Transformation

Next Gen Tech: Energy

02 August 2024

Key takeaways

- The global energy system is transforming to more diversified sources of power generation and storage on the supply side, and electrification of transport, buildings and industries on the demand side. This transformation creates difficulties in balancing the production, transmission, storage and usage of energy, particularly the electricity grid, not to mention the cost and minerals required to achieve it.
- Technology, material science, chemistry and engineering are converging to mitigate the challenges ahead, and here, we share five breakthroughs that may enable the next generation of energy-related innovation.
- Bank of America Institute's 'Next Gen Tech' series explores 30 breakthroughs across artificial intelligence (AI), computing, robots, communication, healthcare, energy and mobility, that are about to alter our lives. Join us as we discuss what's next on the tech horizon.

This publication is part of Bank of America Institute's 'Next Gen Tech' series – focused on sharing 30 breakthrough technologies that will transform the world. Each publication will highlight one of seven categories (artificial intelligence, computing, robots, communication, healthcare, energy and transport), and share advancements within each, so stay tuned for more.

Energy and materials meet deep tech

The global energy system is transforming to more diversified sources of power generation and storage on the supply side and electrification of transport, buildings and industries on the demand side. This creates several difficulties in balancing the production, transmission, storage and usage of energy, particularly the electricity grid, not to mention the cost and materials required to achieve it.

However, clean energy capacity is multiplying, and global investment trends are beginning to reflect the shift to lower carbon energy. And as capacity grows, clean energy prices continue to fall; clean energy technologies continue to get cheaper as scale increases.

So, as technology, material science, chemistry and engineering converge to mitigate the challenges ahead, we reflect on five breakthroughs that could enable the next generation of energy-related innovation.

1) Smart grid infrastructure

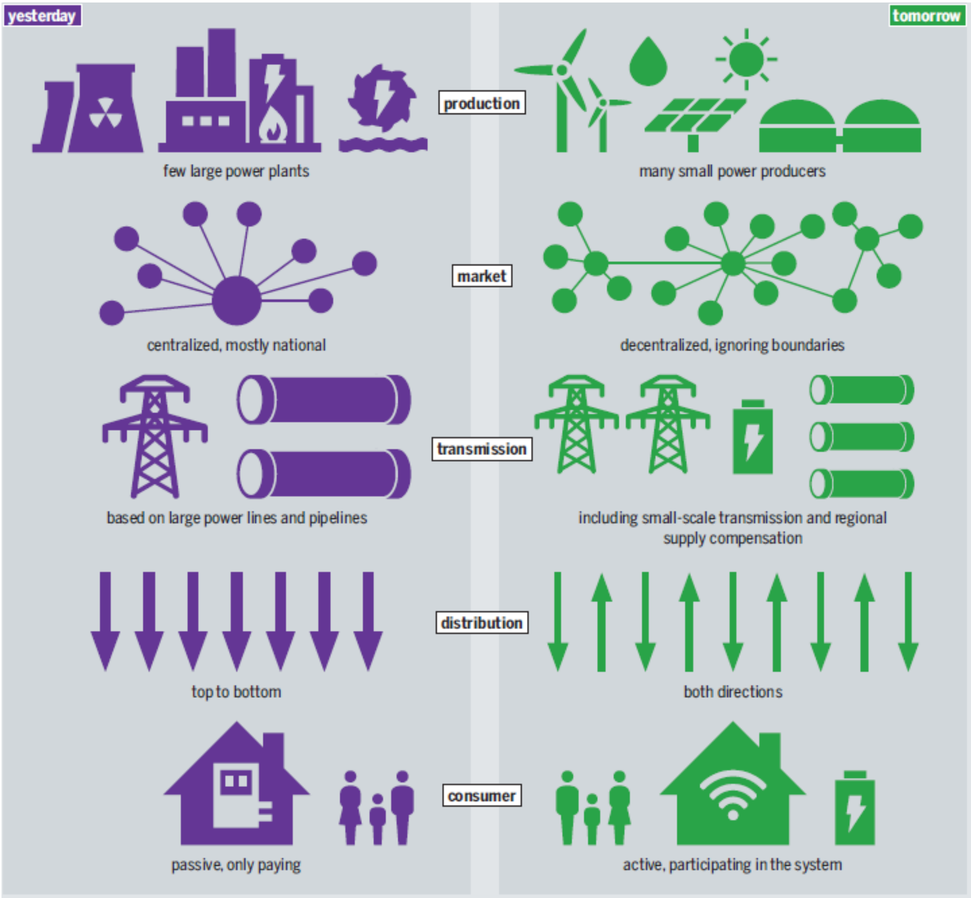
As electricity becomes a larger share of global energy consumption, expanding, upgrading and digitalizing electricity grids could help match shifts in power supply (to more intermittent renewables) in order to meet changing demand (transport, buildings, industry).

