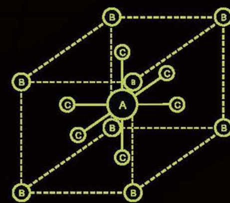
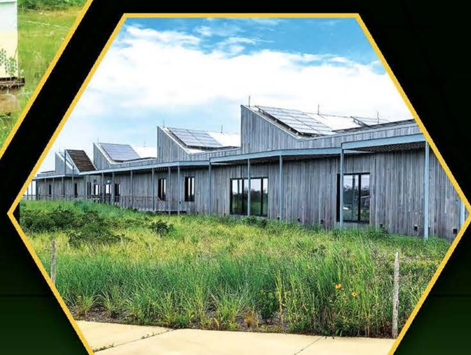
FIFTH EDITION

PHOTOVOLTAIC SYSTEMS ENGINEERING



Roger A. Messenger • Homayoon Abtahi



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Photovoltaic Systems Engineering

The primary purpose of this textbook is to provide a comprehensive set of PV knowledge and understanding tools for the design, installation, commissioning, inspection and operation of PV systems. In recent years, more PV systems have been installed worldwide than any other electricity source. New, more efficient, more reliable and more cost-effective components and processes are rapidly appearing, along with continuously changing codes and standards. To keep up with the rapid changes, understanding the underlying principles is essential.

In addition to practical system design and installation information, this edition includes explanations of the basic principles upon which the design and operation of PV systems are based, along with a consideration of the economic and environmental impact of the technology. Numerous design examples are presented to assist the reader in incorporating the basic principles, components, codes and standards.

The book begins with basic sunlight parameters, system electronic components, wiring methods, structural considerations and energy storage methods Emphasis is on grid-connected systems, but a chapter on stand-alone systems is also included. Homework problems in each chapter focus on basic principles of the chapter but also include open-ended design problems to challenge the reader's creativity and understanding.

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Roger Messenger and Homayoon "Amir" Abtahi

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Preface

The goal of this textbook has always been to present a comprehensive engineering basis for photovoltaic (PV) system design, so the engineer can understand the *what*, the *why* and the *how* associated with electrical, mechanical, economic and aesthetic aspects of PV system design. The book is intended to *educate* the engineer in the design of PV systems so that when engineering judgment is needed, the engineer will be able to make intelligent decisions based on a clear understanding of the parameters involved. This goal differentiates this textbook from the many design and installation manuals that are currently available that *train* the reader *how* to do it but not *why*.

Widespread acceptance of the first four editions, coupled with accelerating growth and new ideas in the PV industry, along with additional years of experience with PV system design for the authors, and, for that matter, a bit of nudging from the publisher, has led to the publication of this fifth edition. In recent years, annual installed renewable capacity has exceeded annual installed nonrenewable capacity in the United States and most of the rest of the world. Who knows, there might even be jobs waiting out there for many who learn the material in this book.

The *what* question is addressed in the first three chapters, which present an updated background of energy production and consumption, some mathematical background for understanding energy supply and demand, a summary of the solar spectrum, how to locate the sun and how to optimize the capture of its energy, as well as the various components that are used in PV systems. Chapter 3 has been shortened a bit so actual design work can begin by about the fifth week of a three-credit course, but it also introduces lithium and a few other emerging battery technologies.

The *why* and *how* questions are dealt with in the remaining chapters in which every effort is made to explain why certain PV designs are done in certain ways, as well as how the design process is implemented. Included in the *why* part of the PV design criteria are economic and environmental issues that are discussed in Chapter 9. Chapter 5 has been embellished with additional practical considerations added to the theoretical background associated with mechanical and structural design.

Since the last edition, energy storage has transitioned from useful to essential. Chapter 6 now deals exclusively with energy storage not only as a backup power/energy source but as an essential means of transitioning the world's energy supply from nonrenewable to renewable.

Chapters 4 and 7 have once again been updated, including revised homework problems, to incorporate the most recently available technology and design and installation practice. In particular, Chapter 4 incorporates more emphasis on higher voltage systems, new developments in IEEE 1547, new fire code requirements and *National Electrical Code* changes in the 2020 Edition, such as rapid shutdown, microinverters, optimizers, utility interconnects and advances in inverter, module and structural technology.

