Revisiting the Terawatt Challenge

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In 2003, Richard Smalley defined the Terawatt (TW) Challenge: Adapting our energy infrastructure to simultaneously address diminishing oil resources and rising levels of atmospheric CO_2. Smalley, best known for the discovery of C_{60} for which he received the 1996 Nobel Prize in Chemistry, turned his attention from 2003 to the end of his life to the challenges of anthropomorphic and natural global energy flows.[1,2] Smalley challenged the world to transform the energy sector, envisioning electricity transmitted by high-voltage direct-current (DC) lines from massively deployed solar plants in sunny areas and remotely sited nuclear plants as well as all local storage using improved batteries. To meet the needs of ~10^{10} people in a world with dwindling oil supply, Smalley asserted that the world would need to transform its fossil-fuel-driven 14-TW (average power) energy system in 2003 to a largely renewable-energy-driven 30-60 TW (average power) system in 2050, which would be possible only if solar-electricity costs could be drastically reduced. Fifteen years later, solar-module costs have been reduced by tenfold and annual deployment of solar photovoltaic (PV) modules has grown by a factor of 100, from ~1 gigawatt (GW) in 2004 to ~100 GW in 2018, with a total of 500 GW installed worldwide, producing 2% of the planet's electricity. As global installed solar generating capacity approaches 1 TW, we revisit Smalley's TW challenge to identify what has changed and quantify the TW Challenge for a baseline scenario and for two scenarios designed as upper and lower bounds determined by the degree we implement electrification and storage. We show that the energy choices we make today will dramatically affect the magnitude of future global energy requirements.

In the sixteen years since Smalley posed this challenge, some things have evolved as he predicted. The world's population has grown and climate change evidence has expanded, increasing the urgency of the challenge. But a few things would have surprised Smalley. Notably, instead of fossil fuel production decreasing, the United States now produces more oil and gas than in Smalley's day, and OPEC is actively curtailing oil production to increase prices. Although an oil shortage could still develop in the future, today's TW Challenge is no longer motivated by a shortage of oil, as in Smalley's day, but by increased urgency to reduce greenhouse gas emissions in response to visible changes in global climate.

Smalley would also have been surprised at how quickly PV deployment has increased,[3] and that the price of solar panels has rapidly dropped by a factor of 10. Global solar electricity generation rose from 4.1 TWh in 2005 to 263 TWh in 2015 (a 64-fold increase, corresponding to 50% annual growth). A similar factor of 64 rise between 2015 and 2025 would result in >16,000 TWh of solar electricity in 2025, which is within a factor of two of the anticipated total global electricity demand (31,000 TWh) in 2025, positioning solar electricity to play the central role that Smalley envisioned. Wind energy has also matured both in reduced costs and global electricity generation, increasing from 104 TWh in 2005 to 834 TWh in 2015 (8-fold growth). A summary of Smalley's analysis relative to the current status is provided in Table 1.

Table 1. Key elements/conclusions of Smalley's analysis[1,2] and current status.

