



# The Great Rewrite: Biology, Intelligence, and Energy in the 2020s

Noor Shaker

# **The Great Rewrite**

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# Preface

For most of history, human capability advanced through the accumulation of knowledge and the refinement of tools. We learned to understand the world through observation. We developed technologies that amplified human labor, extended human senses, and accelerated human communication. But the fundamental constraints remained: biology limited what our bodies could do, intelligence required human cognition to direct every decision, and energy systems operated within the bounds of what previous generations had built.

Between 2020 and 2025, something changed. Decades of fundamental research across multiple scientific domains—molecular biology, machine learning, materials science, renewable energy engineering—reached maturity simultaneously. Manufacturing processes that had been confined to laboratories scaled to commercial production. Technologies that had been limited to controlled demonstrations achieved sufficient reliability for real-world deployment. And capabilities that had seemed perpetually five to ten years away crossed thresholds into operational reality.

The result is a transformation that extends across the biological, the cognitive, and the physical infrastructure of civilization itself.

In medicine, we moved from managing disease to engineering cellular function. In artificial intelligence, machines transitioned from answering questions to autonomously executing complex tasks. In energy, renewable sources surpassed fossil fuels not through policy mandates but through economic superiority. Each shift represents decades of incremental progress suddenly converging into deployed capability.

This book documents convergence through ten detailed narratives spanning 2020 to 2025. The structure reflects three domains undergoing simultaneous transformation:

*Part I: The Rewrite of Biology* follows medicine's transition from reactive management to molecular engineering—preventing HIV transmission entirely rather than suppressing it with daily medications, generating replacement organs from stem cells rather than waiting for donors, bypassing severed neural

pathways with brain-computer interfaces rather than accepting permanent paralysis.

*Part II: The Intelligence Shift* documents artificial intelligence crossing from controlled environments into autonomous operation—vehicles navigating city traffic without human oversight, AI systems planning and executing multi-step tasks independently, and models compressed from data centers to smartphones while maintaining capability.

*Part III: The Planetary Substrate* traces transformations in energy and observation—renewable electricity surpassing coal globally, aviation beginning decarbonization through sustainable fuels, and astronomy shifting from taking occasional snapshots to filming the universe continuously.

These stories share common characteristics. Each represents an inflection point of learning curves that spanned decades. Each required manufacturing at scales that seemed impossible until accomplished. Each crossed thresholds where capabilities once limited to demonstrations became commercially deployed or scientifically operational. And each demonstrates that constraints once considered fundamental—biological limits, cognitive boundaries, physical infrastructure—can be renegotiated when underlying technologies mature and supporting systems are built.

The transformations documented here emerged from thousands of researchers making incremental advances, engineers solving manufacturing challenges, entrepreneurs building companies around maturing technologies, and policymakers creating frameworks that enabled deployment.

The ten chapters that follow document the technologies I identified as most fundamental, most transformative, and most clearly at inflection points between 2020 and 2025. These are not predictions about what might happen but records of what has already occurred—the capabilities now deployed, the thresholds already crossed, the systems currently operational. Understanding what happened in these five years is essential to understanding what becomes possible in the decade ahead.

Enjoy reading,

Noor

# Part III: The Planetary Substrate

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## Energy & Cosmos

For the entire span of human civilization, energy has determined what was possible. The domestication of fire enabled cooking, which increased caloric extraction from food and allowed brains to grow larger. The harnessing of wind and water power enabled mills that ground grain at scales impossible through human muscle. The combustion of coal powered the Industrial Revolution, replacing biological energy with fossilized sunlight stored over millions of years. The exploitation of petroleum enabled transportation, mechanization, and the creation of materials—plastics, fertilizers, pharmaceuticals—that defined the 20th century.

Energy is not one sector among many. It is the substrate upon which everything else is built. Every economic activity—manufacturing, transportation, communication, computation, food production, water purification, heating, cooling—is fundamentally an energy transformation. The cost, availability, and environmental impact of energy determines what is economically feasible, politically achievable, and physically sustainable.

For two centuries, that substrate was fossil fuels. Coal, oil, and natural gas were extraordinary energy sources: dense, transportable, available on demand, and geographically concentrated in ways that shaped global power structures. But they were also finite resources whose combustion released carbon that had been locked underground for hundreds of millions of years back into the atmosphere at rates that geological processes cannot absorb. The resulting atmospheric carbon dioxide concentration has increased from 280 parts per million in pre-industrial times to over 420 parts per million in 2025—higher than any point in the past 3 million years.

The three chapters that follow document transformations occurring not because humanity chose virtue over profit, but because the economics fundamentally shifted. Renewable energy became cheaper than fossil fuels. Sustainable aviation fuel became technically viable. And our capacity to observe the universe crossed thresholds that transformed astronomy from taking occasional snapshots to filming continuous movies of cosmic evolution.

Chapter 8 follows the renewable energy transition from the invention of the silicon solar cell at Bell Labs in 1954, through Germany's feed-in tariffs creating initial demand in the 2000s, through China's ruthless manufacturing scale-up driving costs down 99.9 percent, to the October 2025 crossing where renewables surpassed coal for the first time.

Chapter 9 traces sustainable aviation fuel from Virgin Atlantic Flight 100's transatlantic crossing on 100 percent SAF in November 2023, through the opening of LanzaJet's Freedom Pines plant in January 2024 as the world's first commercial alcohol-to-jet facility, to the European Union's ReFuelEU Aviation mandate taking effect January 2025. The challenge is scaling production 200-fold by 2050, requiring building 3,000 to 6,500 new renewable fuel facilities at \$128 billion annual capital expenditure.

Chapter 10 documents the Vera C. Rubin Observatory achieving First Light in June 2025 after two decades of engineering, construction delays, and technical problem-solving. The narrative emphasizes the shift from static astronomy to transient observation—not photographing the universe once but filming it continuously. The scientific goals span dark matter mapping through gravitational lensing, completing the asteroid census for planetary defense, detecting supernovae in their first hours, and characterizing millions of variable stars that serve as distance markers.

These stories share common characteristics beyond their temporal proximity. Each represents the endpoint of decades-long learning curves. Each required manufacturing at scales that seemed impossible until accomplished. Each crossed thresholds where capabilities once limited to demonstrations became commercially deployed or scientifically operational. And each demonstrates that fundamental constraints are negotiable when underlying technologies mature and supporting infrastructure is built.

The biology was rewritten in Part I through molecular interventions that restored pancreatic function, prevented HIV transmission, and decoded neural activity. The intelligence was shifted in Part II through autonomous AI agents, compressed models running locally, and machines learning to navigate the physical world. The planetary substrate is being transformed in Part III through energy systems transitioning from fossil fuels to renewables, aviation decarbonizing through sustainable fuels, and cosmic observation shifting from snapshots to continuous monitoring.