Can the grid cope? The need for speed, security, and stability

The rising share of electricity will place increasing pressure on the grid to transport electricity. This requires investment, but also changes to how grids are created and connected. Expanding production, storage and interconnections will become essential to balance electricity supply and demand. This also provides an opportunity to shift from the current method of demand-led distribution to a more balanced supply-led model using a combination of price incentives, behavioral changes and technology to optimize the increasingly dispersed energy resources.

Exhibit 1: Structural changes in the energy system are being enabled by diversified energy sources and technology. Key trends: more power generation sources, localized grids, consumer participation in energy management

Clean technologies are shifting from central to decentralized energy opportunity



Source: Energy Atlas 2018, Bartz/Stockmar, CC BY 4.0 (License here: https://creativecommons.org/licenses/by-sa/4.0/)

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The challenges: Demand, diversification, delay, decay

As it stands, the grid cannot accommodate the diversification of supply (increased use of renewable sources) and the electrification of infrastructure and transportation industries, which presents several grid infrastructure-related challenges:

- **The power we're supplying…it's electrifying:** As more end markets electrify, significantly more electricity supply will be needed. For example, electricity usage of a typical household triples once an electric vehicle and heat pump are added to existing consumption. And plans to "electrify" the production process for certain industries (e.g., steel, cement, and chemical production) will increase consumption even more. As such, the International Energy Agency (IEA) projects that the share of electricity in final energy consumption could rise from 20% today to >50% in 2050.

- **Shift in supply *and* consumption** = **complex, new peaks**: Diversifying the supply of energy along with changes in demand patterns (when to charge electric vehicles (EVs), heat water and homes, run heavy industrial equipment, etc.) brings complexity, particularly in projecting changes in peak demand and dispatching the clean energy to accommodate it.

- **Delayed connections and congestion:** Two significant bottlenecks exist on the supply side: 1) solar and wind projects awaiting connection to the grid (e.g., Europe had 600GW (gigawatt) and US 900GW awaiting connection at the end of 2021); and 2) new renewable plants can take five to 10 years to connect and integrate to the grid, per Bloomberg New Energy Finance (BNEF), a strategic, energy-focused think tank.

- **The grid is old**: In 2020, the average age of a cable used to transmit or distribute electricity in Europe was 45-50 years and 35-40 years in the US, according to Nexans. And close to 30% of Europe's power lines are over 40 years old, which now means that much of the infrastructure needs to be replaced or upgraded to more efficient equipment with digital integration.

- **Scarcity**: Critical minerals volume is set to rise significantly for the energy transition. And despite concerns over EV batteries, metal volumes for the grid would be far higher.

The good news: Investment and tech can help solve these challenges

From an infrastructure perspective, meeting rising electrification needs is possible with a combination of both new investment and technologies.

- **Annual grid investments to triple by 2030, quadruple by 2050**: A range of external projections from BNEF, IEA and NGFS (Network for Greening the Financial System) suggest that the $250 billion annual spend on the grid in 2022 could more than triple by 2030, and quadruple by 2050 reaching ~$1 trillion, annually.