By the end of Chapter 4, instructors can assign relevant design problems earlier in the course to avoid having designs due at final exam time. We have found when significant design projects are due just before final exams, the students tend to spend time on design projects that might better be spent studying for the final exam, especially if the final exam counts more toward the overall course grade. Paradoxically, the better designers have sometimes ended up with lower course grades.

Since the publication of the previous edition in 2016, a nearly overwhelming wealth of new research on old and new technologies has been underway. We try to cover the highlights of some of this activity in Chapter 11 but have eliminated some of the historical content to make room for the new stuff.

A modified top-down approach is used in the presentation of the material. The material is organized to present a relatively quick exposure to all of the building blocks of the PV system, followed by design, design, and design. Even the physics of PV cells in Chapter 10 and the material on emerging technologies in Chapter 11 are presented with a design flavor. The focus is on adjusting the parameters of PV cells to optimize their performance, as well as on presenting the physical basis of PV cell operation.

Homework problems are incorporated that require both analysis and design, since the ability to perform analysis is the precursor to being able to understand how to implement good design. Many of the problems have multiple answers, such as "Calculate the number of daylight hours on the day you were born in the city of your birth." We have eliminated a few homework problems based on old technology and added a number of new problems based on contemporary technology. Hopefully, there are a sufficient number to enable students to test their understanding of the material.

We recommend that the course be presented so that by the end of Chapter 4, students will be able to engage in a comprehensive, relevant design project, and, by the end of Chapter 7, they will be able to design relatively complex systems. We like to assign two design projects—a straight grid-connected system based on Chapter 4 material and a battery backup grid-connected system based on Chapter 7 material. At the discretion of the instructor, an additional design of a stand-alone system might be considered at the end of Chapter 8, or the stand-alone design might be assigned rather than the battery backup grid-connected system.

While it is possible to cover all the material in this textbook in a three-credit semester course, it may be necessary to skim over some of the topics. This is where the discretion of the instructor enters the picture. For example, each of the design examples of Chapter 4 introduces something new, but a few examples might be left as exercises for the reader with a preface by the instructor as to what is new in the example. Alternatively, by summarizing the old material in each example and then focusing on the new material, the *why* of the new concepts can be emphasized.

The order of presentation of the material actually seems to foster a genuine reader interest in the relevance and importance of the material. Subject matter covers a wide range of topics, from chemistry to circuit analysis to electronics, solid-state device theory, structural analysis and economics. *The material is presented at a level that can best be understood by those who have reached upper division at the engineering undergraduate level and have also completed coursework in circuits and electronics.*

We recognize that the movement to reduce credit toward the bachelor's degree has left many programs with less flexibility in the selection of undergraduate elective courses and note that the material in this textbook can also be used for a beginning graduate-level course.

While the primary purpose of this material is for classroom use, with an emphasis on the electrical components of PV systems, we have endeavored to present the material in a manner sufficiently comprehensive that it will also serve the practicing engineer as a useful reference book.

The course can be successfully taught as an internet course, with a preference for live participation open to all. Those remote students who were actually sufficiently motivated to keep up with the course generally reported that they found the text to be very readable and a reasonable replacement for lectures. We highly recommend that if the internet is tried, quizzes be given frequently to coerce the student into feeling that this course is just as important as her/his linear systems analysis course. Informal discussion sessions can also be useful in this regard.

The PV field is evolving rapidly. While every effort has been made to present contemporary material in this work, the fact that the preparation of this edition has evolved over a period of a year almost guarantees that, by the time it is adopted, some of the material will be outdated. For the engineer who wishes to remain current in the field, many of the references and web sites listed will keep him/her up-to-date. Proceedings of the many PV conferences, symposia, and workshops, along with manufacturers' data, are especially helpful.

This textbook should provide the engineer with the intellectual tools needed for understanding new technologies and new ideas in this rapidly emerging field. The authors hope that at least 1 in every 4.6837 students will make his/her own contribution to the PV knowledge pool.

