ENERGY 2040

Aligning Innovation, Economics and Decarbonization

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My wife Anu, for years of unquestioning support and love
– Deepak Divan, Ph.D.

My three lovely little grandsons: Grady Rao Sharma, Fionn Cramer Sharma, and Seamus Srinivas Sharma, who would hopefully enjoy a more sustainable and cleaner planet if the ongoing energy transitions go right.
– Suresh Sharma

Acknowledgments

This book and its insights are a result of many decades of working in and with the energy industry – in advanced research, academia, startups; with industry and utility leaders; with researchers, engineers, and field technicians; with regulators, lawyers, and policy wonks; with leading VCs, investors, and entrepreneurs; with global manufacturing organizations; with national labs and research institutions; and with global institutions that shape how the world moves forward. Despite this close association, it was perhaps our entrepreneurial experiences that taught us the most.

We sincerely acknowledge everyone above for the things we learned and for the numerous interactions we have had. Given that we have so many of our colleagues, mentors, staff, mentees, supporters, students, and friends who have made a difference, it is difficult to individually acknowledge everyone. We have tried to capture as much as possible in the form of bibliography, references, and underlying citations for the body of their work.

Along this journey, the most important thing was not to take the status quo, as it was presented, at face value, but to ask fundamental questions that looked beyond the narrow narrative that was being presented. For this, I (Deepak) have to thank my friend and mentor, Don Novotny, who, in response to being presented what we thought was a novel solution, never ceased to flummox me with the most simple and basic of questions – he is deeply missed.

To “poke” at what seemed to be consistent pictures and stories that were accepted by everyone became second nature, allowing us to understand at a deeper level why something was, or was not, really possible, and to answer the question of whether the solutions were ultimately scalable at reasonable cost and along a needed timeline. The repertoire of an almost infinite number of questions showed us the way forward. We became focused on making sure all the key questions were asked – as the questions continued, the answers became self-evident.

As the decarbonization, climate change, and energy access/resiliency threads started getting tangled together, we began to see this as a mission for survival of the human race, certainly with the standard of living we enjoy in the global north. Time was running out, and we could see perhaps one path that could align the forces of innovation, economics, and decarbonization. Only then, we felt, could climate change be meaningfully addressed. We hope we have shown a meaningful way forward.

The number of people and organizations to be thanked and acknowledged is far too many to include here, but a few merit special mention. First of all, the graduate students, research scholars, and staff from the Georgia Tech Center for Distributed Energy, who made all the magic happen, are an integral part of who we are and what we do. Georgia Research Alliance bought into the vision of CDE and funded us to create the technology base that can play a major part in the energy transition. Countless conversations with leadership and staff at EPRI and utilities, including our partner Southern Company, helped us to understand the issues we are seeing. Leadership from DOE and industrial leaders such as GE and Siemens, and many smaller companies provided context and color to what is happening. Conversations with dozens of leading VCs and investors provided glimpses of successes and challenges. The US National Academy of Engineering, through its Board of Energy and Environmental Systems (BEES) and the committee on "The Future of Electric Power in the United States" gave access to a unique group who continually amazes and informs us. Frank Kreikebaum and Mahesh Morjaria provided us with invaluable feedback by reviewing a draft of the manuscript. We also want to call out Joseph Benzaquen from GT-CDE, who has provided valuable feedback on many of the ideas and has helped with very compelling figures. Sean DiLeonardi is also acknowledged for help with organizing the manuscript in the early months.

Finally, this book could not have been done without the patience, love, and support from our respective families, especially our spouses – Anu for Deepak, and Lata for Suresh.

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Prologue

Much has happened since early 2020 when the idea for this book was developed. Even though we were all preoccupied with an unprecedented global pandemic, it was clear to us, even then, that the two intertwined mega-issues that would survive the immediate challenges, and that we as humans had to deal with sooner rather than later, were energy and climate change. In the days since, it has become abundantly clear that, with the best of intentions, we are confused and struggling to converge on a preferred path forward. Many new technologies seem to have come from nowhere, and to have gained velocity as they are adopted across the world. But it is not clear that the much talked about "energy transition" is well understood, and many issues are certainly not resolved. Widely varying views of what is happening paint either optimistic utopian scenarios or dark dystopian scenarios, both of which are probably incorrect, at least at some level. The deeply technical nature of this transformation can make it difficult for the common man to understand the nuances of what is driving the rapid change, and what the trade-offs are. Oversimplification of the issues can lead to a misunderstanding of the challenges, and what should be done about them. We are becoming a society that is deeply divided on all manner of issues, including in the critical areas of climate change and energy.

