: Build the Sustainable Energy Economy – Energy Intensity).

The global generation and storage portfolio to meet the electricity demand was calculated by scaling the US resource mix by 6x. As noted above, this is a significant simplification and could be an area for improvement in future analyses, as global energy demands are different from the U.S. in their composition and expected to increase over time. This analysis was conducted on the U.S. due to availability of high-fidelity hourly data.

Sustainable Energy Economy [PWh/year]

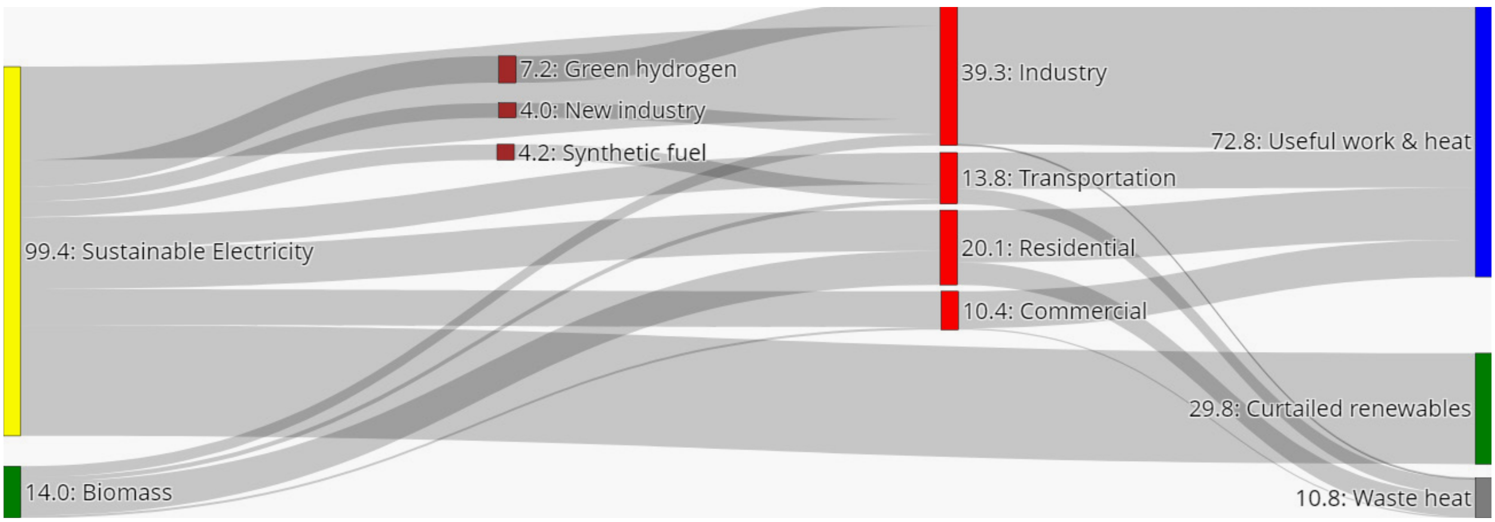


Figure 15: Sustainable Energy Economy, Global Energy Flow by Sector, IEA & Tesla analysis

z Remaining ~9PWh/year of fossil fuels are consumed through non-energy uses

Batteries for Transportation

Vehicles
Today there are 1.4B vehicles globally and annual passenger vehicle production of ~85M vehicles, according to OICA. Based on pack size assumptions, the vehicle fleet will require 112 TWh of batteries[aa]. Autonomy has potential to reduce the global fleet, and annual production required, through improved vehicle utilization.

Standard-range vehicles can utilize the lower energy density chemistries (LFP), whereas long-range vehicles require higher energy density chemistries (high nickel). Cathode assignment to vehicle segment is listed in the table below. High Nickel refers to low to zero cobalt Nickel Manganese cathodes currently in production, under development at Tesla, Tesla's suppliers and in research groups.

Vehicle Type	Tesla Equivalent	Cathode	Pack Size (kWh)	Vehicle Sales	Global Fleet	Global Fleet (TWh)
Compact	[TBD]	LFP	53	42M	686M	36
Midsized	Model 3/Y	LFP	75	24M	380M	28
Commercial/ Passenger Vans	[TBD]	High Nickel	100	10M	163M	16
Large Sedans, SUVs & Trucks	Model S/X, Cybertruck	High Nickel	100	9M	149M	15
Bus	[TBD]	LFP	300	1M	5M	2
Short Range Heavy Truck	Semi Light	LFP	500	1M	6.7M	3
Long Range Heavy Truck	Semi Heavy	High Nickel	800	2M	13.3M	11
Total	**-**	**-**	**-**	**89M**	**1,403M**	**112**

Table 7: Vehicle Fleet Breakdown

aa To approximate the battery storage required to displace 100% of road vehicles, the global fleet size, pack size (kWh)/ Global passenger fleet size and annual production (~85M vehicles/year) is based on data from OICA. The number of vehicles by segment is estimated based on S&P Global sales data. For buses and trucks, the US-to-global fleet scalar of ~5x is used as global data was unavailable

Global Electric Fleet

Ships and Planes
With 2.1PWh of annual demand, if ships charge ~70 times per year on average, and charge to 75% of capacity each time, then 40TWh of batteries are needed to electrify the ocean fleet. The assumption is 33% of the fleet will require a higher density Nickel and Manganese based cathode, and 67% of the fleet will only require a lower energy density LFP cathode. For aviation, if 20% of the ~15,000 narrow body plane fleet is electrified with 7MWh packs, then 0.02TWh of batteries will be required.

These are conservative estimates and likely fewer batteries will be needed.