- **Wired for growth:** Electrifying the economy at this pace and scale requires a supersized grid. The cable needed to connect this grid is projected to double from nearly 51 million miles in 2022 to upwards of 108 million in 2050, per BNEF, and if laid in a single line it would be long enough to reach the sun.

Grids get digital

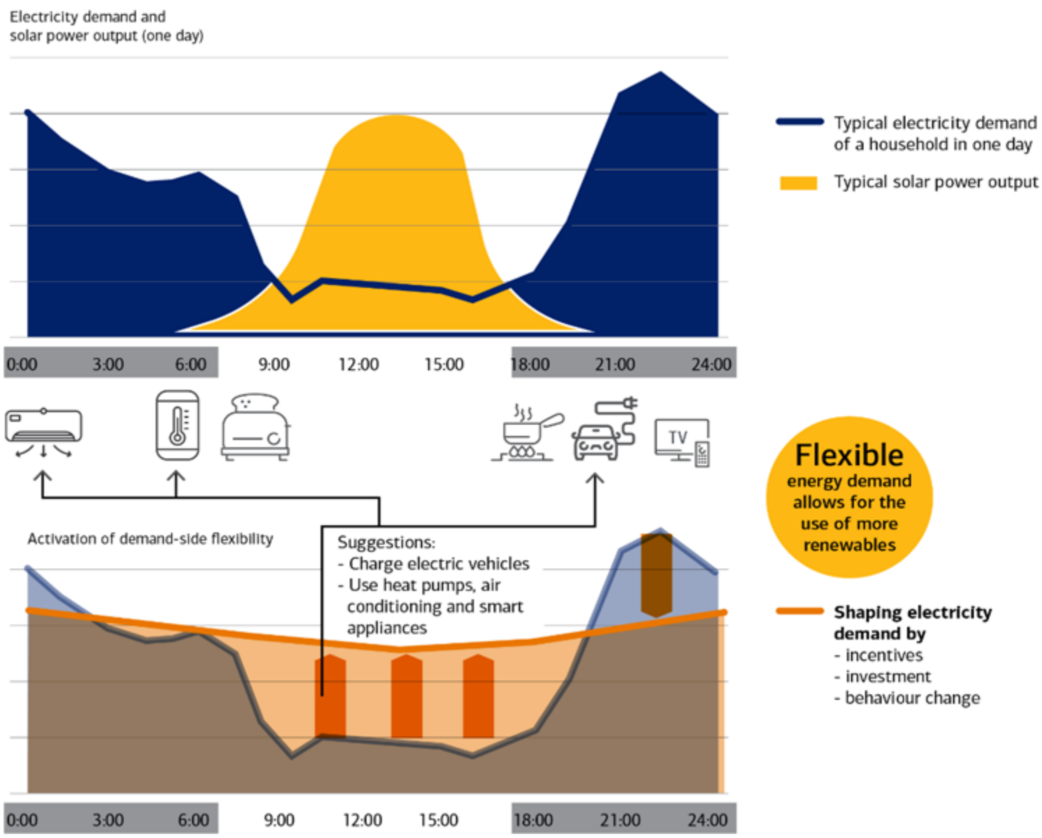
The changing energy generation/consumption patterns will require better monitoring, optimization, and control, all of which can be enabled through digitalization and automation. A third of all grid investment to 2050 is projected to be in digital technologies, per BNEF. This would shift the spend from mostly monitoring today to more automation and control of electricity.

This potential shift to a digital grid presents several opportunities. For one, the lights stay on: digital solutions could help reduce risk of power outages from default detection, cybersecurity, and adverse weather-related events.

A digital grid also improves stability and resilience by incentivizing energy use to off-peak demand hours, therefore reducing costs to the operator and customer. For example, EVs/heat pumps can be more efficient if they are programmed or controlled to consume energy at off-peak times. And home energy storage systems can provide power back to the grid at peak times, reducing the strain on the overall grid and power generation.