During the pandemic, with some shelter from the day-to-day emergencies that otherwise dominate our daily lives, we (the authors) had time for introspection and could see that despite our many seemingly irreconcilable differences at a societal level, we were also all united by a few common aspirations. Rather than vilifying people with a different point of view, it became important that we attempt to understand the underlying reasons behind why and how reasonable people could hold such widely differing positions. Until we deeply understood everyone's perspectives, we felt we would not be able to develop a unifying conversation that would be understood by everyone.

Massive and fast-moving changes in many energy-related areas are either already upon us or seem likely over the next 10–20 years. Disruption on such a global scale produces winners and losers. Who decides who wins and who loses? Who pays for any additional costs that may come from addressing climate change issues? In the face of such a moral dilemma, how can we converge on an acceptable path forward? It seemed critical to us that we understand and be guided by history, so we did not repeat the same mistakes. But we were also concerned that a massive and fundamental paradigm shift may already be underway, making it very challenging to blindly apply the lessons of history. The institutions and policies that have guided us over the last fifty, even a hundred, years have worked well in the past, but now seem challenged to cope with the new intersecting realities of multiple rapidly changing fronts that are seemingly moving along uncoordinated trajectories. This fast-evolving story is global and complex, making it challenging to unpack the fundamental drivers.

Both climate and energy are top-of-mind issues, with a vast and still growing stream of books and publications written by international and national committees, think tanks, academics, venture capitalists, policy wonks, and major authors. Many of the energy related books we read were wonderful, exciting our imagination, closing gaps in our understanding, and outlining the complex interplay of history, science, politics, and economics that underpinned the evolution of this complex field. Books on climate were scientifically compelling, laying out the data and consequences of inaction in a manner that could not be contested. There was no lack of prescriptive action from both sides, all to achieve the objectives that they espoused. But to our mind, the division between energy and climate change represented a rift in the discourse that has in turn divided our communities and even the world. A path to decarbonization or climate impact mitigation is often viewed as anti-economic, while the need to ensure the economic welfare of our families is seen as being against humanity.

What was missing in the discussion, we felt, was a holistic, and yet grounded, view of energy, its growth and impact on climate, and an understanding of how innovation, fast-moving technologies, and the human spirit can act as agents of change. It seemed to us that it was possible to create strong alignment between the forces of economics and climate change, and when this was achieved, there was no limit to how fast we could adopt and adapt to meet both goals. With simultaneous rapid change on many fronts comes uncertainty in terms of outcomes – which makes us uncomfortable committing to major initiatives into the unknown. Rather than freezing us in our tracks, we can use that uncertainty to create a new twenty-first-century ethos, where we create solutions that are democratized, flexible, interoperable, equitable, and scalable. A rigid scaffold, on which all development and progress occurs along a prescribed 20-year plan, is not how things evolve in nature – but that is how we have viewed and wanted our own world to be: rigid and predictable. We want familiarity and for our lives to remain undisrupted. Maybe fast-evolving, twenty-first-century technologies can offer a new approach to building a future world that meets human needs but is also designed to preserve our planet for future generations.

This body of work has been inspired and informed by our own experiences, our market research, and more recently, lessons learned from an experiment we led at the Center for Distributed Energy at the Georgia Institute of Technology in Atlanta, Georgia, USA. Our goal was to develop a coherent view of the current energy transition, especially where it intersected with the electricity grid, which we felt would be an even more important part of a future energy infrastructure. We were a little concerned about what we, as two technology and innovation practitioners, could contribute to this widely researched and published area. We wanted to see if we could develop an actionable pathway to evolve a future energy infrastructure that is aligned with game-changing transformations going on in energy innovations, economics of energy, and its impact on climate through decarbonization.

It may be appropriate to briefly share our backgrounds, and to see how our experiences helped shape the context and content of this book. Deepak has spent 40 years in academia and in founding and running startups, and currently serves as Professor, GRA Eminent Scholar, and the Founding Director of the Center for Distributed Energy at the Georgia Institute of Technology. He is an elected member of the US National Academy of Engineering and has been active in research, working closely with industry to develop and translate technologies to market in many of the related technology areas. As a serial entrepreneur, he has worked to understand how new disruptive technologies make their way to market, and has raised money from leading VCs, building teams, launching new products, and grappling with why the obvious pathways were not so obvious in the regulated utility world. He has served as an advisor to organizations such as EPRI and GE Research in the early days, and has served on the NASEM Board on Energy and Environmental Systems. He has been an invited speaker at many global meetings, including at COP 22 in Marrakesh in 2016, and at the UN Global Solutions Summit in 2023. He was also a member of the recent NASEM Committee on "The Future of Electric Power in the US" and contributed to the influential consensus report that was issued in 2021. Over 45 years of working within IEEE societies, including in leadership positions, has given him visibility and familiarity with cutting-edge technologies being developed, not only in the USA, but across the globe.