Element	Smalley's analysis in 2003-2005	Suggested solution	Current status
Oil	Oil production predicted to peak around 2005 and then decrease through 2050	• Identify alternatives	New technology has reinvigorated fossil fuels.
Atmospheric CO_2	Increasing carbon dioxide levels may cause unacceptable global warming, motivating adoption of low-carbon energy system	• Identify solutions • Identify business case for carbon sequestration	Evidence of climate change has increased, increasing urgency. Business case for sequestration has not yet materialized.
Clean options	Energy efficiency, hydroelectricity, biomass, wind, wave and tidal energy are each too small to provide a solution on their own	• Identify alternatives	Advances in energy use efficiency and wind power have been significant, but not a complete solution
Chemical options	Natural gas (imported) and clean coal would require carbon sequestration, which might be too costly.	• Business case for sequestration	Sequestration technology has advanced, but business case still needed for widespread adoption
Nuclear	Could provide adequate power, but challenges include radioactive waste, terrorism and cost	• Place nuclear plants in remote areas	Nuclear accidents and high costs have led to decline in nuclear electricity generation
Geothermal	Might be too costly or the resources that are low cost may not be sufficient	• Decrease cost	Technology advances by the fossil-fuel industry could be enabling, but market share has not grown
Solar	Ample resource, but might be too costly (price in 2003 ~20-50 cents/kWh)	• Decrease cost by 100x	Cost has decreased by ~10x and deployment rate has grown 100x
Role of electricity	Distribute energy via high-voltage DC transmission lines instead of via oil trucks. Need grid with distributed power sources and local storage: *e.g.*, batteries, hydrogen, fuel cells	• Efficient local storage • Improve batteries and supercapacitors by 10-100x • Power cable materials	Battery storage has advanced. DC-DC converters and DC transmission are more common. Grid is becoming "smarter" and more decentralized.
Transportation	2003 assessment: Hydrogen likely to be primary fuel for transportation because electric vehicles have limited range 2005 assessment: "Hydrogen economy is… likely to remain a distraction"	• Decrease fuel-cell cost by 10-100x; • Direct photoconversion of sunlight + water to H_2 • H_2 storage	Electric vehicles have made significant technology and market-share gains. Hydrogen fuel cells have also progressed.
Energy needed	8-10 billion people by 2050 would require 30-60 TW average power	• ~50% from solar, wind and geothermal	Population growth is similar to what Smalley predicted. Energy intensity has increased somewhat.

In light of these changes and, more importantly, as parts of the world are actively implementing a near-term transition to a low-carbon energy system, it is useful to revisit Smalley's TW

Challenge. Doing so can guide prioritization of research, policy, and commercial investments by better understanding how choices in electrification and storage will affect the total energy-system efficiency and the related investment that will be needed in low-carbon technologies.

Approach

The world has begun an energy transition – it is naturally useful to project how that transition could evolve. Many research groups and organizations such as the IEA, IRENA, BNEF, the WWF and Greenpeace have analyzed future energy scenarios using detailed models with extensive inputs befitting the complex and interacting energy landscape. All of these studies provide value to the community, but each makes many assumptions that can affect the conclusions of the modeling, often making it difficult to understand why the studies reach somewhat different conclusions.[4-6] Here we present a complementary approach that identifies and explores the effects of a very small number of key assumptions and applies them at the global level, following Smalley's approach.

Global annual energy needs can be calculated by estimating the average annual energy demand per person and multiplying this by the world's population. We will use projections by the United Nations and others[7] (see supplemental material). Estimation of the energy intensity in 2050 is more challenging, especially as the energy system is transformed to reduce greenhouse gas emissions, possibly increasing or decreasing energy demand.

A transformed energy system in 2050 will be a complex mixture of many technologies, with a range of efficiencies and convenience. To facilitate discussion of this complex topic, we consider a baseline Scenario A that extrapolates current trends, and two hypothetical scenarios that bracket our future energy trajectory, constructed to be the most and least efficient systems we envision to be tenable. Scenario B will provide a lower limit by assuming an optimally efficient system using electrification as described below. Scenario C will provide the upper limit by including the need to extensively store energy from the variable solar and wind energy sources. Scenario B was easily chosen as the most efficient scenario we could envision. Scenario C was more difficult to select because we could always envision a way to be less efficient. So, Scenario C was chosen to describe a world that retains our current infrastructure, including not only our internal-combustion-engine cars, but our gas stoves and fireplaces, but instead of using fossil fuels, Scenario C drives today's infrastructure with hydrocarbons synthesized from direct-air-capture carbon dioxide and renewable electricity.

We first consider the historical data for energy intensity, then analyze the impacts of electrification and storage on the efficiency of energy delivery to understand how these will affect energy intensity. We then calculate the anticipated energy demand for each scenario.

Energy intensity

We discuss energy intensity as the energy needed per capita, that is, the average power that a person uses for all aspects of life. Historical data for energy intensity for the world and the various continents are shown in Fig. 1. The range of energy intensities has historically been bounded by North America as the highest and Africa as the lowest energy intensity. The Middle East and Asia have both doubled their use of energy/person in recent decades. There has been some improvement in energy efficiency in North America and Europe.