Exhibit 2: A combination of technology, behavior change, incentives and enforcement could change energy peaks

Future grids require both supply and demand side flexibility



Source: REN21 Renewables 2022 Global Status Report, based on RMI report, Demand Flexibility: The Key to Enabling a Low-Cost, Low-Carbon Grid, 2018

2) Virtual power plants

A virtual power plant (VPP, also referred to as a distributed energy resource (DER)) is an aggregated network of decentralized power generating units, comprising thousands of households and businesses that offer the potential of their collective resources to support the grid (e.g., EVs, thermostats, heat pumps, solar production or battery storage). These devices can be flexibly charged, discharged, or remotely managed/scheduled to meet grid needs. When aggregated they can offer similar services to traditional power plants.

VPPs offer significant potential to collectively balance an electricity grid while saving billions more in avoiding curtailment, congestion, and deferring transmission upgrades by managing end-user's peak demand and increasing utilization of the existing grid assets.

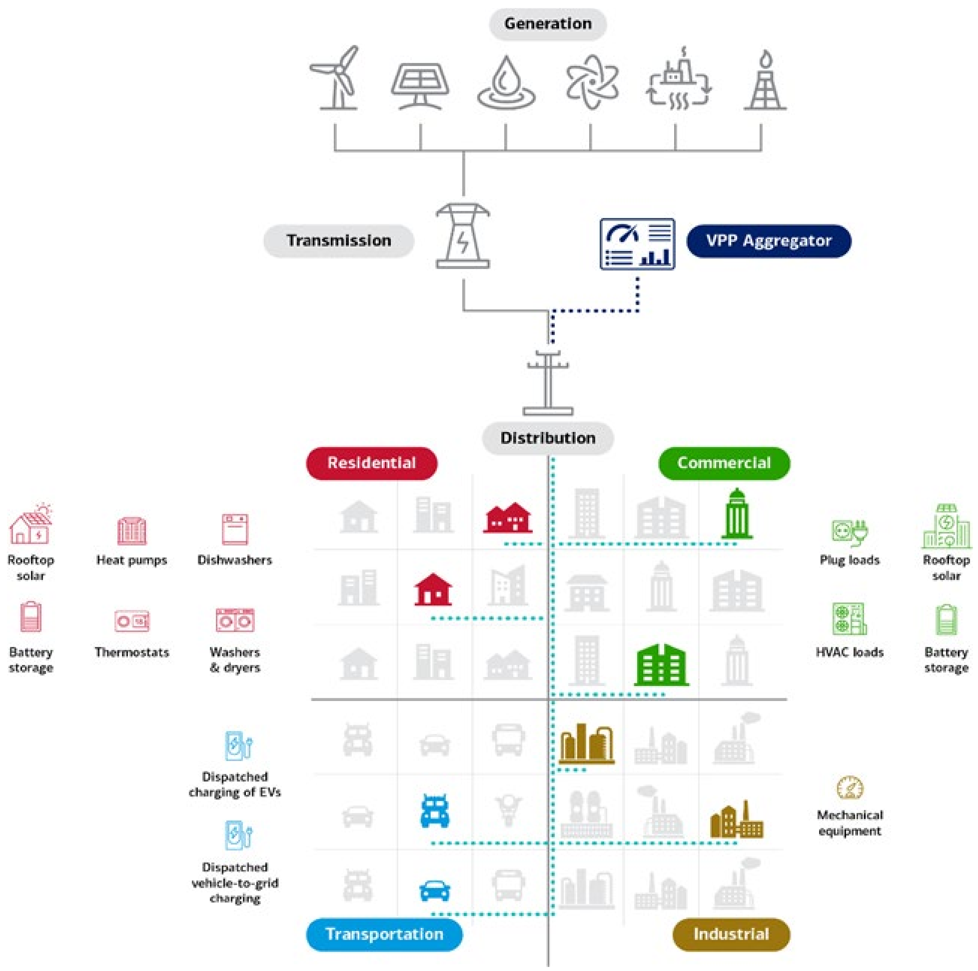
VPPs offer real cost and infrastructure savings

Per the US Department of Energy (DOE), there are several business models emerging for the use of VPPs including a combination of: 1) access to residential customers' solar and battery storage; 2) access to battery storage only; 3) managed EV charging (scheduling, shifting, or directly accessing EV battery charge via vehicle to grid programs); 4) flexible industrial demand; and 5) smart thermostats.