Suresh, similarly, has had a wide range of experiences in industry and business, starting his early career as a Naval Aviation Officer in India and the UK, subsequently working in technology and business leadership roles for many years at GE Energy, both in the USA and other global locations. He led the global development and implementation of several new technologies for the energy, aviation, and aerospace industry. The coauthors have learned a lot through a shared entrepreneurial experience at Innovolt, and then over the past seven years at the Center for Distributed Energy at Georgia Tech, where Suresh held the unique position of Entrepreneur in Residence (EIR). Suresh's passion for understanding the intricacies of innovation and entrepreneurship have led to many books on diverse topics, including *Industrializing Innovation* (2019) and *The 3rd American Dream (2014)*, books that intersect heavily with the issues under discussion here.

We hope you enjoy reading the book as much as we have enjoyed writing it.

Atlanta, GA, USA Deepak Divan
October 2023 Suresh Sharma

Acronyms, Abbreviations, and Scientific Units

Technical Acronyms

AGC	Automatic Generator Control
AMI	Automated Metering Infrastructure
CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Sequestration
DER	Distributed Energy Resources
DERMS	DER Management System
DFIG	Doubly Fed Induction Generator
DMS	Distribution Management System
DSP	Digital Signal Processor
EMS	Energy Management System
EV	Electric Vehicle
FIT	Feed in Tariff
FPGA	Field Programmable Gate Array
GHG	Green House Gases
HEV	Hybrid Electric Vehicle
HILF	High Impact Low Frequency
HVDC	High Voltage DC
IGBT	Insulated Gate Bipolar Transistor
IRP	Integrated Resource Plan
LCOE	Levelized Cost of Energy
LDC	Least Developed Country
LDES	Long Duration Energy Storage
LMP	Locational Marginal Pricing
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MPPT	Maximum Peak Power Tracking
MTDC	Multi-Terminal DC
MVP	Minimum Viable Prototype
PHEV	Plug-in Hybrid Electric Vehicle
PMU	Phasor Measurement Unit
PV	Photovoltaic

RPS	Renewable Portfolio Standard
RTMR	Real Time Must Run
SAIDI	System Average Interruption Duration Index
SCADA	Supervisory Control and Data Acquisition
SCED	Security Constrained Economic Dispatch
SMES	Superconducting Magnetic Energy Storage
UPS	Uninterruptible Power Supply
V2G	Vehicle to Grid
V2H	Vehicle to Home

Institutions/Non-technical

DOE	Department of Energy
EPACT 1992	Energy Policy Act 1992
EPRI	Electric Power Research Institute
COPXX	Conference of Parties
FERC	Federal Energy Regulatory Commission
HDI	Human Development Index
IEA	International Energy Agency
IEEE	Institution of Electrical and Electronics Engineers
IFC	International Finance Corporation
IOU	Investor-Owned Utility
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producer
ISO	Independent System Operator
NAE	National Academy of Engineering
NARUC	National Association of Regulatory Utility Commissioners
NASA	National Aeronautics and Space Administration
NASEM	National Academy of Science Engineering and Medicine
NERC	North American Electric Reliability Corporation
NIMBY	Not In My Back Yard
NRECA	National Rural Electric Cooperative Association
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
PUHCA	Public Utility Holding Company Act
PURPA	Public Utilities Regulatory Policies Act
ONR	Office of Naval Research
OPEC	Organization of Petroleum Exporting Countries
RTO	Regional Transmission Operator
SGIG	Smart Grid Investment Grant
SPAC	Special Purpose Acquisition Company
US-EIA	US Energy Information Administration

Key Scientific Units

BTU – British Thermal Unit: Unit of energy used as a measure of heat – 1 BTU = 1055 Joules
Quad – Unit of energy – 1 Quad = 10^{15} BTU, or 293 TWh or 33 GW-years

Electrical Power and Energy

Power represents work done, in this case using electricity.
Watt – Unit of power. 1 watt (W) = 1 volt x 1 Ampere
(representative consumption levels – LED light ~5 watts, small US home ~ 10,000 W, Boeing 737 aircraft ~ 25,000,000 watts at takeoff, Chicago peak demand ~ 25,000,000,000 watts)

kW – Kilowatt, equals 1000 W
MW – Megawatt, equals 1000 kW
GW – Gigawatt, equals 1000 MW
TW – Terawatt, equals 1000 GW

Energy is the net work done by the application of a certain level of power for a specified time.
Units of electrical energy are in (Power x Hours) – Wh, kWh, MWh, GWh, and TWh.