# Chapter 8: The Energy Crossing

## The Fossil Tipping Point

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### The Line Was Crossed

On October 8, 2025, Ember—a London-based energy think tank—released a report that documented that in the first half of 2025, renewable energy sources generated 34.3 percent of global electricity. Coal, which had powered the Industrial Revolution and dominated the global energy system for over a century, contributed 33.1 percent.

For the first time in human history, renewables surpassed coal. Solar and wind generation combined grew by 403 terawatt-hours in the first six months of 2025—more than the entire increase in global electricity demand during that period. While humanity's appetite for electricity continued expanding, driven by data centers, air conditioning, and industrial growth, fossil fuels were no longer needed to meet it.

Coal generation had actually declined slightly, down 31 terawatt-hours from the same period in 2024. Global fossil fuel generation fell by 27 terawatt-hours. The world was still burning vast amounts of coal, gas, and oil—but the trajectory had fundamentally shifted. In December 2025, *Science* magazine named the "unstoppable growth of renewable energy" its Breakthrough of the Year. The decisive factor was economic: renewables had become cheaper than fossil fuels in most of the world. What had seemed impossible in 2015 was now simple reality.

### The Economics of Inevitability

To understand why the energy crossing represents an irreversible transition, you need to understand Wright's Law, a principle originally observed in aircraft manufacturing but one that applies with stunning precision to solar panels. Wright's Law states that for every cumulative doubling of production, manufacturing costs decline by a fixed percentage. For solar photovoltaics, that decline has been approximately 20 percent per doubling.

In 1976, solar panels cost \$106 per watt of capacity. By 2000, after multiple doublings of global production, the cost had fallen to around \$5 per watt. By

2020, \$0.38 per watt. By late 2023, Chinese manufacturers were producing panels at \$0.15 per watt—a 99.9 percent cost reduction in less than 50 years. To put this in perspective: if automobiles had followed a similar cost curve since 1976, a \$25,000 car would cost \$2.50 today.

The cost decline wasn't gradual or linear. It was exponential, driven by a virtuous cycle. Lower costs led to greater adoption. Greater adoption drove higher production volumes. Higher volumes enabled manufacturing innovations and economies of scale. Manufacturing improvements drove costs lower still. Each iteration of this cycle made solar more economically competitive, which triggered another round of expansion.

By 2024, in most of the world, new solar and wind installations were the cheapest way to generate electricity—cheaper than new coal plants, cheaper than new gas plants, and in many locations, cheaper than continuing to operate existing fossil fuel facilities. Once a technology becomes cheaper than the incumbent, market forces become self-reinforcing. Capital flows toward the cheaper option. Existing infrastructure gradually becomes stranded. And attempts to resist the transition impose economic costs that become politically unsustainable.

## The Factory Floor of the Planet

In May 2025, a construction milestone passed largely unremarked in the Western media but critical to understanding the energy transition: China's installed solar photovoltaic capacity surpassed one terawatt—one trillion watts—of generating capacity. To grasp the scale, consider that the entire United States electric grid has an installed capacity of about 1.3 terawatts from all sources combined. China had installed more solar capacity than all the generating capacity—coal, gas, nuclear, hydro, and renewables combined—that existed in the United States when China began its solar buildout in earnest around 2010.

And China wasn't slowing down. In 2024 alone, China installed new solar and wind capacity equivalent to approximately 100 large nuclear power plants. In the first half of 2025, China added more solar capacity than the rest of the world combined. By mid-2025, solar generation in China had increased more than twenty-fold in just ten years.

China made a strategic decision in the early 2000s to dominate the manufacturing of clean energy technologies, and it executed that decision with industrial policy of extraordinary scale and persistence. The technology originated elsewhere. Solar photovoltaic cells were invented at Bell Laboratories in New Jersey in 1954. Early development was funded primarily by NASA for space applications and by the U.S. Department of Energy. American and European companies led solar manufacturing through the 1980s and 1990s. But China recognized solar panels as a strategic industrial opportunity. In 2004,

Germany introduced generous feed-in tariffs that created a surge in solar demand. Chinese manufacturers, supported by state-backed financing, built massive production facilities and relentlessly optimized manufacturing processes. They achieved economies of scale that American and European competitors, operating with private capital and quarterly earnings pressures, couldn't match.

By 2025, China controlled approximately 80 percent of global solar panel manufacturing. More critically, China dominated the entire supply chain. Chinese companies produced over 95 percent of the world's polysilicon—the purified silicon that forms solar cells. They manufactured over 90 percent of solar wafers and solar cells. When you bought a solar panel in Texas, Europe, or India, there was an overwhelming probability that every critical component originated in Chinese factories.

This dominance wasn't an accident or a result of unfair subsidies alone, though government support was substantial. It was the outcome of vertically integrated industrial strategy. Chinese companies owned polysilicon refineries, ingot and wafer facilities, cell manufacturing lines, and module assembly plants. They invested in R&D, transitioning from PERC cell technology to more efficient TOPCon and heterojunction designs. They automated production lines to reduce labor costs. They built factories of extraordinary scale—single facilities capable of producing gigawatts of panels annually. And they drove costs down relentlessly. In 2023, Chinese solar manufacturers operated at production costs 55-60 percent below U.S. manufacturers. By early 2024, the gap had widened further as polysilicon prices collapsed due to overcapacity. Chinese manufacturers could sell panels in export markets at prices below what it cost Western competitors to produce them.

Western governments, recognizing the strategic vulnerability of depending on Chinese supply chains, responded with protectionism. The United States imposed tariffs on Chinese panels as early as 2012. Europe followed with anti-dumping investigations. The Inflation Reduction Act of 2022 provided massive subsidies for U.S. solar manufacturing. But by 2025, these efforts had barely dented Chinese dominance. The U.S. had approximately 50 gigawatts of announced solar manufacturing capacity—impressive growth, but still less than 10 percent of China's production capability.

China's strategy wasn't limited to solar. The country controlled approximately 75 percent of global lithium battery production—critical for both electric vehicles and grid-scale energy storage. It dominated wind turbine manufacturing. It produced the majority of the world's electric vehicles—over 70 percent of global EV production in 2024.

The West had invented many of these technologies. But China had manufactured them at scale, driven down costs, and achieved industrial dominance. By 2025,

any country wanting to build renewable energy infrastructure quickly and affordably had little choice but to buy Chinese products.

This created what is called China's "manufacturing diplomacy." Countries across the Global South—Pakistan, Brazil, Kenya, Indonesia, Vietnam—were importing Chinese solar panels, wind turbines, and batteries not because of climate commitments but because these were the cheapest and fastest ways to expand electricity access. China's renewable exports reached \$180 billion in 2024, making clean energy one of China's largest export categories.

## The Surprise Contender

While China's renewable dominance captured headlines, another transition was unfolding with less fanfare but equal significance: India's emergence as a clean energy superpower.