Despite the relatively early shift to electrification, VPPs already have 30-60GW aggregated capacity in the US, evenly split between utilities and wholesale markets, per the DOE. A tripling of VPP capacity could serve 10-20% of peak load nationally, saving $10 billion per year in the US and $17 billion globally, per RMI (formerly Rocky Mountain Institute). How? While 200GW of new peak demand is expected by 2030, hundreds more gigawatt hours (GWh, a measure of energy per hour) of battery capacity could be made available from EVs alone, if they can be accessed.

Exhibit 3: Proliferation of connected devices and technologies can be aggregated by VPPs to balance power supply/demand, e.g., by accessing distributed power sources or incentivizing reduced customer demand

Virtual power plants (VPPs): Aggregating distributed, grid-interactive electric devices



Source: RMI, Virtual Power Plants, Real Benefits Report, January 2023 (Click here for report),

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A consumer electric revolution is underway

Key to the adoption of VPPs is interest and behavior change from customers – shifting times of their electricity consumption or sharing energy production and storage resources with the grid, and by a combination of price incentives paid to customers to make those resources available while lowering energy prices.

EV batteries alone could balance the grid as soon as 2030

As the volume of EVs increases alongside the trend of increasing battery sizes, the volumes of battery capacity deployed cumulatively are set to grow exponentially from ~0.4TWh (terawatt hour) EV battery capacity deployed in EVs globally in 2020 to over 41TWh in 2040, per BNEF. Even accessing a small percentage of that energy could be useful in virtual power plants and grid balancing. According to the National Renewable Energy Laboratory (NREL) and Leiden University, EV batteries alone could be used to satisfy short-term grid storage demand across most regions by 2030 with as little as 12% of participation rates in vehicle-to-grid programs.

The role of AI in grid management

Shifting power supply (to more renewables and decentralized sources) and new electricity demands (EVs, heat pumps, industry) make more accurate demand, production and price forecasts more valuable to balance the grid. AI could play a critical role in enabling this through real-time modelling and automation, in particular.

Per the Massachusetts Institute of Technology (MIT), AI is already being used or considered in grid operations for faster and better decision-making by helping grid operators understand conditions and improve predictions. Every day, grid system operators run complex calculations to predict electricity requirements for the following day to recommend the most cost-effective way to supply it. Previous tests of using a machine learning model to optimize this daily planning showed that this can be done 12 times faster than without AI, reducing time required to 60 seconds. Given these calculations are done several times a day, time savings could be significant. The model is also being adapted to forecast power outages, by incorporating other factors such as weather. Other practical applications of AI already in place between grid operators and companies include aggregating smart meter/EV charging/IoT (internet of things) data for more accurate home energy predictions, and creating automated responses to vary power supply, and dynamic pricing incentives.

3) Perovskite solar cells

While the cost of solar PV (photovoltaic) modules has dropped tenfold in the past decade, the rate of efficiency improvements in the most commonly used silicon wafer technology has flatlined since the 1990s, potentially approaching its theoretical limit. In contrast, emerging PV technologies are showing near linear expansion, particularly in perovskite cells that are improving faster than any other PV material.

Perovskites 101

Perovskites are a family of materials with a crystal structure, with strong light absorption and electric charge properties. They can be tuned to respond to different colors in the solar spectrum by changing material composition. Continued research and innovation shows increased performance when used in solar panels, thus they are at the forefront of research seeking to replace or complement silicon.

Combining perovskites with other materials, such as silicon or other perovskite materials can deliver more power from the same device (referred to as tandem device architectures). While adding perovskite to current materials offers the most optimized route to commercialization today, combining with other perovskite materials is likely where the industry will trend longer term.