	Cathode	Global Fleet (TWh)
Longer Range Ship	Ni/Mn Based	12
Shorter Range Ship	LFP	28
Plane	High Nickel	0.02
Total	-	**40**

Table 8: Electric Ship and Plane Fleet Breakdown

World Model Results – Electrification & Transportation Batteries

Table 9 summarizes the generation and storage portfolio to meet the global electricity demand and the transportation storage required based on the vehicle, ship and plane assumptions. Explanation of how the generation and storage portfolios were allocated to end-uses can be found in Appendix: Generation and storage allocation to end-uses.

	Vehicle Batteries (TWh)	Planes & Ships Batteries (TWh)	Stationary E-chem Batteries (TWh)	Stationary Thermal Batteries (TWh)	Solar Generation (TW)	Wind Generation (TW)	Solar + Wind (TW)	Electrolyzers (TW)	Hydrogen Storage (TWh)
Repower the Existing Grid with Renewables	-	-	22.9	-	6.8	3.8	10.6	-	-
Switch to Electric Vehicles	112	-	3.7	-	3.3	1.5	4.9	-	-
Switch to Heat Pumps in Residential, Business & Industry	-	-	6.7	-	2.7	2.1	4.8	-	-
Electrify High Temperature Heat Delivery	-	-	4.1	41.4	1.3	1.5	2.8	-	-
Hydrogen	-	-	4.4	-	2.1	1.6	3.7	2.5	642
Sustainably Fuel Planes & Boats	-	40	4.4	-	2.1	1.6	3.7	-	-
Total	**112**	**40**	**46.2**	**41.4**	**18.3**	**12.1**	**30.3**	2.5	**642**

Table 9: Generation and Storage Portfolio to Meet the Global Electricity Demand & Transportation Batteries

Vehicle & Stationary Batteries (TWh)

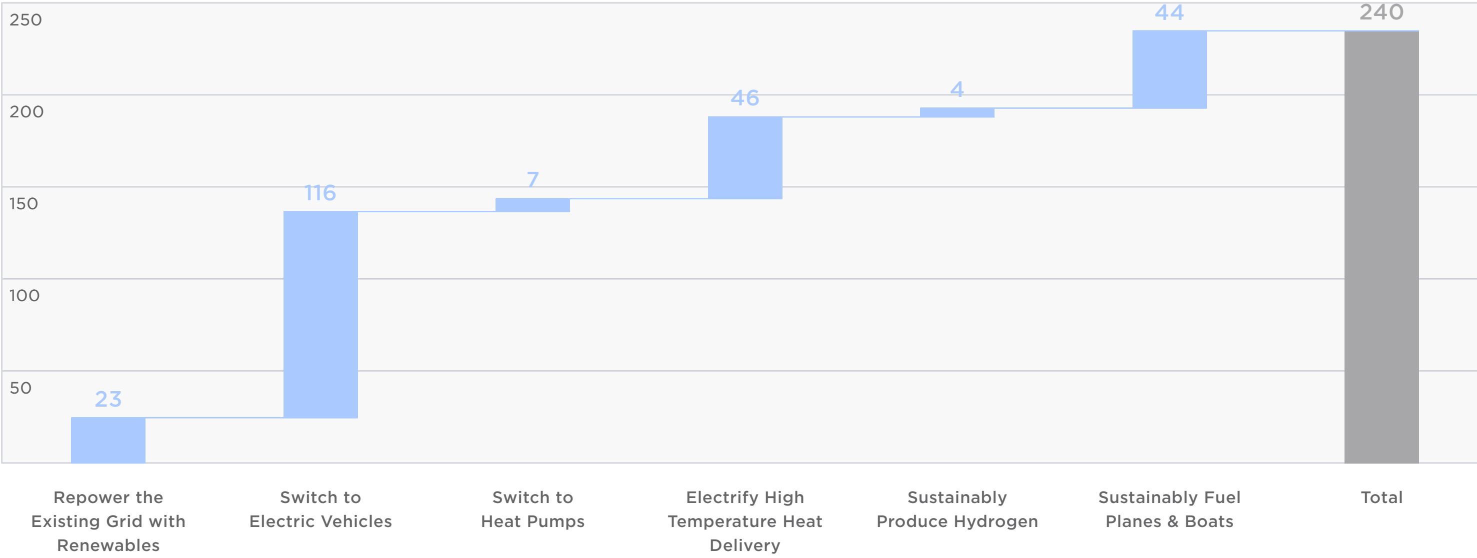


Table 10: Storage Waterfall

Solar & Wind Farms (TW)