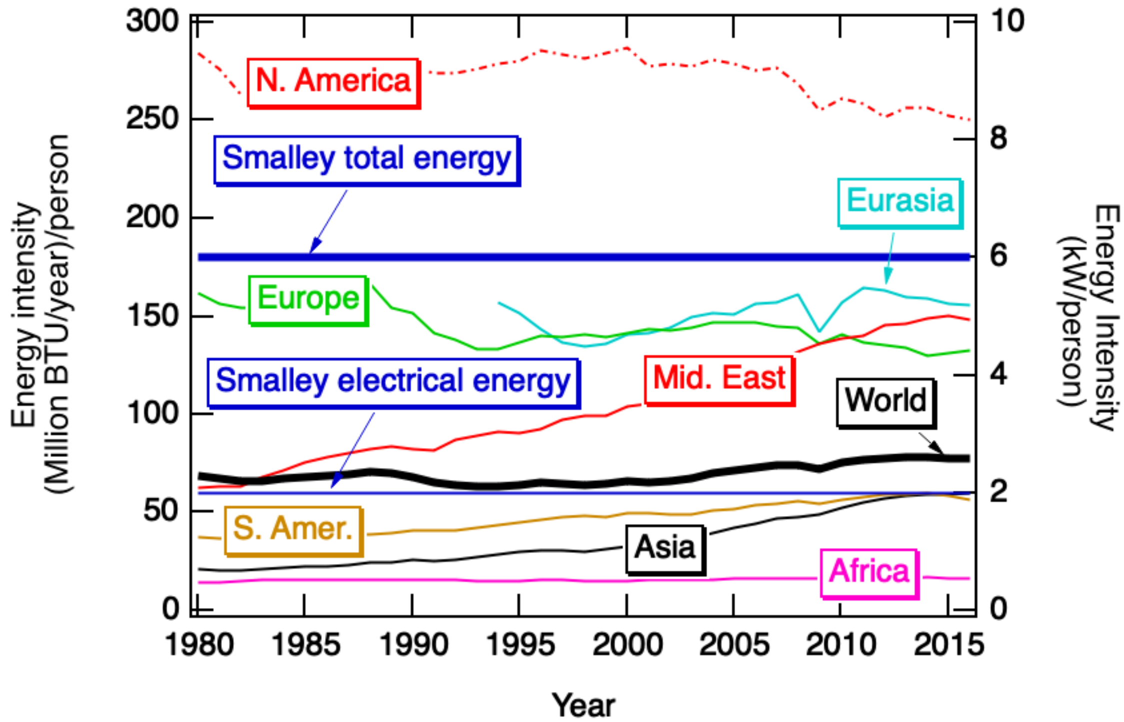

Fig. 1. Average energy intensity for the world and the continents in units of (BTU/year)/person (left axis) and average power consumption in units of kW/person (right axis). Data source EIA. Smalley's estimate of 60 TW energy for 10 billion people is shown by the bold blue line and the corresponding electricity requirement by the thinner blue line.

Even with our energy existing system, one can consider a range of levels at which the world's energy intensity could be stabilized. A high level of 8 kW/person would reflect a high degree of development and consumption. Alternatively, it may be possible to achieve comfortable living at a value between 4 and 5 kW/person, as is currently the case for Europe. Smalley suggested that 10 billion people would require 60 TW total average power or 20 TW of electrical average power. The latter corresponds to 2 kW/person average electrical power.[2]

Prediction of the energy intensity over the coming decades has higher uncertainty than population growth, but a simple extrapolation of the data in Fig. 1 results in a prediction of 3.2±0.5 kW/person. In addition to economic development around the world, we expect that the energy intensity will be affected by transitioning the energy system to a low-carbon system, possibly increasing or decreasing the energy intensity substantially. Therefore, we next discuss opportunities to reduce the energy intensity as well as developments that could increase the energy intensity as the energy transition proceeds.