The key potential benefits they offer over current silicon-based panels include: 1) higher observed efficiency of converting solar rays into usable energy and rapid progress being made, 2) lighter materials, and/or 3) the ability to deposit onto most surfaces, expanding the potential to incorporate solar panels into windows, buildings and other surfaces (not just rooftops). Versatility sets the perovskite cells apart because they are light and flexible, and hence can be installed on walls or curved surfaces.

Challenges to commercialization of perovskite

While perovskite has become highly efficient in a relatively short time, several challenges remain to commercialize the technology, per the US DOE:

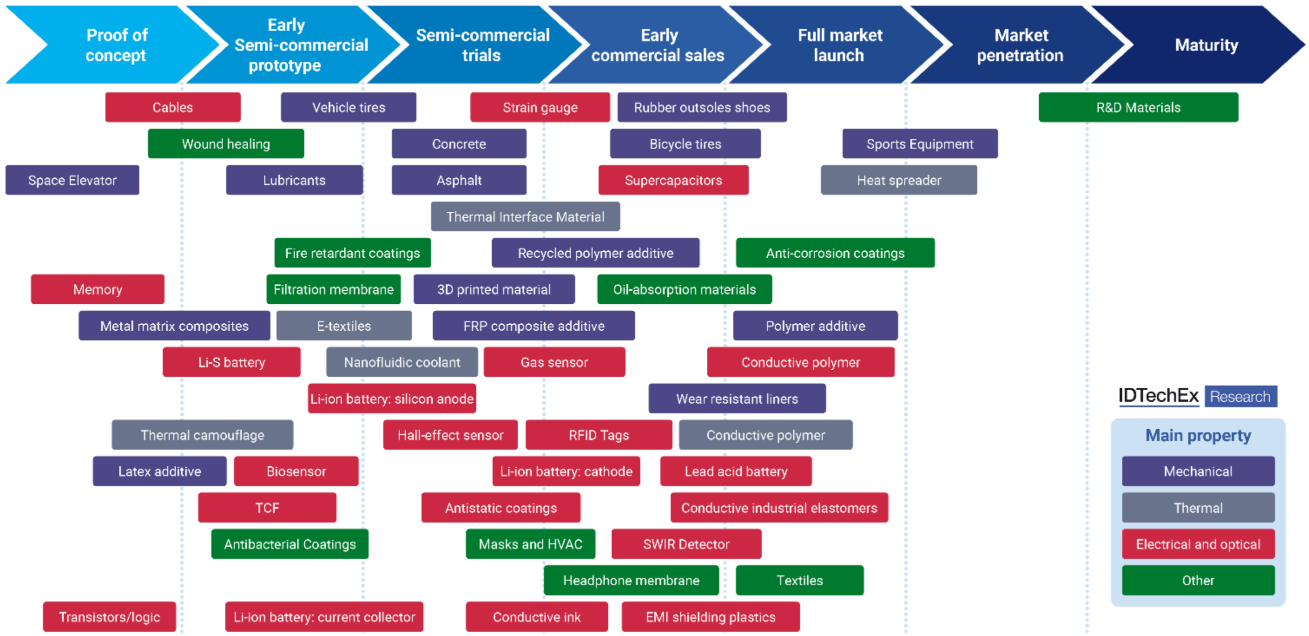
- **Manufacturing scale**: Lab tests of perovskite solar cells are showing rapidly increasing energy conversion efficiency rates; however, this is yet to be proven at commercial manufacturing scale.
- **Stability and durability**: Perovskites can decompose as they react to moisture and oxygen or when they are exposed to light/heat/applied voltage for an extended time.
- **Materials**: While perovskites could use significantly fewer materials than silicon cells, some formations include lead as the inorganic compound – a potential toxicity risk, given the solubility of the commonly used perovskite materials in solar.