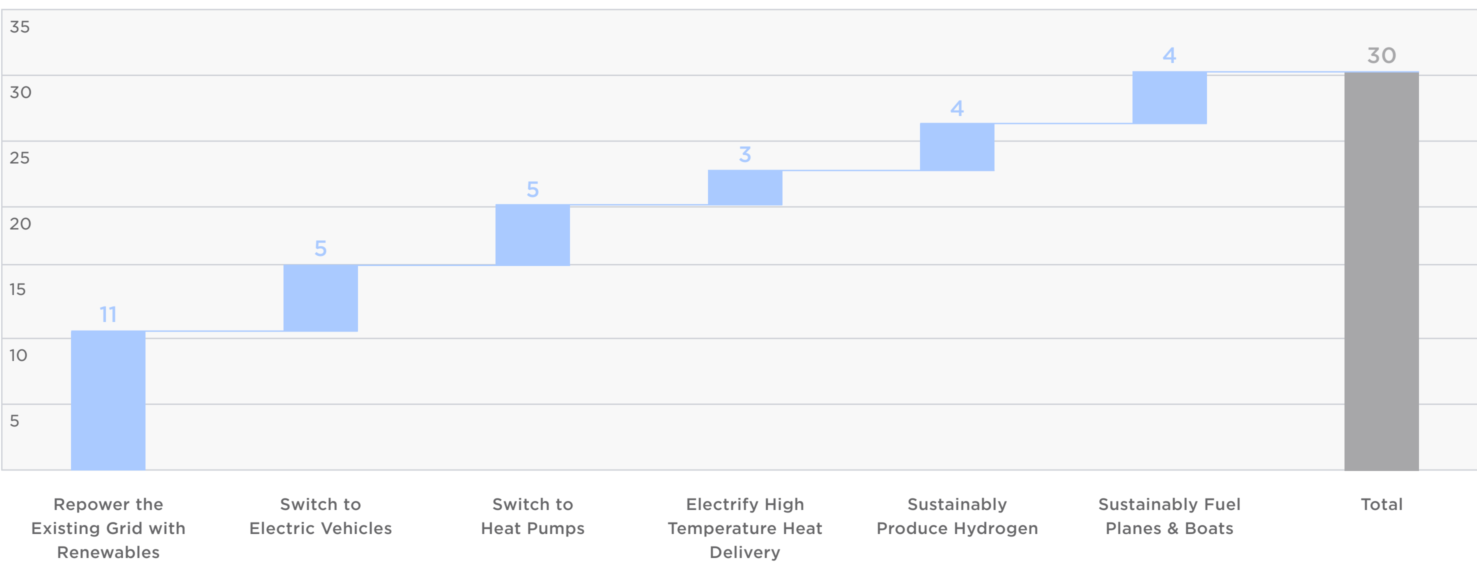


Table 11: Solar & Wind Waterfall

Investment Required

Investment catalogued here is inclusive of the manufacturing facilities, mining and refining operations for materials that require significant growth, and hydrogen storage salt cavern installation. Manufacturing facilities are sized to the replacement rate of each asset, and upstream operations (e.g., mining) are sized accordingly[bb]. Materials that require significant capacity growth are:

For mining: nickel, lithium, graphite and copper.

For refining: nickel, lithium, graphite, cobalt, copper, battery grade iron and manganese.

In addition to initial capex, 5%/year maintenance capex with a 20-year horizon is included in the investment estimate. Using these assumptions, building the manufacturing infrastructure for the sustainable energy economy will cost $10 trillion[cc], as compared to the $14 trillion projected 20-year spend on fossil fuels at the 2022 investment rate[52].

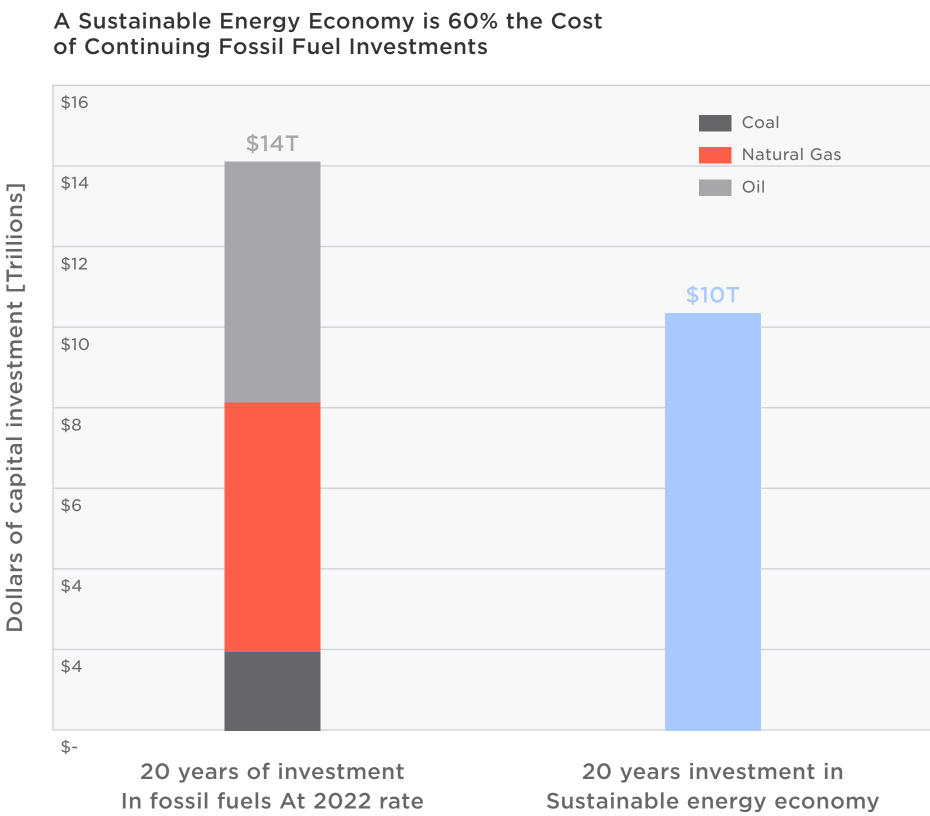


Figure 16: Investment Comparison

bb For example, if 46 TWh of stationary LFP battery storage is required, and the life of a battery is 20 years, then the manufacturing capacity is sized to 2.3 TWh/year

cc In-scope manufacturing capacity investments: wind turbines, solar panels, battery cells, upstream battery inputs, mining, refining, electric vehicles, heat pumps, and electrolyzers, carbon capture, and Fischer Tropsch. Salt cavern hydrogen storage is also included