In 2014, India's solar capacity was 2.82 gigawatts—enough to power a mid-sized city. By August 2025, it had reached 116 gigawatts, a forty-two-fold increase in just over a decade. Wind capacity had grown from 21 gigawatts to 52 gigawatts. India's total renewable energy capacity stood at 234 gigawatts—approximately equal to Germany's entire electricity generation capacity from all sources.

The transformation was particularly striking given India's economic constraints. Unlike China, India wasn't manufacturing most of its solar panels or batteries. It was importing them, predominantly from China. Yet India was deploying renewables at a pace exceeded only by China itself.

The driver was straightforward: economics and necessity. India's electricity demand was growing at 5-7 percent annually, faster than any major economy except China. Meeting this demand with coal would require massive investments in new coal plants, coal mining infrastructure, and rail transport networks. It would worsen air pollution that was already a severe public health crisis—seventeen of the world's thirty most polluted cities were in India. And it would lock India into high-cost energy for decades.

Renewables offered a better path. Solar and wind farms could be built faster than coal plants. They had no fuel costs, eliminating exposure to global coal price volatility. And India had abundant renewable resources: extensive sunny deserts, strong wind corridors along the coasts and in the Western Ghats.

In fiscal year 2024-25, India added 29.5 gigawatts of renewable capacity—more than the country had added in any previous year. The acceleration was driven by competitive auctions that had driven solar power purchase agreements to record-low prices—below \$0.03 per kilowatt-hour in the most favorable locations.

Significantly, the growth wasn't limited to large utility-scale projects. India's rooftop solar sector was exploding. In 2024, 10 million rooftop solar systems were installed on households and public sector banks had approved loans totaling nearly \$13 billion for residential solar. Indians were installing solar not because of environmental commitment but because it slashed electricity bills by 50-70 percent.

The off-grid solar sector grew 182 percent in 2024, bringing electricity to villages and rural areas that had never been connected to the central grid. For hundreds of millions of Indians, their first experience of reliable electricity was solar-powered.

Together, China and India represented an overwhelming force driving global clean energy adoption. In 2024, these two countries accounted for over 60 percent of global renewable capacity additions. When the two most populous nations on Earth, representing 36 percent of humanity and 50 percent of global manufacturing, committed to renewable energy for reasons of economic self-interest, the global energy transition became irreversible.

## The Grid Challenge

The crossing of coal by renewables was celebrated by climate advocates, but it created an immediate engineering challenge that threatened to slow the transition: grid integration.

Solar and wind are variable. The sun doesn't shine at night. Wind speeds fluctuate. This variability is manageable when renewables constitute 5-10 percent of electricity generation—fossil fuel plants can ramp up and down to compensate. But as renewables approached and exceeded 30-40 percent of generation in leading markets, the challenge intensified.

In 2025, this showed up as curtailment—renewable energy that could be generated but is intentionally not generated because the grid can't absorb it. China, despite adding solar capacity faster than any nation in history, was curtailing an estimated 5 percent of potential solar generation in some provinces because transmission infrastructure couldn't move the electricity from generation-rich western provinces to demand centers on the coast. Europe was experiencing similar challenges, with negative electricity prices occurring on sunny, windy days when supply overwhelmed demand.

The solution required three parallel developments: expanded transmission, grid-scale storage, and flexible demand.

Transmission expansion meant building high-voltage lines to connect renewable-rich regions to consumption centers. India was constructing 66

gigawatts of interstate transmission capacity specifically for renewable energy evacuation. China was expanding its ultra-high-voltage DC transmission network, capable of moving gigawatts of power thousands of kilometers with minimal losses. The United States was finally permitting major transmission projects after decades of regulatory paralysis.

Grid-scale battery storage was scaling even faster than solar. Global battery manufacturing capacity was expanding at 40 percent annually, driven primarily by electric vehicle demand. But the same lithium-ion batteries used in vehicles could stabilize electricity grids. In 2024, the world installed approximately 90 gigawatt-hours of grid-scale battery storage—equivalent to batteries for 1.5 million EVs. By 2025, installations were exceeding 120 gigawatt-hours annually.

Battery costs were following their own Wright's Law trajectory. Lithium-ion battery packs cost over \$1,100 per kilowatt-hour in 2010. By 2024, they had fallen below \$100 per kilowatt-hour. At those prices, solar plus storage would be cheaper than fossil fuels even when accounting for variability.

Together, these solutions were transforming how electricity grids operated. The transition wasn't seamless. California was experiencing growing pains, with solar generation so abundant during midday that natural gas plants were struggling to remain economically viable, yet still needed for evening peaks. Texas was building transmission faster than any U.S. state but still faced constraints moving West Texas wind and solar to Houston and Dallas. India's grid frequency stability was being challenged by the rapid influx of variable generation. But these were solvable engineering challenges, not fundamental barriers. The economics were clear: building out storage and transmission was cheaper than building new fossil fuel plants. And once built, the renewable energy system had near-zero fuel costs for decades.

## The Carbon Plateau

The energy crossing had a consequence that received less attention than the milestone itself but carried greater significance: global carbon emissions from the electricity sector were flatlining.

Electricity generation is responsible for approximately 35-40 percent of global CO<sub>2</sub> emissions—the single largest source. For decades, these emissions had risen in lockstep with economic growth. More GDP meant more electricity demand, which meant more coal and gas combustion, which meant more emissions. The relationship seemed immutable.

In 2023, global electricity sector emissions rose slightly, by about 1 percent. In 2024, they fell by approximately 2 percent. In the first half of 2025, despite electricity demand growing 2.6 percent, emissions declined further. The

decoupling had begun. Solar and wind were covering all new electricity demand. Fossil fuel generation was no longer growing. In some markets—China, the European Union, the United Kingdom—fossil fuel generation was declining in absolute terms.

This was happening fastest in China, which for two decades had been the world's largest source of new CO<sub>2</sub> emissions. China's electricity sector emissions appeared to have peaked in 2023 and were declining in 2024-2025 as solar and wind additions outpaced demand growth. If this trend continued—and there was every reason to expect it would, given China's solar buildout trajectory—China's emissions would begin falling in absolute terms within 2-3 years, even as its economy continued growing.

## The American Exception

While China and India drove global renewable expansion, the United States presented a paradoxical picture: leading in some areas, lagging in others, and increasingly subject to political turbulence.

The Inflation Reduction Act of 2022 had catalyzed an unprecedented boom in renewable energy and manufacturing investment. By 2025, over \$400 billion in announced projects—solar factories, battery plants, wind manufacturing, EV assembly—were underway, predominantly in Republican-held districts. Solar and wind installations were growing at 10 percent annually. The U.S. overtook coal with renewables in 2024, and the gap was widening.