4) Graphene

Graphene is the thinnest material in the world (only an atom wide), the strongest (an elephant would need to stand on a pencil to break graphene that is one atom thick), and also a superconductor (capable of sustaining current densities of six times that of copper).[1] Graphene and graphene derivatives have the potential for multiple applications – from today's use in functional ink, polymer additives, tires, coatings and composites, to potentially cheaper semiconductors, fast-charging batteries, lightweight cars, bulletproof vests, environmentally friendly concrete and medical applications. Scientists have been producing proof-of-concept products and discovering various graphene applications despite difficulties in sourcing it – some of which are at or nearing commercialization (Exhibit 4).

Exhibit 4: Uses of graphene span from mechanical and thermal to electrical and optical, with real-world applications in various stages of commercialization.

Commercialization progress of graphene in various applications



Source: IDTechEx - Graphene Market & 2D Materials Assessment 2024-2034: Technologies, Markets, Players

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EV batteries: Improving several performance attributes with graphene

Graphene batteries could have higher energy densities, increased cycle life and faster charging, with several companies already undertaking research and development in this space. In the meantime, blending graphene materials into existing battery chemistries could improve performance across several attributes, and is already beginning to be commercialized.

Graphene supercapacitor case study: Future of hybrid energy systems?

Like batteries, supercapacitors store electricity but do so statically rather than chemically. While less energy-dense than batteries, they can charge/discharge far quicker and last much longer, making them ideal for small bursts of power. Recent innovations in using graphene coated materials have demonstrated 10x improvement in their energy storage capacity.

While this is still only about 10% of the energy storage capability of advanced lithium ion batteries, these breakthroughs could enable supercapacitors to be used in parallel to batteries, as it could 1) triple the life of batteries (given the supercapacitor could take care of acceleration and energy recovery, the stressful part of a battery's life); 2) provide longer cycle life potential; 3) reduce battery size/weight (by up to one third without loss of range); and 4) reduce dependency on rare minerals.

Can graphene supercharge the internet, energy, or industrials?

Graphene's many characteristics imply multiple other potential uses for the material:

- **Telecoms**: The transmission of data could speed up owing to graphene's high conductivity and ability to operate at lower power levels compared to silicon-based devices.

[1] Columbia University, 2008, Chemical Society Reviews, 2015

- **Semiconductors**: Graphene could replace silicon as processing power rates of development slow, improving the data processing, wireless communications, and consumer electronics markets.
- **Construction**: Cement production causes 8% of the world's carbon emissions – three times more than the aviation industry.[2] If reinforced with graphene, the concrete savings would be equal to stopping all the annual emissions of Brazil.[3]
- **Image sensors**: Graphene can detect UV (ultraviolet), visible, and infrared light in one sensor as it can absorb almost all wavelengths of light.
- **Wearable tech**: It could monitor the heart rate, UV exposure, and blood oxygen through a UV patch.
- **Water tech**: Research is ongoing for the use of graphene in membranes for water filtration or desalination, owing to their high permeability (8-9x more efficient than current water filters, per Nanografi) and high adsorption surface area that could enable it to adsorb a wider range of contaminants compared to current filters.
- **Solar cells**: Graphene could be incorporated into solar cells to enhance performance, efficiency, and durability in a number of areas, e.g., the electrodes in existing thin-film cells, or integrated to next-gen perovskite solar cells to improve their stability (per graphene-info).

Challenges to commercializing graphene: Separation, standards, safety

Despite the vast potential, to commercialize graphene requires overcoming issues hindering more widespread development:

- **Separation**: Producing high-quality graphene at scale is hard and not yet proven. The material was initially separated in 2004 by applying scotch tape to graphite repeatedly until left with a single layer of atoms. However, this "mechanical separation" is not replicable at scale. Research is being done to find an alternative to current methods, which produce highly contaminated or oxidized graphene that erodes its characteristics.
- **Lack of standardized material and processes**: The quality of graphene produced is varied and without access to good-quality graphene, it is impossible to develop applications for it.
- **Safety**: Testing trials on the impact of graphene exposure to humans is in the early stages, with further research still necessary ahead of widespread commercialization.

5) Superconductors

Superconductors are materials that carry electrical currents with zero resistance, which saves a lot of energy from being lost compared to traditional materials like copper, which loses part of the charge in the form of heat.