Category	Unit	Annual Capacity (units)	Capital Intensity/Unit	Initial Investment	Total Investment (includes 20yrs. of 5% sustaining capex)	Notes/Source
Solar Panel Factories	GW/yr.	610	$347.3M	$212B	$424B	First Solar Alabama factory estimate, plus internal estimate for solar recycling
Wind Turbine Factories	GW/yr.	402	$26.5M	$11B	$21B	Internal estimate
Vehicle Factories	Car/yr.	89M	$10K	$890B	$1,780B	Internal estimate of industry average
E-chem Battery Factories	GWh/yr.	11,488	$95M	$1,091B	$2,183B	Internal estimate of Industry avg, includes recycling
Stationary E-chem Factories (e.g. Megapack)	GWh/yr.	2,310	$10M	$23B	$46B	Internal estimate of industry average
Stationary Thermal Factories	GWh/yr.	2,070	$24M	$50B	$99B	Internal estimate
Transportation - Mining/Refining	GWh/yr.	9,178	$91.2M	$837B	$1,674B	Internal estimate of industry average based on public industry reports
Stationary - Mining/Refining	GWh/yr.	2,310	$81.9M	$189B	$378B	Internal estimate of industry average based on public industry reports
Generation - Mining/Refining	GW/yr.	1,013	$136.6M	$138B	$277B	Internal estimate of industry average based on public industry reports
Upstream E-chem for Vehicles	GWh/yr.	9,178	$24.1M	$221B	$443B	Internal estimate
Upstream E-chem for Stationary	GWh/yr.	2,070	$16.2M	$34B	$67B	Internal estimate
Heat Pumps	Total	Na	Na	$30B	$60B	Assume $3B mfg capex to replace home heat pumps; conservatively $30B for all heat pumps
Electrolyzers	kW/yr.	2.5B	$230	$577B	$1,155B	Assumes PEM Technology; cost will depend on learning curve achieved[53]
Carbon Capture (synthetic fuels)	Ton CO_2 /yr.	800M	$200	$160B	$320B	Yet to be demonstrated at large scale; cost will depend on learning curve achieved[54,55]
Fischer Tropsch (synthetic fuels)	Barrel per day	5.5M	$70K	$385B	$770B	Assumes efficiency curve as project scale increases[56]
Hydrogen Storage	kg	NA	$19	$362B	$725B	$19/kg[39]
Total	-	-	-	**$5,211B**	**$10,421B**	-

Table 12: Investment Summary

Table 13 Provides additional detail into mining, refining, vehicle factories, battery factories and recycling assumptions. Mining and refining assumptions are an internal estimate of industry average based on public industry reports:

Mining

	Unit	Capital Intensity/Unit	kt Required/Year	Required Capex
Ni	kt/year	$51M	2,850	$145B
LHM (Li)	kt/year	$25M	6,785	$170B
Gr	kt/year	$10M	10,446	$104B
Cu	kt/year	$12.5M	6,600	$83B
			Total Mining Capex	**$502B**

Table 13A: Additional Investment Assumption Detail

Refining

	Unit	Capital Intensity/Unit	kt Required/Year	Required Capex
Ni	kt/year	$20M	2,850	$57B
Co	kt/year	$30M	16	$0
LHM (Li)	kt/year	$30M	6,785	$204B
Fe	kt/year	$14M	6,025	$84B
Gr	kt/year	$17M	10,446	$178B
Cu	kt/year	$20M	6,600	$132B
Mn	kt/year	$14M	530	$7B
			Total Mining Capex	**$662B**

Table 13B: Additional Investment Assumption Detail

Vehicle & Battery Factories

	Unit	Capital Intensity/Unit	Annual Capacity Needed	Required Capex	Notes/Source
Vehicle Factories	Cars/year	$10K	89M	$890B	Internal estimate of industry average
E-Chem Battery Factories	GWh/year	$80M	11,488	$919B	Internal estimate of industry average
Thermal Battery Factory	GWh/year	$10M	2,070	$21B	Internal estimate
Batterypack Factory	GWh/year	$10M	2,310	$23B	Internal estimate
Upstream Battery Materials	GWh/year	$24.9M	9,178	$229B	Internal estimate
			Total Mining Capex	**$2,082B**	

Table 13C: Additional Investment Assumption Detail

Recycling

	Unit	Capital Intensity/Unit	Annual Capacity Needed	Required Capex	Notes/Source
Echem Battery Recycling	GWh/year	$15M	11,488	$172B	Internal estimate
Thermal Battery Recycling	GWh/year	$14M	2,070	$29B	Internal estimate
Solar Recycling	GW/year	$14M	610	$9B	Internal estimate
Turbine Recycling	GW/year	$14M	402	$6B	Internal estimate
			Total Mining Capex	**$215B**	

Table 13D: Additional Investment Assumption Detail

Land Area Required

Solar land area requirement is estimated based on a US Lawrence Berkeley National Laboratory (LBNL) empirical assessment of actual US projects, which found that the median power density for fixed-tilt systems installed from 2011-2019 was 2.8 acres/MWdc[57]. Converting MWdc to MWac using a 1.4 conversion ratio yields roughly 3.9 acres/MWac. Therefore, the global solar panel fleet of 18.3TW will require roughly 71.4 million acres, or 0.19% of the total 36.8 billion acres global land area.

Wind land area requirement is estimated based on a US National Renewable Energy Laboratory (NREL) study which found that the direct land usage is 0.75 acres per MW[58]. Therefore, the global wind turbine fleet of 12.2TW will require an estimated 9.2 million acres, or 0.02% of total land area.

Table 14: Solar and Wind Direct Land Area by Continent

Solar Direct Land Area 0.19% of Land

Wind Direct Land Area 0.02% of Land

Materials Required

Assumptions

The total materials required for solar panels, wind turbines, and circuit miles miles are calculated based on third party material intensity assumptions. Battery material intensity is based on internal estimates. Solar panel and wind turbine material intensity assumptions are from a European Commission report. Solar cells are wafer-based crystalline silicon, and rare earth minerals are eliminated from wind turbines, given the progress demonstrated in developing technologies[59].

