Supplementary Material

Revisiting the Terawatt Challenge

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To complement the "Revisiting the Terawatt Challenge" MRS Bulletin *article, which appears in the style of Richard E. Smalley's original* MRS Bulletin *publication, the authors present this supplementary material to provide quantitative data behind the numbers presented, as well as additional explanation, background material, and references.*

There are many scientific studies on modeling the energy transition, projecting anticipated outcomes.[1–6] Such studies explore the topic from multiple vantage points, including how variable solar and wind resources sometimes complement each other, especially as seasons vary;[7–9] how high-voltage DC transmission can be used to deliver electricity where it is needed;[10] how electrification of transport and heating sectors can affect energy demand;[11] and how power-to-gas storage,[12] off-river pumped hydro power,[13] or a modern smart grid for balancing electricity supply and demand[14] can provide storage options. All of these studies provide value, but each makes many assumptions that can affect the conclusions, often with some of the assumptions being controversial.[15–18] Here, we have chosen a complementary approach that identifies and explores the effects of a small number of key assumptions and applies them at the global level, following Smalley's general approach. In this way, the reader is empowered to question and change those assumptions, enabling the reader to arrive at independent conclusions.

Although the concept of energy intensity is relatively straightforward, quantifying the energy intensity can be complicated. When fossil fuels are used for electricity generation, the energy content of the fossil fuel is typically more than twice the energy of the electricity generated (~40% efficiency*). Electricity is generally referred to as a secondary form of energy and is tabulated separately in the calculation of energy intensity in order to avoid double counting. Although we could choose to quantify the radiative energy striking solar panels as a primary energy input, we have chosen to discuss the "energy used" by including the fossil fuels harvested from the ground, but include only the electricity obtained from solar panels, not the energy in the sunlight striking the solar panels.

We present the demand for energy as an average power for convenience, noting that a person who uses 8760 kWh/year uses 1 kW average power over the year. Thus, when we describe the TW Challenge for every 1 TW of average power, we imply a demand of 8760 TWh/year.

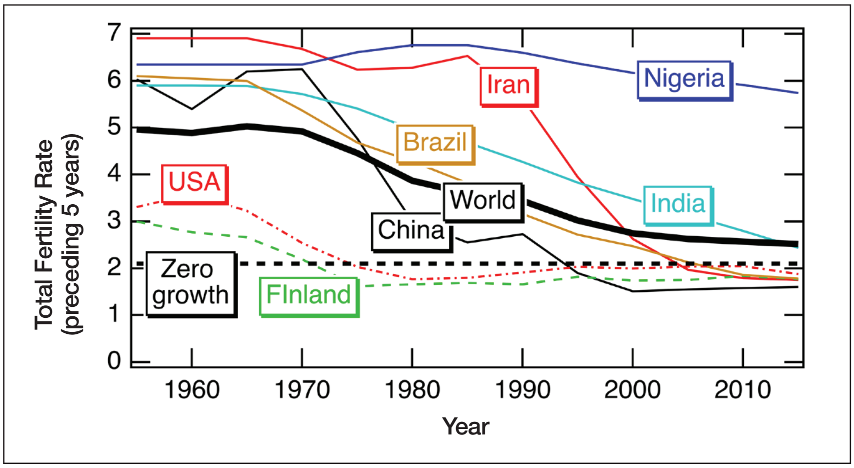

Figure S1. Fertility rates for the world and a country from each (sub)continent.[19] The black dashed line represents the fertility rate typically associated with zero growth.

World population

Overpopulation is a concern, yet there is general agreement that the global population will continue to grow for decades. Fertility rates dropped abruptly in China in the 1970s and in Iran in the 1990s, as shown in **Figure S1**. These decreases in fertility rates reflect government actions; however, even without strong government action, fertility rates have declined

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*The US Energy Information Administration reported that in 2017, the efficiencies ranged from 31% for petroleum to 44% for natural gas; https://www.eia.gov/electricity/annual/html/epa_08_01.html.

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in most countries, with most stabilizing at around two births per female.[19]

While world population projections require estimates of both fertility and mortality rates, changes in fertility rates currently play a larger role. The UN's projection for world population growth is shown in **Figure S2** in black, with the bold line representing the median of 60,000 simulations, and the thinner lines indicating the 95% upper and lower projections. Gerland et al. used a similar probabilistic approach with somewhat different assumptions, resulting in the dashed red projections.[20] The UN projections are slightly higher than Gerland's projections, with both surpassing 10 billion near midcentury and approaching around 11 billion by 2100.