But the momentum confronted political resistance. The Trump administration, elected in 2024, explicitly campaigned on rolling back clean energy policies. In his second term's first months, Trump attempted to rescind unspent IRA funding, blocked new offshore wind leases, and prioritized fossil fuel development. The rhetoric was combative—wind turbines were derided, electric vehicles dismissed as impractical, and climate science questioned.

The political resistance reflected deeper tensions. The U.S. oil and gas industry remained enormously powerful, both economically and politically. The U.S. was the world's largest oil and gas producer, and the fracking revolution had created profound regional interests in fossil fuel continuation. Coal mining communities in Appalachia and Wyoming faced economic devastation as coal plants closed. Auto manufacturing regions feared job losses from the EV transition. But even within the U.S. fossil fuel sector, reality was intruding. Major oil companies—ExxonMobil, Chevron, Shell—were investing billions in carbon capture, hydrogen, and biofuels, hedging against long-term fossil fuel decline. Natural gas producers recognized that renewables plus batteries were increasingly competitive with gas peaker plants. And utility companies, even in

conservative states like Texas and Florida, were building more solar and wind than any other generation source because it was economically optimal.

American politics had become decoupled from American economics on energy. The political debate presented it as renewables versus fossil fuels, environmentalism versus realism, Democrats versus Republicans. The actual economy was making decisions based on costs and profits. And those decisions favored renewables.

## The Point of No Return

In 2025, renewable growth had overtaken demand growth. Every additional terawatt-hour of electricity needed by humanity was being met by solar and wind. Fossil fuel generation was no longer required for growth. It was only needed to replace old renewable capacity or serve as backup during low-resource periods.

This was the mechanism by which the energy transition became irreversible. Once clean energy met all incremental demand, fossil fuel generation couldn't expand even if utilities wanted it to—there was nowhere for it to grow into. The system was locked into a trajectory where fossil fuels declined as a percentage of generation every year, and eventually declined in absolute terms as renewable capacity continued exponential growth.

China exemplified this dynamic. Despite installing the world's largest solar and wind capacity, China wasn't shutting down coal plants—it was still building some. But coal generation in China had peaked in 2023 and was declining despite economic growth. The coal plants were increasingly used as backup capacity, running at lower capacity factors, becoming economically stranded as renewables captured a larger share of generation. Economics would eventually force closures.

For climate advocates who had spent decades pushing for emissions reductions through political action, this economic turning point was bittersweet. The transition was happening, but not primarily because humanity chose to act on climate science. It was happening because Chinese factories had manufactured panels so cheaply that buying them was more economical than burning coal. The right outcome for the wrong reason—or perhaps, more accurately, a different reason that proved more durable than moral imperative.

# Chapter 9: Flight Without Guilt

## Sustainable Aviation Fuel

Noor Shaker

### The Hardest Problem

On November 28, 2023, a Boeing 787 Dreamliner lifted off from London Heathrow, climbed to cruising altitude, and crossed the Atlantic to New York's JFK Airport. Virgin Atlantic Flight100 carried 50 passengers, including Sir Richard Branson and his daughter Holly. The flight lasted seven hours and took place without incident—a routine transatlantic journey in every respect but one. The aircraft burned no petroleum. Not a drop.

Both Rolls-Royce Trent 1000 engines ran on 100% Sustainable Aviation Fuel (SAF)—a blend of 88% hydro processed waste cooking oil and animal fats, and 12% synthetic kerosene made from plant sugars. The fuel flowed through the same infrastructure, performed identically to conventional jet fuel, and required zero modifications to engines, airframe, or ground equipment.

Flight100 saved 95 tonnes of CO<sub>2</sub> compared to a standard fossil-fueled flight. It demonstrated a 40% reduction in particulate emissions that contribute to contrail formation. And it proved something the aviation industry desperately needed to know: sustainable aviation fuel works, at scale, right now, with existing technology.

The celebration was tempered by reality. SAF represented just 0.3% of global jet fuel consumption in 2024. To decarbonize aviation by 2050, that number needs to reach 65%. The gap between proof of concept and global transformation remains enormous. Aviation is the hardest sector of the economy to decarbonize. Electric batteries are too heavy for long-haul flight. Hydrogen requires complete redesign of aircraft, engines, and airport infrastructure, and won't arrive commercially for decades. Biofuels work today, drop into existing systems without modification, and can scale using proven industrial processes. But scaling requires building infrastructure that doesn't exist, mobilizing feedstocks that are limited, and overcoming economics that make SAF three to ten times more expensive than petroleum jet fuel.

The story of sustainable aviation fuel is about overcoming these barriers through chemistry, engineering, policy, and sheer determination. And in 2025, after decades of research and false starts, that transformation is finally accelerating.

## The Carbon Problem

Aviation contributes approximately 2% of global CO<sub>2</sub> emissions—a seemingly modest share until you consider that only a small fraction of humanity flies regularly. The 4 billion passengers who boarded aircraft in 2024 represent the most mobile segment of the global population. As middle classes expand in developing nations, air travel is projected to grow by 4% annually through 2050. Without intervention, aviation emissions will triple.

The problem is physics. Moving a 400-tonne aircraft through the atmosphere at 900 kilometers per hour, fighting gravity and air resistance for thousands of kilometers, requires immense energy. Jet fuel provides roughly 12,000 watt-hours of energy per kilogram. The best lithium-ion batteries deliver about 250 watt-hours per kilogram—a 48-fold disadvantage.

A Boeing 787 flying London to New York burns approximately 18,500 liters of jet fuel, weighing about 15 tonnes. To replace that with batteries, you'd need 720 tonnes of batteries—far exceeding the aircraft's maximum takeoff weight. The plane couldn't lift itself, let alone passengers and cargo.

Hydrogen offers better energy density than batteries but still presents enormous challenges. Liquid hydrogen contains 33,000 watt-hours per kilogram but occupies four times the volume of jet fuel. Aircraft would require completely new fuel tank designs, new engines, and airports would need hydrogen production, liquefaction, and storage infrastructure that doesn't exist.

Boeing and Airbus estimate hydrogen-powered commercial aircraft won't enter service until the 2040s at the earliest. The only viable near-term solution is improving the fuel itself.

## The Chemistry of Flight

Jet fuel—known technically as Jet A-1 or kerosene—is a complex mixture of hydrocarbons. It's predominantly made of paraffins (straight-chain and branched alkanes with 8 to 16 carbon atoms) and smaller amounts of aromatic compounds like benzene rings.

The chemistry is specific. Jet fuel must remain liquid at -47°C, the temperature at cruising altitude. It must have high energy density—as much energy packed into as little weight and volume as possible. It must resist ignition until intentionally combusted, avoiding the risk of explosions. And it must contain sufficient

aromatic compounds to swell rubber seals in fuel systems; without aromatics, seals shrink, and fuel leaks.

For a century, we've extracted this precise chemical mixture from crude oil through fractional distillation—heating petroleum to different temperatures and collecting the kerosene fraction that boils between 150°C and 250°C.