Scale of Energy Consumption

US annual energy consumed ~100 Quads
US peak electricity generation ~ 1000 GW
US annual electrical energy consumption ~ 4000 TWh

Contents

1 Energy and Society: At a Tipping Point

The World in Crisis

The world seems to be poised on the edge of a precipice, careening toward an unsustainable level of carbon emissions that is accelerating the pace of climate change, a factor that imperils our economic well-being and our very existence. With the best of intentions, twentieth century technology, policies, and financial instruments have been unable to address the challenges, setting up the mitigation of climate change as a Faustian bargain between economics and sustainability. Even though there is wide scientific consensus on the severe impact that climate change will have globally, the motivation for meaningful and immediate action has been limited. This is because, up until now, there has been no direct near-term incentive for decision makers to fix the issue, and because any future cost and impact of not taking any action today can be socialized and transferred to future generations (who are not here to fight for their rights).

As intelligent, educated, and rational beings, we understand the urgency of the situation and believe we would do anything to solve the problem – except perhaps change our own behavior and imperil our personal financial future, especially when we personally did not cause the problem. Or perhaps, we worry that the different groups we identify with – our nations, professions, generations, etc. – did not cause the problem, and we have the right to get to a level of prosperity that the others are at, before we start rectifying our ways. Or maybe we are fossil fuel producers and feel that the link between climate change and carbon is tenuous at best (after all the world has gone through many climate change cycles in the past, cycles that were not linked with anthropogenic carbon emissions), and that it would be foolish to compromise our livelihood and economic growth in response to uncertain and unpredictable scenarios. Or perhaps, we have built global businesses that have brought prosperity to the world, and feel that we need to protect our investors, workers, and customers, and that there is no way that unproven new disruptive solutions could ever deliver on their promise in a timely manner without causing economic havoc.

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And we would all be right – in our own way. After all we have spent decades building our personal world view and zone of expertise and feel that we have an economically and morally defensible perspective. As a corollary, we believe others are perhaps not seeing the important elements in this picture. We believe strongly in our point of view and regard as fact only those points that support our opinions and which are then amplified via the internet, social media, and print into waves that ignite passion at all levels. Vilifying our partners along this journey to sustainability is perhaps the worst way of aligning our objectives and achieving progress. Yet, that is precisely where we frequently find ourselves, in opposite camps: haves versus have-nots; developed versus emerging nations; advocates for carbon mitigation versus supporters of economic growth; academic idealists versus practical doers. In such a deeply divided world, how do we get to alignment, to convergence?

Since 1992, when the IPCC report raised the early alarms on anthropogenic carbon emissions and its potential impact on humanity (the planet will do just fine, the people on it may not), we as society have struggled with how to respond. Each successive global summit (with the most recent COP 27 in Cairo and COP 28 in Dubai) has tried to bring all nations together – very challenging given the multitude of issues to be considered, and a highly turbulent political and policy-making process that swings like a yo-yo based on who is in power. Decarbonization goals are set every time, but with poor compliance mechanisms and no real accountability at a national level (in any case, change of political realities can completely alter the near-term strategy, as we saw for the USA during the transitions from the Obama to the Trump and then to the Biden administrations). While this political process is critically important and we are undoubtedly making progress, there is reason to be concerned that the process will not get us to zero carbon emissions in a timely manner.

For those of us old enough to have lived through the second half of the twentieth century, the world still seems very familiar: our homes, cars, and families, the way we live and travel, what we learned in school – the core fundamentals of our lives – remain steady. But something also feels very different. We know that digital technology and electronics have altered how we work, drive, play, communicate, and shop. But our material world does not seem to have been highly disturbed (although changes are now visible at the edges). For many, even as fast paced changes have occurred in the "digital" world, the "real" world seems to be changing at a more measured manageable pace. This is comforting, because no one wants accelerating runaway change to create chaos and uncertainty in their life. Yet we are also worried that rapid change seems to be coming at us from every direction, change that we did not see coming, even a short 10 years ago. Whether we want to acknowledge it or not, we know that the changes in climate simultaneously occurring across the globe cannot all be coincidence. But if the climate is actually changing because of human activity, the problem seems so big and complex that it calls into question whether we can do anything meaningful in terms of impact over the next 20 years, a period that climate scientists have indicated is critical if runaway global warming is to be avoided.

At a fundamental level, energy is at the heart of this challenge – directly accounting for as much as 75% of all carbon emissions when electricity generation, heating and cooling, industry, and transportation are all considered. We cannot reduce carbon emissions without solving the energy problem. But the world will not function without access to as much affordable, reliable, and safe energy as it needs – that must be a priority. To get to zero carbon emissions, we need to either stop emitting CO_2 (Carbon Dioxide) and other greenhouse gases (GHG) or we need to extract them from the atmosphere. We believe this needs to happen sooner rather than later, say by 2040!