Neither the UN study nor Gerland's study predicted that the population will stabilize by 2100, although the growth rate is predicted to slow. A key change that would enable a peak in the population before 2100 would be reduced fertility rates in African countries, especially in Nigeria because of its high current fertility rate and large population. Additionally, global concern over climate change could lead to public support of reduced population growth in coming years. On the other hand, concern about aging populations in China and elsewhere could motivate increases in fertility rates driven by labor and social support system needs. Major changes in the environment because of tipping-point factors would dramatically affect predictions based on smooth evolution.

The uncertainty in world population growth is much less than the uncertainty in energy intensity. However, the prediction is still critical because population growth will require new energy technologies to compete with agriculture, housing, transportation, and others for land. Our analysis assumes 10 billion people in 2050, consistent with the projections in Figure S2.

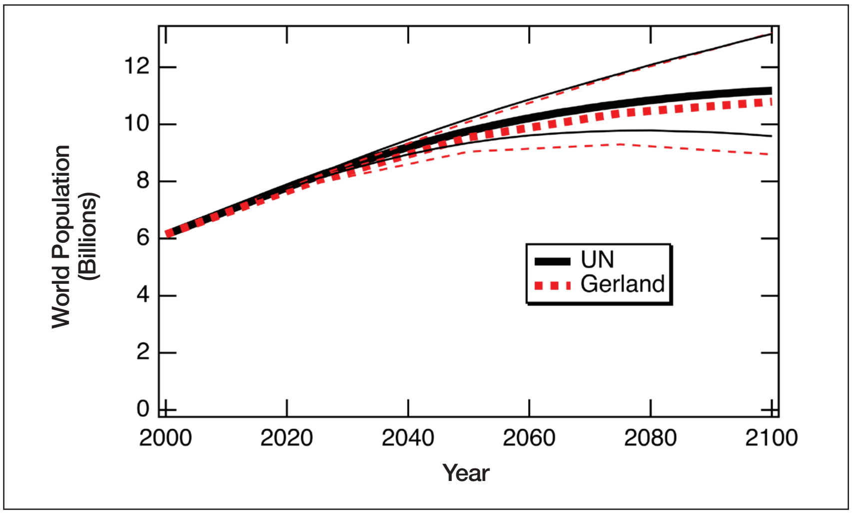

Figure S2. Population growth observed (to 2015) and projected (after 2015) by the UN[19] and Gerland et al.,[20] using the black solid line and red dashed line, respectively. The thinner lines represent the 95% upper and lower simulations for each analysis.

Energy storage

Pumped hydro storage is the best-established storage technology, with a current global capacity of 0.16 TW[21] and round-trip efficiency typically reported to be 70–80%.[22,23] If the pumped hydro-storage infrastructure were greatly expanded, as proposed by Blakers,[24] the loss of energy associated with the storage would be ~20–30% for whatever electricity needed to be stored. Although evaporation losses decrease the round-trip efficiency with time, the primary limitation on using pumped hydro storage as seasonal storage is the low-energy density (pumped hydro has ~1 Wh/l versus >200 Wh/l for Li-ion batteries and 500–10,000 Wh/l for liquid fuels[22,23]), requiring large reservoirs and making it challenging for large-scale seasonal storage.

Typical round-trip efficiencies for chemical storage options (labeled "Power to Fuel") fall in the range of 20–40% (Figure 3, main article). R&D has the potential to improve this efficiency, but the best technology today is likely to be ~30% efficient. For example, Pellow et al.[25] reported ~30% round-trip efficiency when an alkaline water electrolyzer was used to make hydrogen that was later converted to electricity by a proton-exchange membrane fuel cell.

Some companies are beginning to develop processes for making hydrocarbon fuels from air. For example, Carbon Engineering, a company in Canada, built a pilot line in 2017 that captures CO_2 directly from air using KOH and $Ca(OH)_2$. The CO_2 can then be reacted with renewable-energy-generated H_2 to make hydrocarbons. The pilot plant captures about 1 ton of CO_2 from the atmosphere per day, which is enough to produce about a barrel of hydrocarbons per day.[26] Graves et al. estimated a potential 70% efficiency for taking CO_2 from air and converting it to hydrocarbons.[27] Although this may be achieved for a mature process, in the 2050 time frame, we anticipate that a 50% efficient process would be more probable, and when combined with a typical efficiency of electricity generation from the resulting fuels, results in a round-trip efficiency consistent with the "Power to Fuel" bubble in Figure 3 in the main article.