Increased efficiency from electrification

Electrification of the transport sector can play a significant role in reducing energy use. Fig. 2a compares the energy use of electric vehicles (EVs) with that of conventional internal combustion engine vehicles. EV energy use is subcategorized by the power source: electricity from fossil fuels or from solar. The rightmost bar indicates the solar energy in kWh that is needed to drive an EV one km. This value (0.2 kWh/km) is the median rating for the current top fifteen EVs in the U.S. market. The middle bar indicates the equivalent fossil fuel energy needed, which increases to 0.53 kWh/km due to the efficiency (38%) of current fossil fuel power plants. The leftmost bar indicates the equivalent gasoline energy needed for a combustion engine. The median value for 2018 U.S. vehicles is 27 mpg or ~0.8 kWh/km. Internal combustion engines suffer from lower thermal efficiency and higher energy loss from braking compared with electric engines. In combination, EVs directly charged with solar electricity require < 1/3 the energy required by combustion vehicles. The efficiency improvement is significantly less if the electricity is produced from fossil fuels.

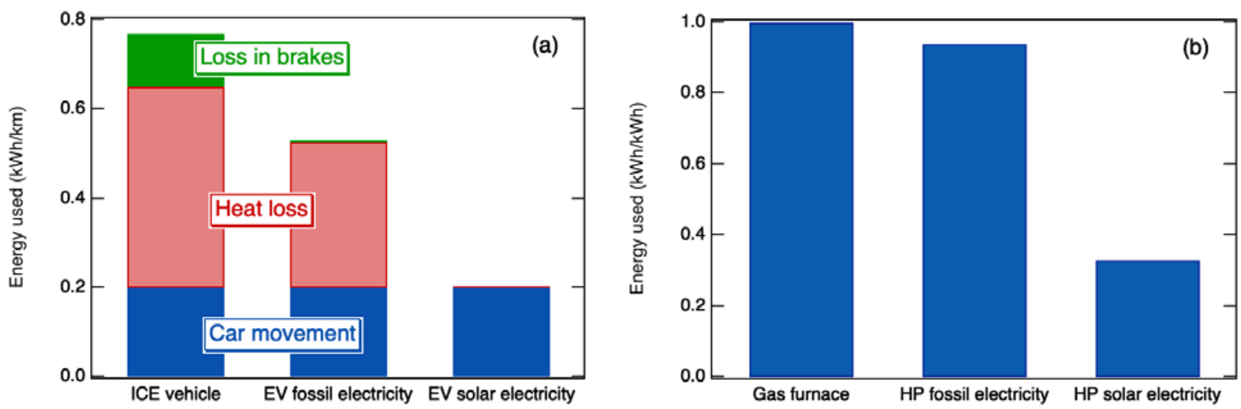

Figure 2. (a) Energy (kWh) used to drive 1 km by an average 2018 US internal-combustion engine (ICE) vehicle (left bar), by an electric vehicle (EV) with regenerative braking charged by electricity generated from fossil fuels (middle bar) and for an EV charged directly by solar (or wind) electricity (right bar). (b) Energy used for heating: a 100%-efficient gas furnace compared with a heat pump (HP) with COP = 3 driven by fossil and solar (or wind) electricity. Supporting data can be found in DOE websites and the BP Statistical Review of Global Energy.

Energy use can also be reduced by electrifying heating systems. In Fig. 2b, we compare different types of heating systems, indicating the kWh equivalents of chemical or electrical energy needed to deliver one kWh of heat (kWh/kWh). The left bar indicates the chemical energy needed for a 100% efficient gas furnace (typical furnaces are 70%-80% efficient, high-end furnaces can be above 90%). The middle bar indicates the energy needed for a heat pump using fossil fuel electricity generated by a 38% efficient power plant. The assumed coefficient of performance (COP) for the heat pump, the ratio of delivered heat energy (output) to electrical energy (input), is assumed to be three. Based on our survey of different types of electric heat pumps, a COP of three is a good average under common working conditions.[8] The right bar indicates the equivalent solar electricity needed to drive the same heat pump. As with transportation, the comparison shows that the amount of solar energy needed is roughly one third of the equivalent chemical energy.