On the other hand, the level of improvement in human standard of living that access to energy and technology has wrought over the last 100+ years is unbelievable and sets a golden standard that should be preserved. Despite all our accomplishments, and there are too many to count, 700 million people still live off-grid, and 3 billion live with energy poverty so extreme that it impacts their ability to earn a livelihood. Clearly the benefits of energy as available today are not equitably distributed, and we must ensure that any future we move toward resolves rather than exacerbates this inequity. We strongly believe that most people are not against energy being clean and sustainable. Their main concern is that they do not want to go back to an era where energy costs are high and reliability is poor, compromising economic gains that have been made over the last century.

This is the conundrum that is baffling us. Can we have our cake and eat it, too? Can we sustain our economies and move toward global prosperity, while still meeting decarbonization goals and better positioning ourselves to manage the impact of climate change? Are there one or two primary levers that can give us substantial impact and get us most of the way there? Can this process be equitable, bringing the economically disadvantaged to parity with the rest of the world? Or are we condemned to a repeat of history – a battle between haves and have-nots, a story of dominance by the few with geopolitical or economic clout, and increasing disparity in a resource constrained world?

Energy 2040 is about taking a fresh look at the situation we find ourselves in today, identifying the contributing factors that got us here, and understanding where we may be headed. To do that, we need to explore and harmonize a complex, multifaceted story of energy involving topics as varied as the economics of sustainability, the process of scaling new technologies, academic research, government regulation, digitalization, and energy equity – to name but a few. Many books being published today have considered the problem of energy more narrowly, including only one or two of these topics. *Energy 2040* offers a more grounded and yet holistic and comprehensive look at our energy past, and present, in order to outline potential paths to an energy future that is both sustainable and economically viable.

It's All About Energy

Energy consumption and human development are deeply interconnected. Based on UN Sustainable Development Goals (SDG), energy directly links and enables virtually every key societal objective [1]. Similarly, Fig. 1.1 shows the linkage between energy consumption and a "human development index" (HDI) score, showing that

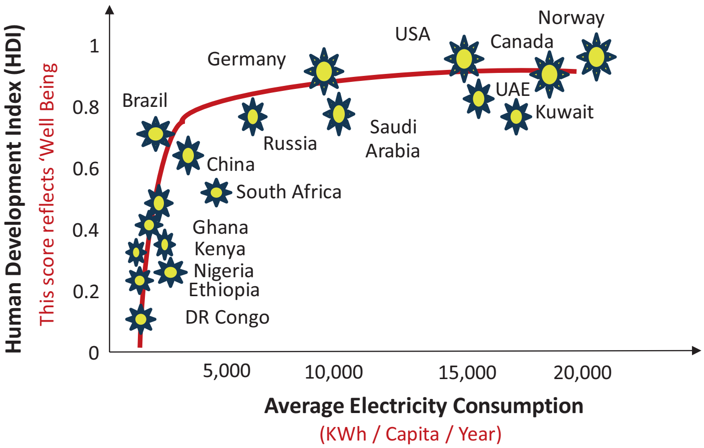

Fig. 1.1 Human development index versus. Energy consumption per capita for a set of different countries. (Representative of Connection between Energy and Well-Being)

an increase in HDI requires a disproportionate increase in energy consumption [2] Energy is clearly critically important for human development and growth.

At the global level, total energy consumed in 2020 was around 550 Quads, or 5.5 times US consumption, with the biggest consumer of energy being China (1 Quad is 10^{15} BTU or 293 million megawatt-hours, sufficient to meet all US energy needs for 3.5 days).

As detailed in Fig. 1.2, in 2019, the USA consumed over 100 Quads of energy. Of that, 80.2 Quads of primary energy came from fossil fuels, which in turn generated 75% of our anthropogenic carbon emissions. A total of 67.5 Quads of energy was rejected as waste heat due to inefficient energy conversion processes, most of which was extrinsic to the planet's natural energy balance and further added to global warming, especially at a regional level [3].

This shows that for every dollar we spend to extract, process, deliver, and convert the primary source to thermal energy, we then proceed to throw away 78% of that energy, and only use 22% for useful work [3]. By way of contrast, losses in the electrical chain, from generation to load, are very low – typically aggregating 7–10% total.