How is this possible? Cooling superconductors to extremely low temperatures (-423° Fahrenheit), allow some electrons to move freely throughout the material instead of being bound to atoms. In normal conductors, electrons are scattered due to impurities, however, in superconductors, there is ordering that prevents this scattering.

Let's talk limitations

For one, too strong a magnetic field can cause loss of superconductivity. Strong magnetic fields above a certain value, cause a superconductor to revert to its normal/non-superconducting state, even if the material is kept well below the transition temperature.

Secondly, extremely cold temperatures or very high pressure are required for superconducting properties to occur, which could be expensive to maintain. This makes it difficult to deploy more widely in ways that could change daily life. The challenge is to find materials that superconduct at everyday temperatures *and* pressures. A room-temperature operating superconductor would allow for all kinds of possibilities, such as improving existing technologies, such as medical imaging devices to moonshot technologies like nuclear fusion reactors.

Relevance to energy? Superconducting cables can remove energy losses and reduce size and cost

Replacing the electrical grid with superconducting transmission lines could carry large currents over long distances with no losses. Superconducting materials can also act as fail-safe devices to guard a portion of the grid or substation against a sudden electrical outage. They can also protect the grid against extreme weather and other catastrophic events.

[2] International Energy Agency (IEA)
[3] Grist

Superconducting cable benefits: Up to 500x more electricity than copper

Electricity grids "lose" around 10% of the energy transmitted owing to heat and resistance. Superconducting cables can almost eradicate this, leading to more energy throughput. More importantly, superconducting cables can carry far higher currents than conventional copper or aluminium cables, making it possible to transport electricity at lower voltages and reducing the need for substations in city centers.

Superconductors also don't produce heat and are shielded electromagnetically, meaning no interference with other cable networks. This avoids cable congestion, making them ideal in urban areas. Furthermore, superconducting cables can be smaller than existing ones, while carrying the same amount or more power.

Challenges to commercialization: Cooling & durability

Research and development of superconducting cables is ongoing; however, the technology maturity is yet to be proven at grid scale. The key challenges that need to be overcome will be: 1) cryogenic cooling requirements: achieving and maintaining the low temperatures required for superconductivity, leading to 2) reliability and durability uncertainty over time in real-world environments, and 3) cost, i.e., the ability to manufacture and maintain the materials required at grid scale projects at a competitive price.

Superconductors are enabling nuclear fusion breakthroughs

Nuclear fusion is the process of joining atoms together, and in doing so, releasing energy; it powers the sun and recreating it on earth for abundant clean, cheap energy has been a goal of many. A combination of breakthroughs in materials alongside improving AI, simulation, quantum computing, supportive regulation and funding could change this.

Breakthroughs in both the magnetic (superconducting magnets to control a plasma in which fusion can take place) and inertial (using lasers to hit a fuel target producing a burst of energy each time) approaches to fusion are rising in frequency, enabled by the improving technology and research focus. Additionally, AI and high-powered computing are improving simulations prior to expensive real-world experiments.

Industrial breakthroughs in healthcare, transport and computing

Beyond energy, superconductors could also unlock several industrial breakthroughs the imaging, computing and transportation sectors.

- **Healthcare: Magnetic resonance imaging equipment:** Superconducting electrons can act as a superconducting quantum interference device (SQUID), a very sensitive detector of magnetic fields 100 billion times smaller than those generated by an ordinary magnet that can be used to map magnetic fields in the human brain.

- **Ultra-high speed computer chips, memory chips and quantum computing:** Room-temperature superconductors could lead to significant chip design and manufacturing opportunities or could be used in high-end quantum computing, but performance and working level temperature are not yet proven (See Next Gen Tech: Computing for more on this topic).

- **High-speed 'Maglev' trains:** These use superconducting magnets to replace typical steel tracks, with the reduced friction increasing speeds to hundreds of miles per hour, achieved through the electromagnetic and electrodynamic suspension.

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