Decreased efficiency from need to store energy

In a fossil-fuel-free world, the need to balance supply and demand for electrical energy at all hours of the day is likely the biggest barrier to using solar electricity to meet the TW challenge. Intercontinental transmission lines could address both the diurnal variation, by connecting locations with different longitudes, and the seasonal variation, by connecting the northern and southern hemispheres. These would require substantial infrastructure investments and would be politically challenging.

To minimize the need for energy storage, it is desirable to use as much electricity as possible at the time of generation. For thermal applications, rather than storing solar electricity in batteries during the day to run heating or cooling at night, the energy is used directly to generate a heated or cooled medium that is stored until after sunset. Such infrastructure is common today in locations with substantial cooling loads and electricity rates that vary with the time of day. Similarly, EVs may be charged directly when electricity is available instead of storing the electricity in a separate battery and then transferring that electrical charge to the EV battery. Some energy uses, such as generation of ammonia, hydrogen, plastics precursors and other chemicals, directly result in energy products that are easily stored. A smart grid could also increase the fraction of electricity that is used directly.

However, some amount of variability will need to be balanced with storage to allow energy use whenever people need it. Short-term electricity storage in fly wheels, supercapacitors, or efficient batteries can be quite efficient, but long-term storage options tend to fare worse. Fig. 3 summarizes typical round-trip (electricity-to-storage-to-electricity) efficiencies for a few long and short-term storage technologies, illustrating this trend. The bubbles in Fig. 3 are placed to reflect both the round-trip efficiency and estimates of the practical time of storage based on both energy-loss rates and large-scale storage feasibility.

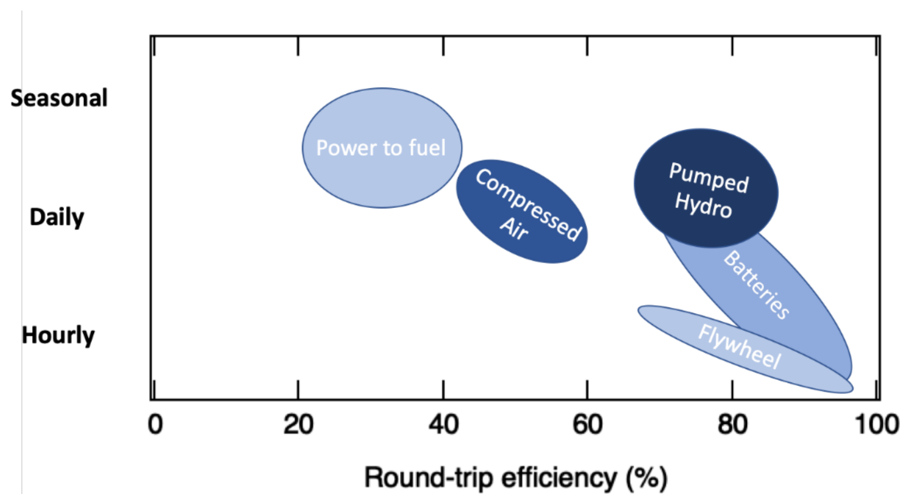

Fig. 3. Practical storage durations mapped versus round trip electricity-to-storage-to-electricity efficiencies for several storage technologies. The darkness of each bubble reflects the technology maturity (cumulative deployment).

Terawatt scenarios: Placing bounds on the TW challenge

Based on this analysis, the magnitude of the TW challenge will likely be within a lower limit associated with complete electrification and direct energy use (Scenario B), and the need to extensively store energy from the variable solar and wind energy sources (Scenario C), as described above. Lower and upper bounds can be established by assessing these two idealized but very different pathways to low-carbon energy systems. Practicality suggests that the world will choose a hybrid approach, likely with elements of each of these and other scenarios, but defining these bracketing, though unrealistic, scenarios will help clarify the ramifications of the choices we make. The scenarios are summarized in Table 2.

Table 2. Definition of scenarios and associated size of the TW challenge. The "PV needed" calculation assumes 50% of energy is derived from PV with a 16% global average capacity factor* consistent with EIA 2015 values.