So, from an economic perspective, we all need plentiful, abundant energy to power our needs – from lighting to electronics to transportation to space heating, cooling, and industry. True, our ancestors lived in the dark and did not have any modern conveniences, but by the end of the twentieth century we had generally resolved that situation, at least in the developed countries. As we moved out of the twentieth century, it seemed that we were at a stable place in terms of energy, and that disturbing the status quo with unproven technologies would be problematic and very expensive. Emerging markets were focused on economic growth and were building coal plants as fast as they could to fuel their economies. The International Energy Authority, as well as every major energy company and gas and electric

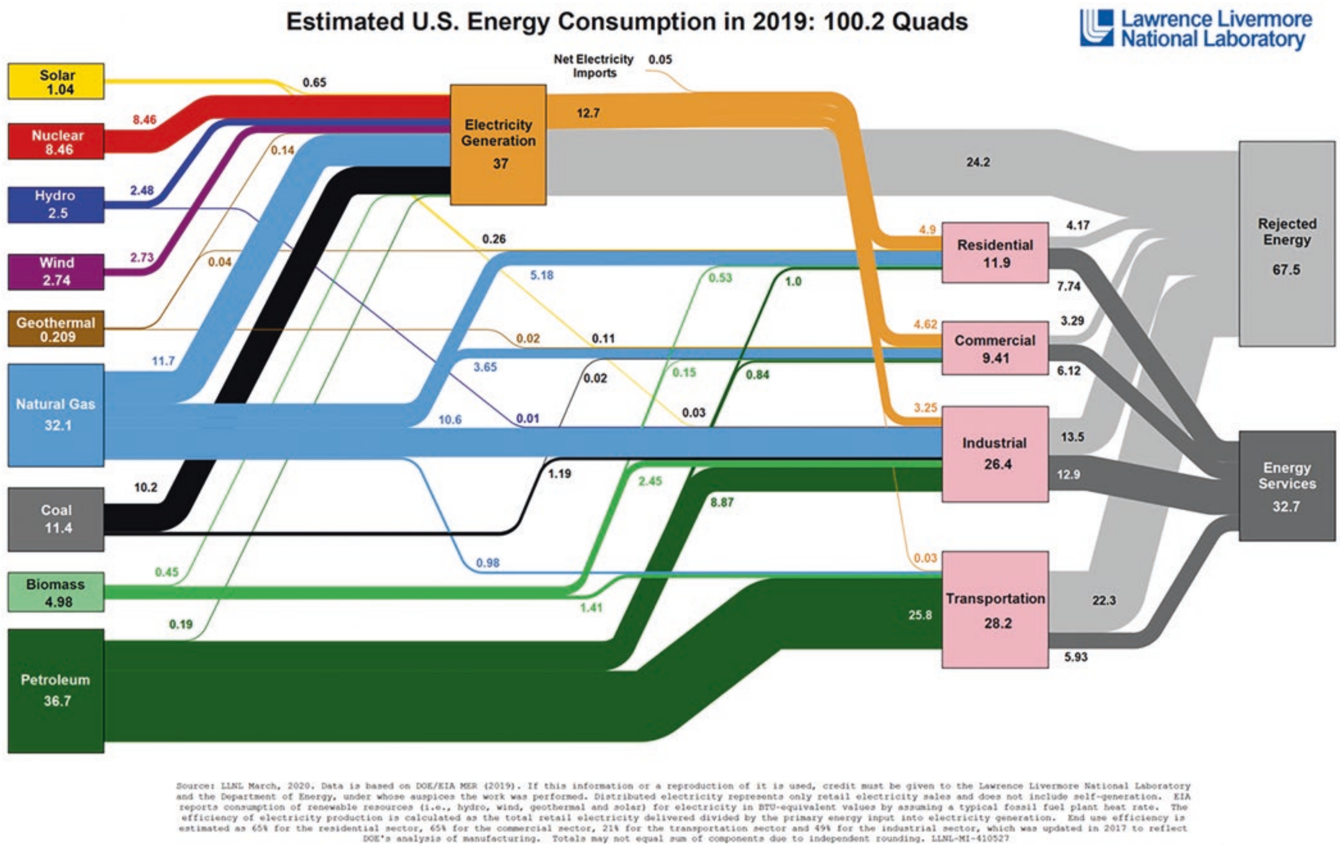

Fig. 1.2 78% of energy from fossil fuels is rejected as waste heat

utility in the world, thought renewable energy was aspirational and would only gradually increase in penetration, driven mainly by policy and incentives (not by economics). Major automotive companies were building better cars and were looking to expand markets globally, and the focus was on the internal combustion engine – after all GM had tried electric cars with the EV1 in the 1990s and the noble initiative had failed! Everybody was aligned as to where we were going!