Based on IEA's 2050 Net Zero pathways study, approximately 60 million circuit miles will need to be added or reconductored globally to achieve a fully sustainable, electrified global economy. Distribution capacity will primarily be expanded by reconductoring existing lines and expanding substation capacity that can accommodate significant growth in peak and average end-user demand. High-voltage transmission will primarily expand geographic coverage to connect large wind and solar generation capacity to densely populated areas. For purposes of estimating material requirements, 90% of the 60 million circuit miles will be reconductoring of existing low-voltage distribution systems and 10% will be new circuit-miles from high-voltage transmission, which is the current ratio of US circuit miles between high-voltage transmission and low-voltage distribution[60,61].

ton/GW	Solar	Wind	Notes
Concrete	56,200	328,250	-
Steel	62,800	119,500	-
Glass	42,900	8,050	-
Plastic	7,900	-	-
Aluminum	7,500	1,050	-
Copper	4,300	2,975	-
Iron	-	19,400	-
Silicon	2,000	-	-
Zinc	-	5,500	-
Polymers	-	4,600	-
Manganese	-	790	-
Chromium	-	525	-
Nickel	-	340	-
Molybdenum	-	109	exclude, design out
Neodymium	-	96	exclude, design out
Silver	4	-	-
Praseodymium	-	18	exclude, design out
Dysprosium	-	8	exclude, design out
Terbium	-	4	exclude, design out
Boron	-	3	exclude, design out

Table 15: Generation Materials: Tons per GW[62]

kg/kWh	High Ni	LFP	Ni/Mn Based	Thermal
Ni	0.75	-	0.40	-
Co	-	-	0.06	-
Al	0.09	0.33	0.12	-
Mn	-	-	0.73	-
Fe	-	0.78	-	-
P	-	0.42	-	-
Cu	0.17	0.27	0.23	-
Gr	0.59	1.05	0.89	4.00
Si	0.04	-	-	-
LHM (Li)*	0.54	0.61	0.63	-

Table 16: Battery Materials: kg per kWh

kg/km	Concrete	Steel	Aluminum	Copper	Glass	Lead
HV Overhead	209,138	52,266	12,883	-	1,100	-
HV Underground	17,500	-	-	11,650	-	14,100
MV Overhead	-	802	-	1,488	-	-
MV Underground	-	-	824	663	-	-
LV Overhead	-	-	981	-	-	-
LV Underground	-	177	531	-	-	-

Table 17: Transmission Materials: kg per km[63]

Using the above assumptions, 12,815 million tonnes in total (444 million tonnes annually) will be required to manufacture 30 TW of generation, 240 TWh of battery storage, and 60M transmission miles.

* LHM is equivalent to LiOH-H2O and has approximately 6x the mass as the Lithium alone

Total Materials

Material	Generation	Battery	Transmission	Total
Nickel	4	36	-	40
Cobalt	-	1	-	1
Aluminum	150	52	210	412
Manganese	10	8	-	18
Iron	2,826	113	495	3,434
Copper	115	49	-	164
Graphite	-	353	-	353
LHM (Li)	-	118	-	118
Silver	0.07	-	-	0.07
Zinc	66	-	-	66
Phosphorus	-	61	-	61
Concrete	4,991	-	2,019	7,010
Plastic	145	-	-	145
Glass	883	-	11	893
Silicon	37	2	-	38
Polymers	56	-	-	56
Chromium	6	-	-	6
Total	**9,288**	**793**	**2,734**	**12,815**

Annual Materials

Material	Generation	Battery	Transmission	Total
Nickel	0	3	-	3
Cobalt	-	0	-	0
Aluminum	5	3	7	15
Manganese	0	0	-	1
Iron	94	6	16	117
Copper	4	3	-	7
Graphite	-	19	-	19
LHM (Li)	-	7	-	7
Silver	0.002	-	-	0.002
Zinc	2	-	-	3
Phosphorus	-	3	-	3
Concrete	166	-	67	234
Plastic	5	-	-	5
Glass	29	-	0.4	30
Silicon	1	-	-	1
Polymers	2	-	-	2
Chromium	0.2	-	-	0.2
Total	**310**	**43**	**91**	**444**

Table 18: Total Material Intensity [Mt]

Material Extraction

The mass flows associated with these materials (i.e., how much earth is moved) relies on ore grade and through-process yield. Using an internal estimate of industry average compiled from public industry reports (See Table 19), the required annual mass flow is estimated to be 3.3 gigatonnes (Gt). Mass flows can reduce if aluminum (50% ore grade) is substituted for copper (1% ore grade), which is possible in many use cases. It is assumed that 50% of lithium is extracted from brine 100% ore grade, if this is not the case, then the mass flow associated with lithium would increase by 0.8Gt.

According to the Circularity Gap Report 2023, 68Gt of material, excluding biomass, is extracted from the earth each year – fossil fuels account for 15.5Gt of this[64]. In a sustainable energy economy, material extraction will decrease by 10.8Gt – with most fossil fuel extraction replaced by 3.3Gt of renewable material extraction. The assumption is that fossil fuel extraction associated with non-energy end uses (i.e. plastics and other chemicals) continues, approximately 9% of the fossil fuel supply, according to the IEA.

	Ore %	Through-Process Yield	Peak Ore Mined (Mt)
Nickel	1.0%	79%	370
Cobalt	0.4%	77%	5
Aluminum	44.9%	90%	37
Manganese	41.9%	75%	2
Iron	61.5%	65%	293
Copper	0.9%	81%	955
Graphite	16.9%	86%	128
LHM (Li)	0.7%	58%	860
Silver	0.002%	75%	185
Zinc	5.6%	82%	48
Phosphorus	12.5%	50%	52
Concrete	100%	65%	360
Plastic	100%	100%	5
Glass	100%	100%	30
Silicon	80%	38%	4
Polymers	100%	100%	2
Chromium	34.5%	65%	0
Total			**3,335**

Table 19: Annual Material Extraction Required[dd]

Material Availability
The total material in Table 18 extraction is evaluated against 2023 USGS resources to assess feasibility. For silver, the USGS does not publish a resources estimate, so reserves were used. The analysis suggests that solar panels will require 13% of the 2023 USGS silver reserves, but silver can be substituted with copper, which is cheaper and more abundant[65]. Graphite demand can be met with both natural and artificial graphite - the former is mined and refined, and the latter is derived from petroleum coke[66]. As a result, the graphite resource base was increased to account for artificial graphite production from oil products. If only a small fraction of the world's oil resource is used for artificial graphite production, graphite resources will not be a constraint[67]. Ongoing development is aimed at evaluating other carbon containing products as feedstock for artificial graphite production, including CO2 and various forms of biomass[68].