Sustainable aviation fuel must replicate this chemistry without petroleum.

The challenge is that nature didn't evolve plants, bacteria, or algae to produce aviation-grade kerosene. Biological organisms make fats, oils, alcohols, sugars, and cellulose—molecules with oxygen atoms that reduce energy density and can cause problems in jet engines. The oxygen must be removed. The carbon chains must be rearranged to the right lengths. The final product must be chemically indistinguishable from petroleum jet fuel. This requires sophisticated chemistry. And in 2025, multiple pathways have proven they can deliver it.

## The HEFA Revolution

The most mature SAF technology is called HEFA—Hydroprocessed Esters and Fatty Acids. The process begins with lipid feedstocks: used cooking oil, animal fats from slaughterhouses, or vegetable oils. These triglycerides—molecules with three fatty acid chains attached to a glycerol backbone—contain 10 to 20% oxygen by weight. In the first step, called hydrodeoxygenation, the lipids are heated to 300–400°C under high pressure with hydrogen gas and a metal catalyst. The catalyst breaks the ester bonds, removes the glycerol, and strips away oxygen atoms, forming water and propane as byproducts.

The second step is hydrocracking and isomerization. The long chains are broken into shorter fragments and rearranged into branched structures. Branching is critical—it prevents the molecules from stacking neatly and crystallizing at low temperatures, which would clog fuel lines at altitude. The final product is synthetic paraffinic kerosene, or SPK. It's chemically similar to petroleum jet fuel but slightly different—lacking aromatic compounds. Current ASTM standards allow up to 50% SPK blended with conventional fuel, which provides sufficient aromatics from the petroleum component.

HEFA works. Companies like World Energy, Montana Renewables, Neste, and Phillips 66 are producing it commercially. In 2024, U.S. HEFA capacity reached approximately 30,000 barrels per day—about 1.3 billion liters per year. Global production hit 1 million tonnes of SAF in 2024, double the 2023 output. For 2025, production is expected to reach 2.1 million tonnes—0.7% of total jet fuel consumption.

HEFA's limitation is feedstock. The global supply of waste cooking oil and animal fats is finite—perhaps enough to produce 2 to 3% of aviation fuel needs.

Vegetable oils could theoretically scale further, but using agricultural land to grow fuel crops competes with food production and risks deforestation, potentially releasing more carbon than SAF saves.

To go beyond a few percent of jet fuel, aviation needs pathways beyond HEFA.

## Alcohol-to-Jet: The Breakthrough

In a rural town in Georgia, 100 miles from Savannah, sits a facility that represents the future of sustainable aviation fuel. LanzaJet's Freedom Pines Fuels plant in Soperton opened in January 2024 after a \$300 million investment and 15 years of research. On November 13, 2025, the company announced it had fully operational production—making history as the world's first commercial-scale plant to produce jet fuel from ethanol. The achievement unlocked a fundamentally different pathway.

Alcohol-to-jet, or ATJ, starts with ethanol—the same alcohol in beer, wine, and whiskey. Ethanol can be produced from corn, sugarcane, agricultural residues, municipal solid waste, or even captured carbon dioxide. Global ethanol production exceeds 30 billion gallons annually. It's a plentiful, well-understood industrial chemical. The challenge is transforming ethanol into jet fuel.

The first step is dehydration. Ethanol is heated over an acidic catalyst which removes water and forms ethylene (C<sub>2</sub>H<sub>4</sub>). The second step is oligomerization. Ethylene molecules are combined—linked together—to form longer chains. This is catalyzed by another metal catalyst. The third step is hydrogenation and isomerization—similar to HEFA. The chains are structured to resist low-temperature crystallization. The result is jet fuel chemically indistinguishable from petroleum kerosene.

Freedom Pines will produce 9 million gallons of SAF annually, plus 1 million gallons of renewable diesel for road transport. The fuel delivers 70% lifecycle CO<sub>2</sub> emissions reductions compared to petroleum jet fuel when using low-carbon ethanol feedstocks.

The significance extends beyond the single plant. ATJ validates a second major pathway to SAF, one not limited by waste oil availability. With 30 billion gallons of global ethanol production, ATJ potentially provides feedstock for 10 to 15% of aviation fuel needs without competing with food production, assuming ethanol from cellulosic sources and waste.

## The Mandate Imperative

Technology alone won't scale SAF. Economics and policy are equally critical.

In January 2025, the European Union's ReFuelEU Aviation regulation took effect, establishing the world's first binding SAF mandates. The regulation requires that 2% of aviation fuel supplied at EU airports must be SAF in 2025, increasing steadily and reaching 70% by 2050.

The mandate is already reshaping the industry. SAF production capacity currently under construction could supply the 3.2 million tonnes required in 2030, but producers must ramp up quickly and continuously to meet escalating requirements. The International Air Transport Association estimates that reaching net-zero by 2050 will require 3,000 to 6,500 new renewable fuel facilities globally. The annual capital expenditure needed is approximately \$128 billion—comparable to building 80 to 160 large-scale oil refineries.

The U.S. approach differs from Europe's. Rather than mandates, the Inflation Reduction Act provides tax credits—the Sustainable Aviation Fuel Credit offers \$1.25 per gallon for fuels meeting minimum emissions reductions, with an additional \$0.01 per gallon for each percentage point of emissions reduction beyond 50%. For SAF delivering 70% emissions reductions, the credit reaches \$1.45 per gallon. Combined with state incentives like California's Low Carbon Fuel Standard, which provides additional credits based on carbon intensity, these incentives can close much of the cost gap with petroleum jet fuel.

The Department of Energy's SAF Grand Challenge, launched in 2021, aims to produce 3 billion gallons of SAF annually by 2030 and 35 billion gallons by 2050—enough to meet 100% of U.S. aviation fuel demand.

## The Feedstock Bottleneck

The fundamental constraint on SAF scaling is feedstock availability. HEFA's reliance on waste oils and animal fats limits production to perhaps 7 to 8 billion gallons annually—about 10% of global jet fuel demand. Virgin oils could theoretically expand this, but using palm oil, soybean oil, or canola diverts crops from food or drives land-use change that releases carbon.

Lifecycle analysis shows that SAF from virgin palm oil can actually produce higher emissions than petroleum when indirect land-use change is included—deforestation to clear land for palm plantations releases stored carbon that takes decades to recapture.

The debate over feedstock sustainability has become contentious. Environmental groups argue that any food-crop-derived fuel risks pushing agriculture onto marginal lands or forests. Industry argues that waste-stream utilization and advanced feedstocks can scale without environmental damage. The solution

likely involves portfolio diversification: HEFA from genuine waste streams, ATJ from cellulosic ethanol produced from agricultural residues and energy crops grown on degraded land, and eventually e-fuels from renewable electricity and captured carbon.

The key insight is that no single feedstock will power global aviation. The solution is a diverse portfolio, with each pathway contributing based on regional availability and comparative advantage.