The first 20 years of the twenty-first century have completely changed our perspective. Wind and solar are now cheaper than coal and natural gas. Electric vehicles are ramping up at an unbelievable pace, with every major automotive manufacturer committed to electrification. Where did this come from, and why did we not see it coming? The good news is that most major countries, large corporations, and many energy companies (including electric utilities) are finally embracing a goal of 50% carbon emissions reduction by 2030 and 100% carbon emissions reduction by 2050. This alignment, at least in terms of high-level goals, is very important. But does it mean we are finally over the hill and now it is simply a matter of implementing the vision?

The scale at which this change is needed (we are talking major disruption and societal transformation here), and the pace at which it has to happen (in the next 20–30 years!) is daunting. To achieve this goal, it understandably feels likely that we do not have the time to develop and adopt risky new solutions to hit 2030 and 2050 targets. Many feel that we must move fast and implement proven solutions that we have already developed. But do we fully understand the new world we are creating and the new questions that need to be asked? Will the new world look like an incremental evolution from our existing world, or will it be different in fundamental ways? Will the old rules still apply, and if not, do we know what the new rules are? Will solutions developed with yesterday's questions and technology solve tomorrow's problems, especially if we do not even know what the new issues are? Who are the experts who can guide us in this transformation? Given that predictions made by all levels of experts over the last 20+ years have been consistently and spectacularly wrong, how can we rely on the guidance of experts (who typically became experts on yesterday's systems and technologies) on how an unknown and possibly unknowable future will evolve? How many years will this change take, and what will the economic consequences of this change be? How do we get to this new world if we don't even know where we are going? We can surely try to prepare for what we know we don't know, but how can one anticipate and prepare for something that we don't know that we don't know?

Apologies to our gentle reader for posing all these difficult questions right at the start of this book. But we feel that many reasonable people are probably struggling with some version of these questions, even as we try to cope, both professionally and personally, with the pace at which our own lives are being transformed. That these issues can have severe impact on our pocketbooks and the safety of our families and loved ones, takes it from the abstract and makes it very personal. Yet, given the divided world we live in, it is not clear that there is an obvious pathway that can lead us forward and help overcome the challenges that humanity faces.

What is the overall new future we want? Not from a narrow, siloed perspective, but holistically, including many interacting adjacencies and issues of long-term sustainability. Perhaps nothing is more critical than understanding what that final goal is, not in technical terms, but in easy-to-understand human terms.

For example, reducing atmospheric CO_2 levels to <300 ppm is not a humanly relatable goal. Most people do not want to generate any CO_2, they only want to live their lives – the CO_2 is an undesired outcome.

> *Most people do not want to generate CO_2 intentionally, they only want to live their normal lives. CO_2 is an undesired outcome.*

Once a minimal set of goals is agreed upon, can we then set up metrics to assess that we are making progress toward these goals, and whether the proposed strategies can achieve scale (with all the glorious complexity that this invokes) in a meaningful timeframe and at acceptable cost? Can we define solution attributes and requirements, as well as a roadmap to get us from where we are to where we want to be? We hope this book will provide a fresh perspective on where we think we want to go as a society, and to discuss pathways that could get us there.

How Did We Get to Where We Are?

We live in a world today that has been shaped by over 6000 years of human ingenuity and innovation. Pursuit of fact-based science and technology has allowed us to unlock secrets of how the universe operates and to use this understanding to make our lives better (and sometimes worse!). Today, the changes, driven by science, technology, and innovation, are happening with unprecedented speed, and are driving impact that can be extreme in many ways; again, making our lives much better or much worse! Surely, science and innovation can guide us through the new upcoming challenges as well. The journey from scientific discovery to innovation to market adoption and finally impact at scale is at the heart of how we have achieved wave after wave of new innovations that have enhanced our lives and completely transformed our world – from an agrarian society to the modern world we live in today. But this could not have been achieved without generations of scientists, engineers, investors, entrepreneurs, and businesses (including their employees) working across the globe to solve tough problems, and to help their customers adopt these solutions. Finally, government, policy, and finance are major factors that significantly impact the success, scale, timeline, and equity of solutions that result in societal transformation.

If we just look at the history of how transformative ideas have moved from science to impact at scale, we typically see long time horizons, often stretching 50–100 years and more. If we look at automobiles, the first prototypes built in 1859 showed the way, but automobiles finally reached the masses and gave them the boon of personal mobility well after World War II, almost 100 years later. Ubiquitous access to electricity, even in the developed nations, took almost 70 years, and is still at best a work in progress in many parts of the world, more than 140 years later. Even for PV solar cells, first conceived and built in the 1950s, it took almost 70 years before they became competitive in the broader energy market. On the other hand, we see technologies like mobile phones and the internet, where service is now available globally to over 6 billion users over a much shorter period of 20–30 years. If it takes us 100 years to address the issue of carbon emissions and its adverse impact of our life, then we will have achieved little. Can this be done in 20 years? Do we understand the fundamental drivers that make some technologies move fast, while others take forever? Can we systematize the process, reduce risk, and assure positive outcomes – thus unlocking the flood gates of investment and adoption? Can we accelerate the process of scaling for positive impact, while avoiding adverse impacts, thus addressing the proverbial all-important Law of Unintended Consequences before it presents an impenetrable barrier in our path forward?