In sum, there are no fundamental materials constraints when evaluating against 2023 USGS estimated resources. Furthermore, Resources and Reserves have historically increased – that is, when a mineral is in demand, there is more incentive to look for it and more is discovered[69]. Annual mining, concentrating, and refining of relevant metal ores must grow to meet demand for the renewable energy economy, for which the fundamental constraints are human capital and permitting/regulatory timelines.

dd Assume 50% of the Lithium was extracted from brine. 100% ore mined for that portion of Lithium supply

Materials to Build Required 30TW Generation, 240TWh Storage, and 60M Miles of Conductors Relative to 2023 USGS Estimated Resources

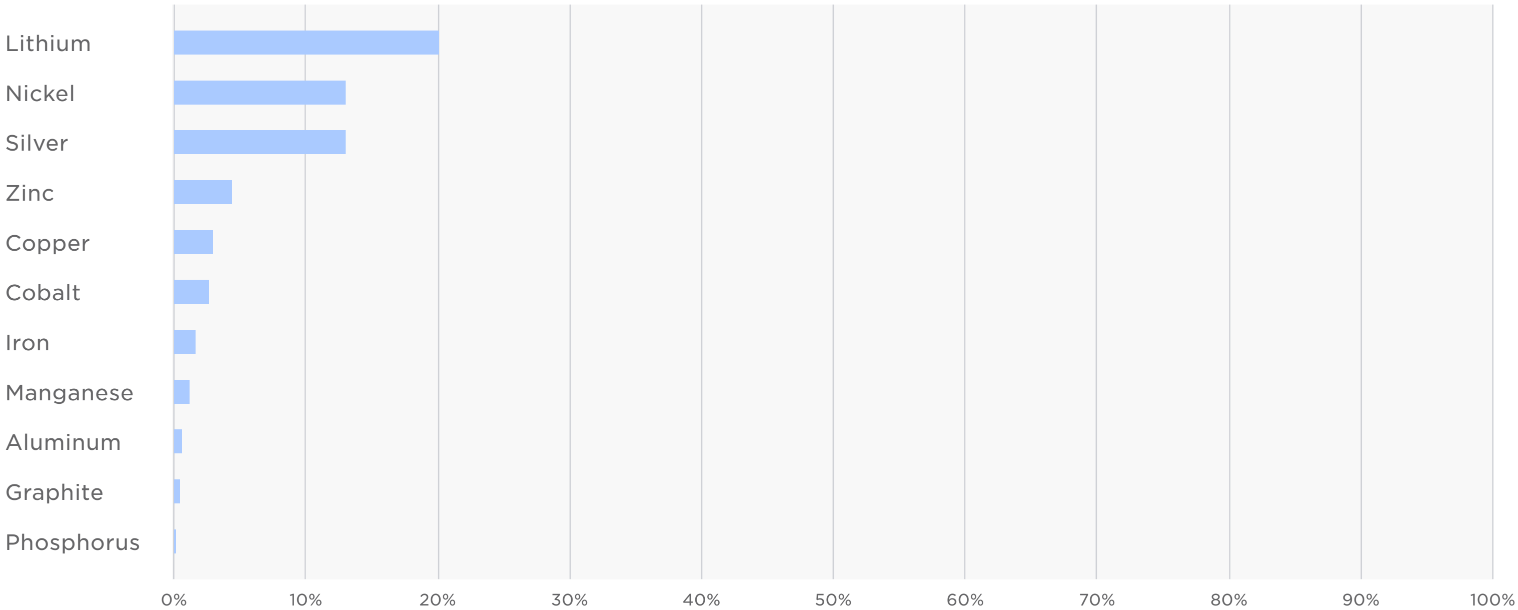


Figure 17: Materials Required Relative to 2023 USGS Estimated Resources