## The Cost Challenge

SAF remains 2 to 10 times more expensive than petroleum jet fuel, depending on feedstock, process, and market conditions. HEFA SAF costs approximately \$2.50 to \$4 per gallon at current production scales. These costs reflect small-scale production, immature supply chains, and limited economies of scale. As production volumes increase, costs should decline through learning curves typical of industrial scale-up.

Analysis suggests that at mature scales—producing billions of gallons annually with optimized processes—HEFA and ATJ could reach \$2 to \$3 per gallon, competitive with petroleum when carbon prices or incentives are included.

Airlines operate on thin margins—typically 3 to 5% net profit. Fuel represents 25 to 30% of operating costs. Even a 50% increase in fuel costs—say, from \$2 to \$3 per gallon—translates to a 12-15% increase in total costs, requiring ticket price increases that could reduce demand.

Policy mechanisms mitigate this. Tax credits, low-carbon fuel credits, and carbon pricing all reduce the effective cost premium. Mandates distribute costs across all passengers rather than penalizing airlines that volunteer to use SAF. If all carriers must use 2% SAF, competitive dynamics preserve because all face the same costs.

## The Path Forward

As of December 2025, SAF production is accelerating, costs are declining, policies are strengthening, and airlines are committing.

Global production reached 2.1 million tonnes in 2025, representing 0.7% of jet fuel consumption—small but growing rapidly. Production capacity under construction will add millions of additional tonnes annually through the late 2020s.

The U.S. saw production more than double between 2024 and 2025, reaching approximately 44,000 barrels per day. Europe's mandates are driving investment

in production capacity across the continent. SkyNRG is developing plants in the Netherlands. British Airways and Shell are building facilities in the UK. France and Germany are providing subsidies for domestic production.

Asia is emerging as a key market. Japan has committed to 10% SAF by 2030. Singapore is building SAF production capacity to supply its massive international aviation hub. China is investing in biomass-to-liquid technologies.

## What Remains

The hard problems remaining are primarily about scale, economics, and coordination.

Feedstock logistics require systems to collect, transport, and process millions of tonnes of waste oils, agricultural residues, and municipal waste. These supply chains must be reliable, cost-effective, and sustainable.

Financial structures need to support facilities costing \$500 million to \$4 billion with 20-to-30-year payback periods in an industry subject to volatile commodity prices and policy changes. Project financing requires long-term offtake agreements, government support, or innovative structures that share risk between producers, airlines, and governments.

International coordination is essential. Aviation is global; airlines fly across borders. Harmonized standards, mutual recognition of SAF certifications, and coordinated policies will accelerate deployment more effectively than fragmented national approaches.

Public acceptance will be tested. As SAF costs are passed to consumers through ticket prices, people will decide whether they're willing to pay more to fly. Most analyses suggest SAF adds \$5 to \$50 to a typical flight ticket depending on route and SAF percentage—modest for many travelers but potentially significant for price-sensitive segments.

The industry estimates that SAF could contribute 65% of the emissions reductions needed to reach net-zero by 2050, with the remainder from more efficient aircraft, operational improvements, electric and hydrogen propulsion for short routes, and offsets.

This means SAF isn't everything—but it's the crucial enabler. Without SAF, net-zero aviation is impossible. With SAF, it becomes achievable.

# Chapter 10: The First Light (Vera C. Rubin Observatory)

Noor Shaker

## A Moment Two Decades in the Making

On a clear Chilean night in June 2025, atop Cerro Pachón mountain at 2,682 meters elevation, the largest digital camera ever built opened its eye to the cosmos for the first time. Engineers in the control room watched monitors as photons that had traveled millions of years through space struck a mosaic of 189 silicon sensors, converting ancient starlight into 3.2 billion pixels of data. The images released on June 23, 2025, stunned the astronomical community. A single frame captured 10 million galaxies—roughly 0.05% of the 20 billion the observatory would eventually record over its ten-year mission. Another composite image, assembled from 678 separate exposures taken in just over seven hours, revealed the Trifid and Lagoon Nebulae in unprecedented detail: clouds of gas and dust sculpted by stellar winds, rendered from two trillion pixels of data.

This was the Vera C. Rubin Observatory achieving first light, and it marked a fundamental shift in how humanity observes the universe. For the first time, we weren't taking snapshots—we were filming a movie.

## Why "First Light" Matters

In astronomy, "First Light" is the term for when a new telescope captures its first images of the night sky. It's a test, a validation, and a celebration—the moment when years or decades of engineering become operational science. But for Rubin Observatory, First Light meant something more profound: it was the beginning of an unprecedented campaign to document not the static universe, but the *transient* universe—the cosmos in motion.

Previous telescopes, even the most powerful, operated like photographers taking occasional portraits. Hubble Space Telescope captured exquisite images of individual galaxies, nebulae, and distant phenomena. Ground-based surveys mapped the positions of millions of stars and galaxies. But they sampled the sky infrequently. If a supernova exploded, an asteroid wandered too close to Earth, or a distant star suddenly flared, we might miss it entirely—or discover it days, weeks, or years after the event.

Rubin Observatory was designed differently. Its mission: scan the entire visible southern hemisphere sky every few nights for ten years, creating a comprehensive time-lapse record of everything that changes. The result would be the largest astronomical movie ever made—a decade-long film showing the universe evolving in real time.

## The Monster Camera

At the heart of this ambition sits a technological marvel: the LSST Camera (Legacy Survey of Space and Time Camera), the largest and most powerful digital camera ever constructed. The camera is the size of a small car—1.65 meters wide, 3 meters long, weighing over 6,600 pounds. Its focal plane, the light-sensitive surface where images form, measures 64 centimeters in diameter—roughly the size of a car tire. The entire assembly required a custom vertical lift and precision mounting device to install it on the telescope in March 2025, a process demanding millimeter-level accuracy with thousands of pounds of delicate equipment. The sensor array contains 189 individual charge-coupled devices, each capturing 16 megapixels, arranged in a carefully calibrated mosaic to function as a single 3,200-megapixel imager. To put this in perspective: a typical smartphone camera has 12-50 megapixels. The Rubin camera has the equivalent resolution of 260 modern phone cameras combined. Each image it captures contains roughly 3 gigabytes of data—enough to fill 378 4K ultra-high-definition television screens if displayed at full resolution.

## Extreme Engineering

The focal plane operates at approximately -150°F, maintained by sophisticated cryogenic refrigeration systems. This extreme cooling reduces thermal noise—random electrons that create false signals—ensuring the camera can detect extraordinarily faint objects. The pixels themselves are 10 micrometers square, small enough that cosmic rays striking individual sensors during exposures create visible artifacts that must be identified and filtered out computationally.