To understand what we need to do to get to a more desirable future, we first need to understand how and why we are where we are, as well as where we want to go. Maybe that will provide us with guidance on why things now need to be done significantly differently from what our past experiences suggest, and where new thinking may be needed. If there is uncertainty about how the future will evolve, do we freeze in our tracks and make no major bets, or are there "no regret" investments that we can make today that will support our journey along a number of different but likely scenarios as they evolve, which can collectively move us toward the primary goals that we have set? Are there simple fundamental principles underlying today's complex energy infrastructure that will provide clarity on what type of energy system is needed for the future? Do we know how to realize such a system, and where the gaps are, if any? Given the trillions of dollars invested in today's infrastructure, the tens of millions of people who work in related industries, and the billions of people who benefit from the existing energy system – it is clear that any major change has the potential to disrupt people's lives and economic well-being, at least in the near-term, and should, in the ideal world, be carefully thought through and managed. This will require alignment between all major stakeholders and a flexible and adaptable implementation plan focused on the fundamental questions.

Accelerating Change

As we look around us, we see accelerating change across a wide range of sectors related to energy. New twenty-first century technologies hold the promise of completely changing the manner in which our societal energy needs are met. Dozens of new technologies are carbon-neutral or carbon-negative and exhibit steep and sustained learning rates, promising lower costs and rapid scaling even while meeting global sustainability goals. These new technologies include solar photovoltaics (PV), batteries, electric transportation, blue and green hydrogen, CO_2 capture, water purification, direct air capture of greenhouse gases (GHGs), permanent sequestration of CO_2 and GHGs, new energy-efficient carbon-neutral methods for producing raw materials, chemicals and food, and replacement of fossil fuels with renewable carbon-neutral fuels. If we could wave a magic wand and move to a world that incorporated many of these technologies, we could certainly solve the anthropogenic carbon emissions problem – but could this be done in time, and what price (in economic and human terms) would we pay to get there? If the impact is so obvious and the outcome so desirable, then why is this discussion even happening? Don't we have all the resources of the government and private sector aligned to solve these problems and to roll out the new and improved tomorrow as quickly as possible?

In the USA we have the Department of Energy, the National Science Foundation, national labs, research universities, and major corporations, along with hundreds of similar governmental, nongovernmental, and private organizations across the globe, who are spending billions of dollars doing high-risk scientific research that will underpin the key technologies and businesses that can mitigate climate change, with many technologies now becoming visible and showing promise. We have governments, the World Bank, International Finance Corporation (IFC), major corporations, venture capitalists, and investors all focused on taking energy technologies to market and scaling these to address our climate challenges. Philanthropic funding from billionaires and from large investment funds is focused on commercializing technologies that will significantly reduce the level of CO_2 in the atmosphere in a 20 year span. In the USA, states such as California, along with many countries in Europe, are establishing policies that are forcing change – requiring electric vehicles and higher renewables on the grid. These policies have in turn triggered a tsunami of development with many new products becoming available to meet the new requirements.

We feel this is all wonderful and is very much needed. *Yet, we are worried by a nagging doubt that there are significant gaps.* A desire or wish is aspirational and does not constitute process, strategy, or an executable plan. Moving fast does not mean we are moving in the right direction, especially when what we do impacts others who are moving equally fast, but on independently determined trajectories and without much coordination. Availability of significant funding brings large numbers of recently minted "experts" and solution providers to the feeding trough, who all claim that theirs is the right solution. Loud voices proclaim every little success on the internet, social media, and the press, creating a cacophony that is difficult to pierce through. Whether it is solar, batteries, EVs, hydrogen, smart grids, microgrids, nuclear fusion, small modular reactors, carbon capture and sequestration, biofuels, or electric aviation – there is no shortage of researchers and companies proclaiming victory and taking issue with all other competitive solutions. This is normal with the rollout of new disruptive technologies, a lot of jostling for position as the evidence accumulates and winners and losers emerge. Unfortunately, this all takes time – which we do not have. Is there an alternate method for mitigating risk while accelerating the adoption and scaling of multiple competing solutions? After all, the total available market for new energy solutions is huge, and it is in the best interest of policy makers and governments to make sure that the end goal is achieved, and that scale is reached quickly and cost effectively.