<table>
<tr><th rowspan="2">Scenario label</th><th rowspan="2">Idealistic assumptions</th><th colspan="3">2050 estimates:
10 billion people
3.2±0.5 kW/person for baseline</th></tr>
<tr><th>Energy demand relative to baseline</th><th>TW challenge (average power)</th><th>PV needed to provide 50% (DC)</th></tr>
<tr><td>A. Baseline (business as usual)</td><td>• Extrapolation of past data</td><td>100%</td><td>32±5 TW</td><td>100±20 TW</td></tr>
<tr><td>B. Total electrification (Lower bound on energy requirements)</td><td>• Electrify everything
• Supply all electricity from renewable electricity
• Deliver 100% of electricity directly to end use</td><td>37%</td><td>12 TW</td><td>37 TW</td></tr>
<tr><td>C. Current infrastructure (Upper bound on energy requirements, Example of many scenarios using long-term energy storage)</td><td>• Retain internal-combustion engine transportation
• Retain natural gas infrastructure for industrial processes, heating, etc.
• Retain most of today's power plants
• Use renewable electricity to make hydrocarbons from CO_2 in air to replace all fossil fuels used today (assume 50% efficiency)</td><td>180%</td><td>58 TW</td><td>180 TW</td></tr>
</table>

*Capacity factor is the energy delivered relative to what could have been delivered if the plant ran continuously at its rated power.

We estimate the magnitude of the TW challenge using the three scenarios described in Table 2, focusing, for simplicity, on estimates for 2050. Similar to Smalley, we assume a global population of 10 billion.[7] From Fig. 1, we predict that the energy intensity will be 3.2 ± 0.5 kW/person for the business-as-usual baseline case (Scenario A). Thus, for the baseline TW challenge in 2050, we obtain 32 ± 5 TW average power. If we assume that 50% of that energy will be supplied by PV with a 16% capacity factor consistent with EIA data from 2015, we estimate that 100 TW of PV modules will be required.

Table 2 also summarizes estimates of the TW challenge if the energy system would be transformed into the most efficient (Scenario B) or least efficient (Scenario C) scenarios. If we assume under Scenario B that today's energy (e.g. coal and natural gas) used for electricity generation is replaced with the energy of the generated electricity and all other energy use is reduced to 1/3 based on full electrification (Fig. 2) only 37% of the baseline energy would be required.

On the other hand, if we use all future installations of renewable electricity to turn carbon dioxide and water into hydrocarbons, and use those in today's infrastructure instead of fossil fuels, we will need *more* energy. According to the IEA World Energy Outlook, roughly 80% of energy was derived from coal, oil and gas in 2017. If the process for converting renewable electricity to hydrocarbons is 50% efficient, then the energy needed to supply those hydrocarbons would be double that (160% of the baseline), increasing the total energy demand to 180% of the baseline. The basis for the 50% efficiency estimate is described in the supplementary materials. There is high uncertainty in this estimate, as the existing air-to-fuel demonstration projects are still on a small scale and mostly use natural gas for part of the process. The near-term efficiency for conversion of CO_2 to hydrocarbons from renewable energy is likely to be much lower than 50%, while there is potential to increase the efficiency above 70% long term.[9] Other long-term storage options are available, but we found that 50% round trip efficiency to be a plausible assumption for many. If the 50% efficiency were replaced with a 30% efficiency, the 180 TW would increase to almost 300 TW.

As tabulated in Table 2, the three estimates for the TW challenge for solar meeting 50% of energy demand range from 12 TW to 58 TW average power or 37 TW to 180 TW of DC capacity. The possibility of reducing the TW challenge by almost a factor of five provides strong motivation to develop a more efficient energy system, including aggressively electrifying our energy system and, at the same time, identifying opportunities to deliver renewable energy directly to the end application.

Implications for the photovoltaic industry

An obvious question is whether the solar industry is positioned to deliver on this challenge. While both solar thermal and solar PV technologies can contribute, here we focus on the PV industry because it is much better established. From 2001 to 2015, PV shipments increased by a factor of 145, which is equivalent to an average increase of ~43%/y. Figure 4 shows PV growth scenarios that would extend historical growth to meet each of the scenarios described in Table 2, with the least efficient scenario using 35%/y growth until 2030, followed by a more moderate 13%/y growth rate from 2030 to 2040 and 2%/y between 2040 and 2050. The other scenarios could be met with lower growth rates as indicated in Fig. 4.