The optical system includes six massive rotating filters that allow observations across different wavelengths of light. Different materials emit or absorb specific wavelengths, so imaging the same region of sky through multiple filters reveals information invisible to a single color. A distant quasar might appear in ultraviolet but not infrared. A dying star surrounded by dust glows brightly in infrared while nearly invisible in blue light. The filter mechanism must swap these meter-wide glass filters reliably thousands of times per night without introducing vibration that would blur images.

Perhaps most remarkably, the camera's field of view spans 3.5 degrees—about seven times the width of the full moon as seen from Earth. This covers 9.6 square degrees of sky per exposure, roughly the area of 40 full moons.

Combined with the 8.4-meter primary mirror telescope (one of the largest survey telescopes in the world), this gives Rubin extraordinary light-gathering power across an unusually wide field—a combination called *etendue* that no other observatory matches.

The result: Rubin can photograph an area the size of 40 full moons in a single 15-second exposure, with sensitivity to detect objects 100 million times fainter than visible to the naked eye. To put that in tangible terms, it could spot a candle flame from thousands of miles away.

## Filming the Cosmos: The Transient Universe

Traditional astronomy studied the universe as if it were frozen. We measured the positions of stars, calculated the distances to galaxies, analyzed the composition of nebulae. On human timescales, most of the universe appears static. Stars shine steadily for millions of years. Galaxies maintain their shapes for billions. But this apparent permanence is an illusion created by our brief lifespans and infrequent observations. The universe is in constant flux. Stars explode as supernovae. Asteroids hurtle through the solar system. Black holes tear apart passing stars, creating brilliant but brief flares. Distant galaxies flicker as supermassive black holes devour surrounding matter. Variable stars pulse with rhythmic changes in brightness.

Astronomers call these phenomena the *transient universe*—cosmic events that change on timescales from seconds to years. Studying them requires not occasional snapshots but continuous monitoring, something previously impossible at large scale.

## The Rubin Approach

Rubin Observatory's strategy is deceptively simple: photograph the entire visible southern sky repeatedly, compare new images to previous ones, and immediately alert astronomers to anything that changed. Every clear night, the automated telescope systematically scans predetermined regions of sky, capturing pairs of 15-second exposures. Sophisticated software compares each new image against a reference library built from previous observations.

Did a new point of light appear in a galaxy where none existed before? That's a supernova—a star exploding with the brightness of a billion suns. Did a faint point shift position slightly compared to last week? That's an asteroid. Did a star

double in brightness and then fade back? That's a variable star, its pulsations revealing information about stellar physics and cosmic distances.

The system operates with remarkable speed. Within 60 seconds of capturing an image, the data travels via dedicated fiber-optic network from the mountaintop in Chile to processing facilities in California, where algorithms identify changes and issue automated alerts to astronomers worldwide. This near-real-time notification allows follow-up observations while transient events are still unfolding—catching supernovae in their first hours, tracking asteroids before they're lost, studying stellar flares as they peak.

Over ten years, Rubin will revisit each patch of southern sky hundreds of times, building a temporal dataset of unprecedented depth. The result won't be a single image of the sky but thousands of images of the same regions taken over a decade—a true motion picture of the cosmos.

## The Dark Matter Hunt

Rubin Observatory bears the name of Vera C. Rubin, the American astronomer who in the 1970s provided conclusive evidence for dark matter's existence. The choice of name is deliberate—studying dark matter is central to Rubin's scientific mission, and the observatory's unique capabilities make it the most powerful dark matter detector ever built.

In the 1970s, Vera Rubin and her collaborator Kent Ford measured the rotation speeds of spiral galaxies. According to Newtonian physics, stars farther from a galaxy's center should orbit more slowly, just as outer planets in our solar system orbit the Sun more slowly than inner planets. But Rubin observed something baffling: stars at the edges of galaxies moved just as fast as stars near the center.

The implication was revolutionary. Either our understanding of gravity was fundamentally wrong, or galaxies contained far more matter than we could see—invisible material providing additional gravitational pull. The scientific consensus settled on "dark matter"—matter that doesn't emit, absorb, or reflect light, making it invisible to telescopes, yet exerts gravitational force.

Today we know that dark matter constitutes approximately 85% of all matter in the universe. Everything we can see—stars, planets, gas, dust, people—is just 15% of the cosmic matter budget. The remaining 85% is invisible, detectable only through gravitational effects. Identifying what dark matter actually is remains one of physics' greatest unsolved mysteries.

Rubin won't detect dark matter directly—by definition, dark matter doesn't emit light the camera can capture. Instead, it will map dark matter's gravitational influence across the universe using a technique called *weak gravitational lensing*.

Einstein's general relativity predicts that mass warps spacetime. Light traveling through warped spacetime bends, causing distant galaxies to appear distorted when viewed past massive foreground structures. It's analogous to how a glass lens bends light to magnify or distort images, except here the "lens" is gravitational curvature caused by mass—including dark matter.

For a single distant galaxy, this gravitational lensing creates subtle distortions—typically elongating the galaxy's shape by just a few percent. No single observation reveals much. But Rubin will photograph billions of galaxies, measure the slight shape distortions of each, and statistically analyze patterns across vast regions of sky.

Where dark matter concentrations exist—in galaxy clusters, along cosmic filaments, in invisible halos surrounding galaxies—the collective distortion of thousands of background galaxies reveals the dark matter's presence and distribution. By comparing observed distortion patterns to theoretical predictions from different dark matter models, cosmologists can test hypotheses about dark matter's properties: Is it made of undiscovered particles? Does it interact with normal matter in ways we haven't detected? How is it distributed throughout the universe?

Rubin's unprecedented combination of wide field of view, deep sensitivity, and repeated observations makes it uniquely powerful for this work. Previous surveys provided snapshots—valuable, but limited. Rubin will build the most detailed three-dimensional map of dark matter ever created, tracing its distribution across billions of light-years and billions of years of cosmic history.

Beyond dark matter, Rubin will study dark matter's even more mysterious counterpart: dark energy. Where dark matter's gravity pulls the universe together, dark energy appears to push it apart, accelerating cosmic expansion. This discovery—that the universe's expansion is speeding up rather than slowing down—earned the 2011 Nobel Prize in Physics and remains deeply puzzling.

Rubin will contribute to dark energy research by discovering and characterizing tens of thousands of Type Ia supernovae—stellar explosions that serve as "standard candles" for measuring cosmic distances. By precisely measuring how the relationship between distance and expansion rate changes over cosmic time, astronomers can constrain dark energy's properties and test whether it's constant throughout time and space or varies in ways current theory doesn't predict.

## The Asteroid Census

While physicists eagerly await dark matter maps, planetary defense specialists were celebrating Rubin's First Light for different reasons: asteroids.

In just 10 hours of test observations during commissioning, Rubin discovered 2,104 asteroids never previously recorded, including seven near-Earth asteroids—space rocks whose orbits bring them into Earth's neighborhood. For context, all ground and space-based observatories combined typically discover around 20,000 asteroids per year. Rubin alone is projected to discover millions of new asteroids within its first two years of operation.