Scenario B: Total electrification

Most efficient scenario

The "Total electrification" scenario represents the best possible energy efficiency, requiring installation of a smaller number of solar panels, wind turbines, and other renewable electricity sources. It makes two idealistic assumptions: (1) It's possible to electrify everything, experiencing an efficiency benefit of a factor of three, and (2) Every kWh can be delivered directly to its end use without the loss of efficiency anticipated for storing the energy. While both of these idealistic assumptions will be impossible to achieve at a 100% level, we take the 100% point as the bound rather than attempting to analyze the practical limit. Understanding the benefits of implementing the energy system in this way is more useful than analyzing the practical limit.

Scenario C: Current infrastructure

Least efficient scenario

The use of long-term energy storage in a significant way will decrease the overall efficiency of the energy system, increasing the resources needed to meet the TW Challenge. To establish an upper bound, we consider the "Current infrastructure" scenario (see Table II, main article), which resembles today's energy system. In this scenario, we replace today's fossil fuel sources with hydrocarbon sources derived from CO_2 from the air using renewable energy, allowing us to retain our current transportation infrastructure and to retain many fossil fuel plants, only replacing coal-fired plants with natural gas or other liquid hydrocarbons. This scenario requires massive development of infrastructure for making enormous quantities of hydrocarbons (both methane to use in the natural-gas system and liquid fuels for fueling vehicles), but avoids most other infrastructure development requirements. Therefore, it represents an interesting alternative path that is relatively easy to define and would require changes affecting only a small segment of the population instead of affecting almost 100% of people. This scenario is of interest for the academic exercise of evaluating the upper bound of energy needed for the TW Challenge, rather than of practical applicability, since the world is already taking steps toward Scenario B.

We considered including hydrogen in a practical long-term storage scenario. We expect that such a scenario will be qualitatively similar to Scenario C but could be defined in many ways, depending on which parts of today's infrastructure are converted to hydrogen. The reader may quickly analyze the TW Challenge for a hydrogen scenario by deciding on the relevant round-trip efficiency and what fraction of the energy system would use hydrogen storage.

Smalley noted that solar energy is Earth's largest energy resource and, together with wind and geothermal energy, he estimated that it could provide 50% of the energy to meet the TW Challenge. Solar electricity was 19% of the electricity generated by the state of California in 2018, demonstrating the feasibility of accommodating variable generation at that level. In this analysis, we assume that the TW Challenge may be met with a mixture of energy sources, with solar providing 50% of the energy. The reader may easily adjust the resulting numbers for a different assumption. As described previously, the rightmost column of Table II (main article) tabulates the TW of modules needed to meet the assumed 50% solar piece of the Challenge.

Implications

The implication of this analysis is that if humans can more flexibly connect their future energy consumption to the time-dependent availability of solar and wind electricity, future energy systems can be both more efficient and smaller in size. While it is highly unlikely that all future energy demand can be satisfied with no storage, the greater the mismatch between renewable electricity generation and energy demand, the greater the need not only for storage but also for overall energy production, especially if the storage is inefficient. Electric vehicles (EVs) may be particularly important in this equation, as, collectively, they could provide a large effective battery bank if they can be charged while the sun is shining. In contrast, future energy scenarios that rely heavily on storing energy in fuels may pay a heavy price in efficiency losses and total electricity generation required.

The world has already begun adopting renewable electricity generation, EVs, and heat pumps. The added cost of charging EVs while the sun is shining is minimal; it primarily requires installing daytime charging stations. Many systems already have the ability to run heat pumps when electricity is abundant and then store the heat or cold for a later time. Adjusting these systems to operate when the sun is shining instead of in the middle of the night may cost very little. Thus, in the near term, the world is positioned to quickly decrease energy needs by adopting EVs and heat pumps and then maximizing their operation with renewable electricity. The first parts of transitioning a significantly increased fraction of use to solar and wind electricity could happen quickly. The later stages where seasonal storage may become critical is the tougher challenge.

Although photovoltaic prices have decreased into an attractive range, the continued historical, large growth rate is likely to require aggressive supportive policies around the world and attention to resource and sustainability issues. The methodology for the deployment calculation is the same as described in Reference 28.

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