Global Minerals Reserve/Resource Base – Correcting Public Perception

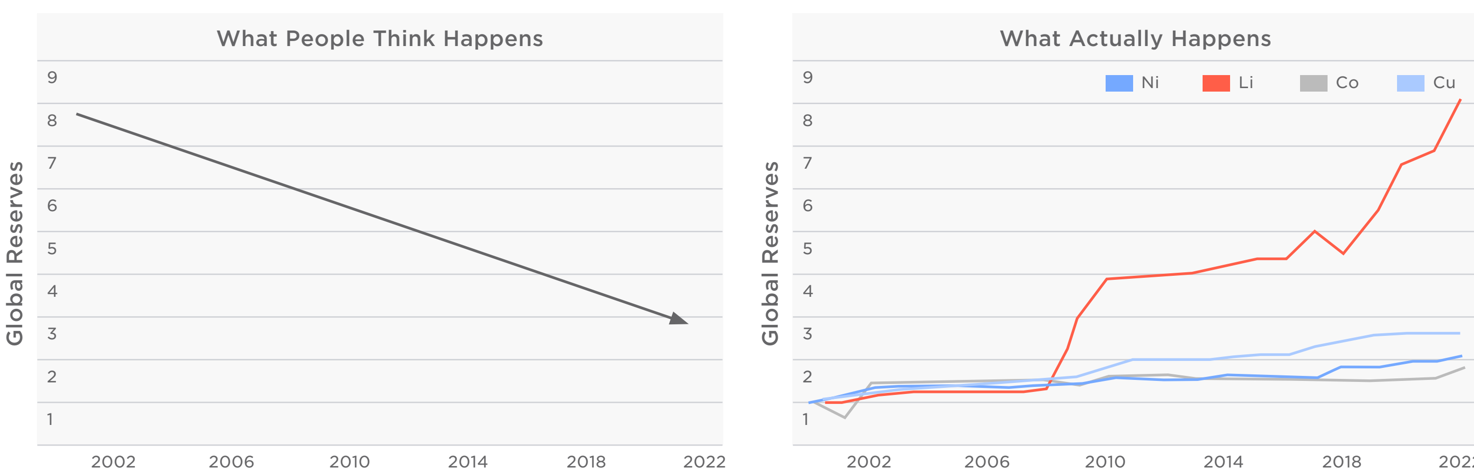


Figure 18 Global Minerals Reserve/Resource base - Correcting Public Perception

Recycling

To support this plan, significant primary material demand growth is required to ramp manufacturing for the sustainable energy economy, once the manufacturing facilities are ramped, primary material demand will level out. In the 2040's, recycling will begin to meaningfully reduce primary material demand as batteries, solar panels and wind turbines reach end-of-life and valuable materials are recycled. Although mining demand will decrease, refining capacity will not.

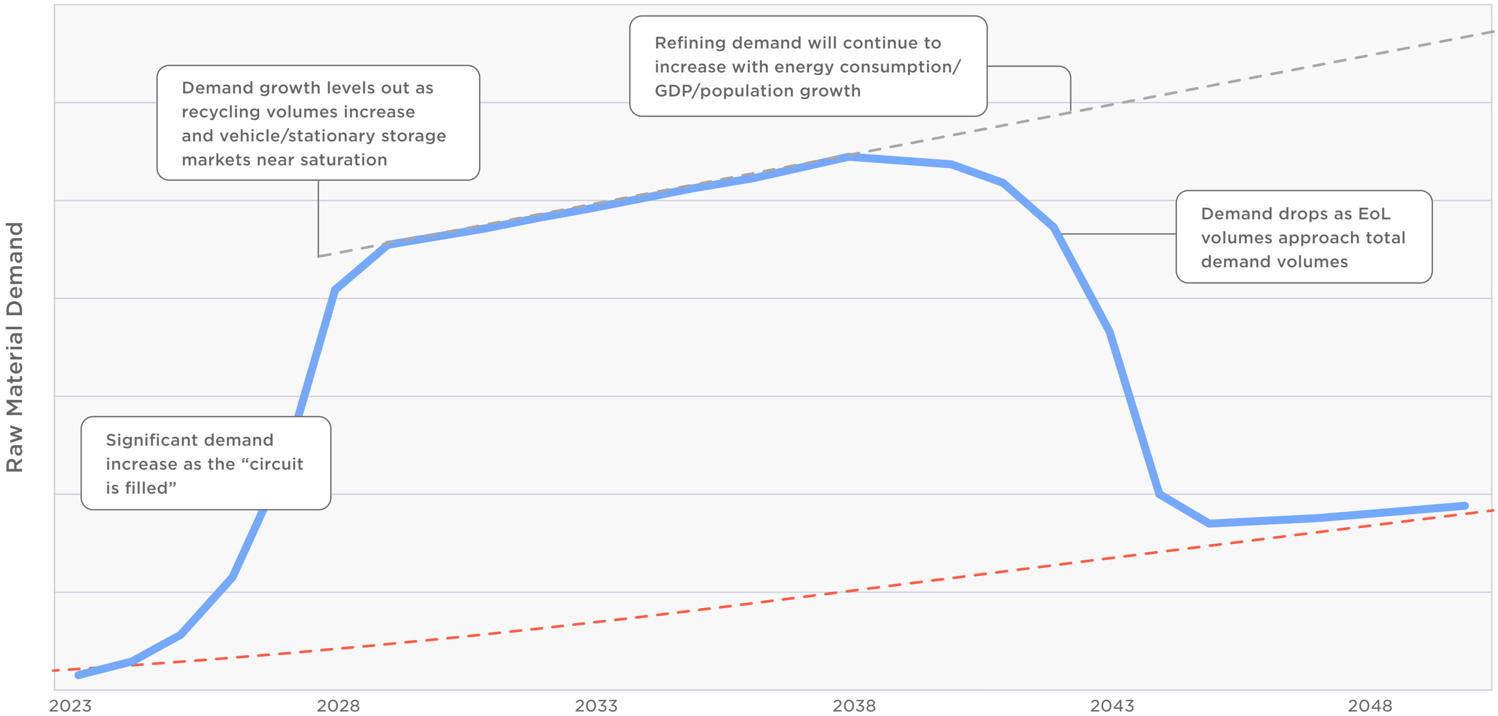


Figure 20 Illustrative Recycling Impact on Process Flow, assuming 80% critical material recovery