Earth exists in a shooting gallery. The solar system contains millions of asteroids—rocky remnants from the solar system's formation 4.6 billion years ago. Most orbit harmlessly in the asteroid belt between Mars and Jupiter, but many follow trajectories that cross Earth's orbit. Occasionally, these cosmic wanderers strike Earth. Small ones (meter-sized) burn up harmlessly in the atmosphere. Larger ones can devastate regions or, in the case of kilometer-sized impactors, cause mass extinctions. The dinosaurs' demise 66 million years ago resulted from a 10-kilometer asteroid impact.

We've identified roughly 40% of near-Earth asteroids larger than 140 meters—large enough to destroy a city. The remaining 60% are undetected, invisible unless they happen to pass close enough during the brief period a telescope is pointing in the right direction. NASA and international space agencies aim to catalog at least 90% of potentially hazardous asteroids to enable early warning and possible deflection missions if one is found on a collision course.

Rubin transforms this effort from a slow, multi-decade search to a rapid census. Its wide field and repeated sky coverage means it will detect asteroids through motion—the same patch of sky photographed a few nights apart shows most points of light in identical positions, but asteroids noticeably shift. Automated algorithms identify these moving objects, calculate orbits, and flag those with trajectories approaching Earth.

Moreover, Rubin will detect *interstellar objects*—visitors from other star systems passing through our solar system. Only two have ever been identified: 'Oumuamua in 2017 and Comet Borisov in 2019. These objects move fast, typically visible for only weeks before departing into interstellar space. Rubin's continuous monitoring makes it the most effective telescope for catching these rare cosmic tourists, each offering a precious sample of material formed around distant stars.

## Supernovae, Variable Stars, and Cosmic Fireworks

The same strategy that finds asteroids reveals a universe far more dynamic than static photographs suggest.

Stars don't die quietly. When massive stars exhaust their nuclear fuel, they collapse catastrophically, triggering explosions so violent they briefly outshine entire galaxies. These supernovae blast heavy elements—carbon, oxygen, iron—into space, seeding future generations of stars and planets with the material necessary for life. Every atom of calcium in your bones, iron in your blood, and oxygen you breathe was forged in a supernova explosion billions of years ago.

Detecting supernovae the moment they begin—within hours of the explosion—is scientifically invaluable but historically rare. Most supernovae are discovered days or weeks after peak brightness. Rubin's rapid revisit schedule means it will catch supernovae in their infancy, allowing telescopes worldwide to watch the explosion unfold in real-time, revealing physics impossible to study from "after-the-fact" observations.

Rubin's First Light images already showcased this capability—a video compiled from early observations tracked 46 pulsating stars whose brightness regularly changes. These variable stars are scientifically precious. Certain types, called Cepheid variables, pulsate with periods directly related to their intrinsic brightness. By measuring a Cepheid's pulsation period, astronomers know its true luminosity; by comparing that to its apparent brightness, they calculate its distance. This "standard candle" technique is fundamental to measuring cosmic distances and thus understanding the universe's scale and expansion.

Rubin will discover and characterize millions of variable stars, building the most comprehensive catalog of stellar variability ever assembled. Each pulsating star becomes a data point constraining stellar evolution models, cosmic distance measurements, and galactic structure.

Among the most spectacular transient phenomena are tidal disruption events (TDEs)—when a star wanders too close to a supermassive black hole, typically lurking dormant at a galaxy's center. The black hole's intense gravity creates tidal forces that rip the star apart, stretching it into a stream of gas. As this material spirals into the black hole, friction heats it to millions of degrees, creating a brilliant but brief flare visible across billions of light-years.

TDEs are rare—perhaps one per 10,000 galaxies per year—but Rubin will monitor tens of millions of galaxies continuously, catching dozens of TDEs annually. Each event provides a unique laboratory for studying black hole physics, general relativity in extreme gravitational fields, and the otherwise invisible supermassive black holes at galactic centers.

## The Ten-Year Mission

Full science operations began in late 2025, initiating the ten-year Legacy Survey of Space and Time. The survey plan is meticulously designed: each clear night, Rubin systematically photographs predetermined regions of the southern sky, ensuring every accessible area is revisited approximately every three nights.

The scientific goals are correspondingly ambitious. The survey aims to catalog 20 billion galaxies, tracing cosmic structure across 10 billion years of history while mapping dark matter distribution across billions of light-years through gravitational lensing. It will discover millions of asteroids, completing the census of potentially hazardous near-Earth objects and detecting interstellar visitors passing through the solar system. Thousands of supernovae will be caught within hours of explosion, enabling real-time follow-up observations. By discovering and characterizing millions of variable stars, the survey will improve cosmic distance measurements and measure the expansion history of the universe to constrain dark energy properties. It will also reveal the violent past of galaxies by finding stellar streams, tidal tails, and substructure that trace ancient mergers—effectively creating an archaeological record of how galaxies formed and evolved.

Beyond these planned science objectives, Rubin will inevitably discover the unexpected. History suggests that whenever we build substantially more powerful astronomical instruments, they reveal phenomena we didn't predict. Quasars, gamma-ray bursts, exoplanets, dark energy—all were surprises discovered by observations that weren't specifically designed to find them.

## Why 2025 Was the Year

Rubin Observatory's First Light didn't happen suddenly. The project began in the 1990s with early conceptual designs. Serious development started in 2001 and construction funding was authorized in 2014. The camera alone took over a decade to build, at a cost approaching \$700 million.

But 2025 was when decades of engineering, countless setbacks, pandemic delays, and relentless technical problem-solving finally converged into operational reality. The massive camera was transported from California to Chile, lifted into position with millimeter precision, cooled to operating temperature, calibrated, and successfully tested. First Light arrived, and with it, confidence that the observatory worked as designed.

Over the coming decade, Rubin will generate discoveries that redefine our understanding of the universe. Some will answer long-standing questions about dark matter, dark energy, and cosmic structure. Others will raise entirely new

questions we haven't yet imagined. Every clear night in Chile, 3.2 billion pixels will capture light from billions of galaxies, asteroids in our cosmic neighborhood, and transient explosions across the observable universe.

## About the Author

*Dr. Noor Shaker* is an award-winning AI scientist, inventor, entrepreneur, and public speaker pioneering innovations at the intersection of technology and medicine. A former professor of artificial intelligence, she has founded three companies specializing in AI, quantum computing, and drug discovery. Her groundbreaking inventions have enabled breakthroughs in early cancer detection and personalized treatment, transforming how diseases are diagnosed and managed.

Named an MIT Innovator Under 35 and featured in Forbes and The Guardian, Dr. Shaker's work has shaped healthcare systems across the United States and the Middle East, demonstrating her commitment to advancing science and improving lives on a global scale.

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The End