Each curve is a continuation of previous (demonstrated) growth rates but would require massive capital input that may be difficult to mobilize in the described time frame, especially since many governments have phased out the programs that stimulated the PV market so effectively. Material supply rates for PV manufacturing would need to increase by a factor of 30-200 over current levels, which in turn would require modifications to PV module design such as reduction of silver usage to avoid material shortages.

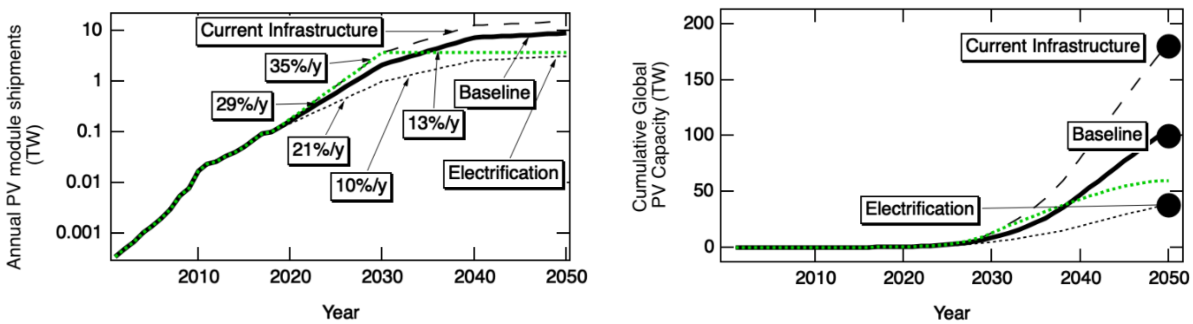

Fig. 4. Historical and projected PV growth scenarios that could meet the TW Challenge estimated for the three scenarios, which use 35%/y, 29%/y, or 21%/y until 2030, and lower rates later. The annual shipments are shown on the left and the cumulative global capacity on the right.

Discussion and Conclusions

As the world embarks on a major energy transition, difficult decisions will need to be made about investments in research, infrastructure development and product deployment. It is too early to predict which transportation technologies will dominate in 2050, but decisions are already being made to simultaneously develop the infrastructure to support electric vehicles, fuel-cell vehicles and natural gas vehicles. Similarly, we may choose to invest in a smart grid that is effective at balancing supply and demand for electricity by primarily controlling loads rather than generators and in reduction of factory capital costs to enable factories to be cost effective even when run intermittently. On the other hand, if we choose a path that relies on large-scale seasonal storage, the TW challenge may be highly dependent on the efficiency of the seasonal storage, motivating major research investment on improving that efficiency. As we make these choices, it is useful to consider how each choice and proposed pathway will affect the overall challenge.

Though Richard Smalley did not anticipate the resurgence of the U.S. oil and gas recovery nor the rapid growth of electric vehicles, his perspective in 2003-2005 was visionary. Revisiting his analysis in 2019, we estimate that continuing on our current trajectory will require 32 TW ± 5 TW of average global power in 2050. If 50% of this were supplied by solar, it would require a total installation of ~100 TW of solar panels, based on a 16% capacity factor. A decision to prioritize pathways using electrification and avoiding the need for long-term storage could cut that number by almost a factor of three, while using hydrocarbon synthesis from air to power our current infrastructure (or other scenarios requiring substantial long-term storage) could increase it by almost a factor of two. Whether the world will need ~180 TW of solar or only ~37 TW of solar will likely depend on successful implementation of electrification and direct delivery of energy to the end application, reducing the need for seasonal storage and optimizing overall system design. The PV industry could supply any of these levels by 2050 if historical growth rates can continue, but will require massive capital investment and addressing materials shortages, especially if the need for storage increases the total energy needed. As the situation comes into sharper focus 15 years later, we see that the magnitude of the challenge depends strongly on our choices for electrification and storage.

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