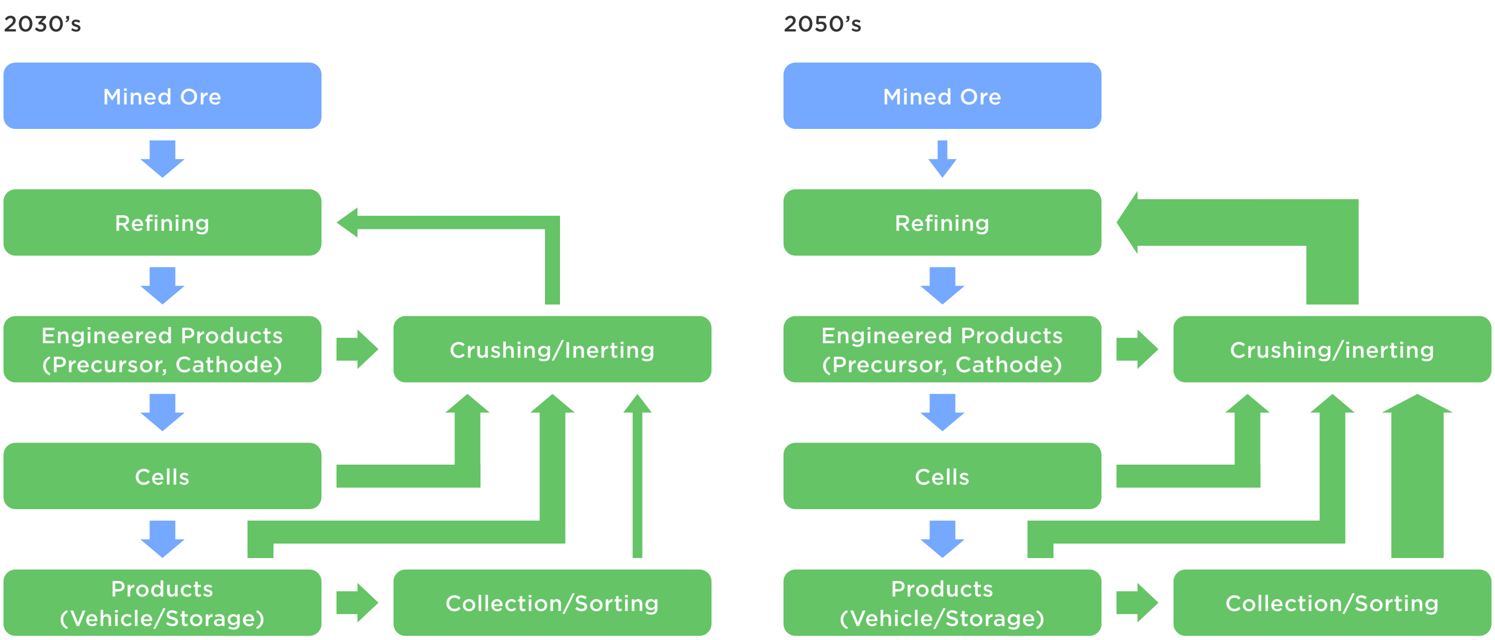


Figure 19: Illustrative Recycling Impact on Process Flow, assuming 80% critical material recovery

Conclusion

A fully electrified and sustainable economy is within reach through the actions in this paper:

1. Repower the Existing Grid with Renewables
2. Switch to Electric Vehicles
3. Switch to Heat Pumps in Residential, Business & Industry
4. Electrify High Temperature Heat Delivery and Hydrogen Production
5. Sustainably Fuel Planes & Boats
6. Manufacture the Sustainable Energy Economy

Modeling reveals that the electrified and sustainable future is technically feasible and requires less investment and less material extraction than continuing today's unsustainable energy economy.

240 TWh Storage	**30** TW Renewable Power	**$10T** Manufacturing Investment	**1/2** The Energy Required
0.21% Land Area Required	**10%** 2022 World GDP	**ZERO** Insurmountable Resource Challenges	

Figure 2: Estimated Resources & Investments Required for Master Plan 3

Appendix: Generation & Storage Allocation to End-Uses

In this analysis, generation and storage needs are estimated at the system level, i.e., answering the question: how much wind/solar and storage is required to reach a sustainable energy economy. The model does not explicitly calculate the required generation and storage to electrify each end-use separately. As an illustration, the allocation of the total system needs to each end-use is calculated using the output from the capacity expansion model.

To do so, the coincidence between the hourly demand profile and the solar and wind generation, after curtailment, is calculated for each end-use. Wind and solar installed capacity is allocated to each end-use based on their annual weighted average coincidence factor. For instance, 12% of the annual wind generation coincided with the EV charging demand. As the model output indicated the need for 15.2 TW of wind, 12% of that total was allocated to EV charging or about 1.9 TW. The same methodology was applied to allocate battery storage capacity to each end-use, by matching storage discharges to end-use demand. Generally, end-uses with the least flexibility to shift the demand, such as residential heating, are allocated more storage than end-uses like industrial high-grade heat where the availability of thermal storage is assumed.

This allocation methodology is a directional illustrative estimate of the impact of each end-use on the total solar/wind and storage requirement, as the need from each end-use is interrelated and cannot fully be separated from each other.

End-Use	Global Electricity Demand (TWh)	Solar (TW)	Wind (TW)	Stationary Storage (TWh)
Repower Existing Grid with Renewables	22,538	6.8	3.8	22.9
Switch to Electric Vehicles	9,314	3.3	1.5	3.7
Switch to Heat Pumps in Homes, Businesses and Industry	11,486	2.7	2.1	6.7
Electrifying High Temperature Heat Delivery and Hydrogen	17,472	3.4	3.1	49.5[ee]
Sustainably Fuel Plane and Boats	9,028	2.1	1.6	4.4

ee Including 8 TWh of stationary electricity storage, excluding h2 storage.

Appendix: Energy Intensity

Manufacturing the batteries, solar panels, and wind turbines in the sustainable energy economy itself requires 4PWh/year of sustainable power. To arrive at power demand, the energy intensity of manufacturing is estimated as shown in the figures below:

	Turbine[70]	Solar[71]
GWh Consumed Per GW Produced	1,052	1,072
GW/Year Production	402	610
Total PWh Consumed	**0.42**	**0.65**

Table 20: Annual Energy Intensity of Wind Turbine and Solar Panel Production

	High Ni[gg]	LFP[gg]	Ni/Mn Based[gg]	Thermal[72,ff]
GWh Consumed Per GW Produced	312	190	342	125
GW/Year Production	3,481	7,715	292	2,070
Total PWh Consumed	**1.09**	**1.47**	**0.10**	**0.26**

Table 21: Annual Energy Intensity of Battery Production

ff Energy intensity of graphite is used as a proxy for thermal batteries
gg Internal estimate

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