Tesla's Master Plan Part 3

By John Benson

May 2023

1. Introduction

Like many others, I occasionally find Mr. Musk's oversized ego a bit irritating. However this is a trait he shares with many other great engineers (Edison, Ford and Tesla to name three). And like these he can be forgiven because it is one of the attributes that enables him to accomplish great things. Not just for his personal wealth, but for our society. Again, to name three: bootstrapping the modern electric vehicle into existence, industry-leading battery energy storage systems that mitigate intermittent renewable energy, and major advances in space-travel.

This post will be a four page summary of the title paper. I cannot improve on this paper, and will not try to supplement it with my own writings, even though I write on most of the subjects covered in the title paper. A signature of a great engineer is a great plan, and this appears to be one. It is short, succinct and well-illustrated.

What I will do is describe what it does. The prior master plans were mainly focused on evolving Elon's businesses. This master plan is described below.[1]

Today, we are publishing Master Plan Part 3, which outlines 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.

2. Structure

Three steps:

Electricity Demand: *Forecast the electricity demand of a fully electrified economy that meets global energy needs without fossil fuels.*

Electricity Supply: *Construct a least-cost portfolio of electricity generation and storage resources that satisfies hourly electricity demand.*

Material Feasibility & Investment: *Determine the feasibility of material needs for the electric economy and manufacturing investment necessary to enable it.*

3. 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.)

[1] The Tesla Team, "Master Plan Part 3," April 5, 2023, https://www.tesla.com/blog/master-plan-part-3

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…

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***

Author's comment: I've left out text describing how the models for this paper were created from this brief summary. However, there are enough details and references to highly credible sources to have me believe that these simulations are real and highly believable.

Each of the above six steps is provided with enough details and illustrations to be understood by any technically astute reader.

The above steps also describe both elimination of fossil fuel use and increases in electrical demand. The latter are used below in the development of this plan.

4. 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. 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. 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.

Author's comment: The paper thoroughly reviews all currently viable renewable energy technologies, but assumes that there is no new nuclear nor geothermal deployments. I believe that the latter are reasonable simplifications for the continental U.S., but probably not so much for the global case.

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 on page 20.*

5. Batteries

Author's comment: There is modeling of these requirements, but this paper suggests that sustainable fuels will also be needed for some long-distance transport.

Note that this modeling uses existing battery chemistries, which is a useful starting point. However my research has led me to believe that rapid battery evolution will result in new designs and chemistries that will greatly increase battery outputs and capacities over the next few decades.

Today there are 1.4B vehicles globally and annual passenger vehicle production of ~85M vehicles, according to International Organization of Motor Vehicle Manufacturers (OICA). Based on pack size assumptions, the vehicle fleet will require 112 TWh of batteries. 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.

Note that battery used for renewable and other grid electric support requirements in the final evaluation tables starting on page 24.

6. 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. 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, as compared to the $14 trillion projected 20-year spend on fossil fuels at the 2022 investment rate.

There are several lengthy tables required to develop the investment costs described above. These start on page 27.

7. 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. 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. Therefore, the global wind turbine fleet of 12.2TW will require an estimated 9.2 million acres, or 0.02% of total land area.

8. Materials Required

The total materials required for solar panels, wind turbines, and circuit 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.*

Based on IEA's 2050 Net Zero pathways study, approximately 60 million circuit miles will need to be added or have conductors upgraded globally to achieve a fully sustainable, electrified global economy. Distribution capacity will primarily be expanded by having conductors upgraded, using 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 conductor upgrading 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.

Again, several lengthy tables are required to develop these material requirements. These start on page 31. Among these are several brief paragraphs and figures describing acquisition methods.

9. Conclusion

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.

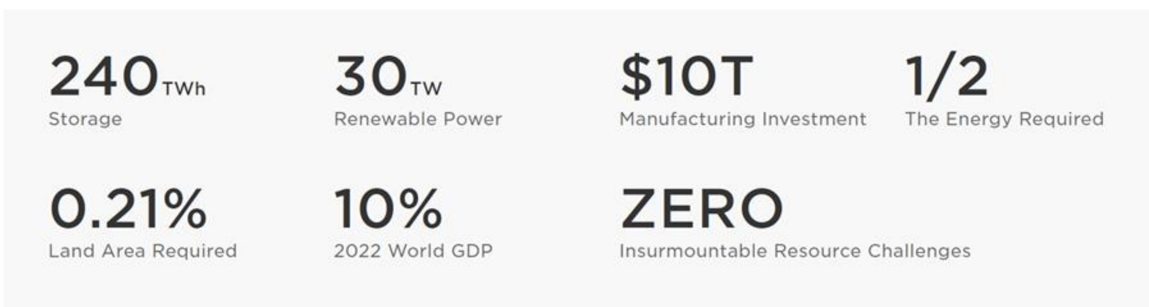

Figure 2: Estimated Resources & Investments Required for Master Plan 3