We apologize at the outset for the occasional presentation of information that may be considered to be practical or, perhaps, even interesting or useful. We fully recognize that engineering students expect the material in engineering courses to be of a highly theoretical nature with little apparent practical application. We have made every effort to incorporate heavy theory to satisfy this appetite whenever possible.

We also wish to note that we have endeavored to base the contents of this work on human intelligence as opposed to artificial intelligence (AI). We sincerely apologize if any part may appear as AI, despite our efforts to avoid it.

Furthermore, since the publication of the previous edition of this book, we recognize that the printed word has begun to disappear and be replaced by material on line. This creates a major challenge for publishers to adapt to this evolution. In particular, referencing the work of others is coming under more intense scrutiny, and obtaining permission to incorporate the results of the work of others in our attempt to provide a coherent presentation of the PV system design process has become more difficult. We have made every effort to credit the work of others, as we have done in the previous four editions. We sincerely hope that authors of cited works will appreciate that we are doing our best to inform students about the information they have so diligently prepared. Our sincere thanks to the authors who have generated the materials we have referenced.

Disclaimers

NREL

It's been said that no two snowflakes are the same. And, for that matter, it is unlikely that the weather on any two days at any location will be exactly the same. The minute-by-minute temperature and cloud cover will differ between any two days, whether they are one after the other or the same date in two successive or non-successive years. As a result, estimating the performance of a photovoltaic (PV) system is at best, an inexact science, since performance is critically weather dependent.

However, the longer the period that is included in a prediction or simulation of PV system performance, the more reliable the prediction becomes, since weather conditions tend to average out over the long term. Still, predicting the future is not nearly as reliable as recording the past. As a result, *when system performance is simulated in this text* using the System Advisory Model (SAM) developed by the U.S. National Renewable Energy Laboratory, because of the careful modeling tools used by NREL, SAM is one of the most reasonable tools to use to estimate annual energy production for a PV system. But no claim has been made that SAM is exact or perfect, and thus when SAM is used to estimate system performance, it must be done with the understanding of the following disclaimer:

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In other words, using SAM for educational purposes is just fine, but blaming SAM if a system is built and does not work as predicted by SAM is not OK.

NFPA/NEC, ASCE, AND PVSE

Codes and standards are essential to the safe implementation of all technologies, including photovoltaics. In addition to local, statewide and regional codes, two national codes play especially important roles in the safe design of photovoltaic systems—NFPA 70, National Electrical Code and ASCE Standard 7, Minimum Design Loads and Associated Criteria for Buildings and Other Structures. Since technology continues to advance, these codes need to keep up with these advances. As a result, just as the design professionals get to know them pretty well, they come out with a new edition.

The reader should understand that the *enforcement* of these codes and standards is the job of local building departments. As a result, there is generally a delay between the *publication* of a standard and the *adoption* of a standard. For example, in Florida, enforcement of the 2020 National Electrical Code began in December 2023, even though a 2023 edition is now available. Similarly, the 2016 Edition of ASCE 7 was used through the end of 2023, even though a 2022 Edition was available in 2022.

This edition of *Photovoltaic Systems Engineering* uses NEC 2020, ASCE 7–16 and ASCE 7–22 as references for PV system design, recognizing that by the time it is published and after it is in use for a while, these publications will change again, and again, and . . . . This is why it is so important to *understand* how to *use* these important documents, so when they are updated, it will be a routine exercise to dig into the new edition and recognize the changes that will affect the design process. And this is why we make every effort to explain how to use these documents as we move through the design of numerous systems.

Thus, as in the case of NREL SAM, the authors and publishers emphasize that the final authority on any design intended for construction lies with the local code enforcement jurisdiction. The reader must understand that reference to the materials in the design examples is intended to introduce a process of incorporating currently accepted (2024) design practices into a design. Neither code, standard nor this publication can be held responsible for accurately portraying any particular code or ordinance.

Acknowledgments

Thanks to a long list of photovoltaic (PV) pioneers for making this publication possible. Only a few decades ago, photovoltaics was considered to be an emerging technology. Some thought it would never make it on a large scale. But others with more persistence have persevered over the years such that PV is no longer a hobby but is a mature, widely accepted, large-scale, worldwide technology that is growing faster than most advocates ever imagined.

One of these PV pioneers is Jerry Ventre, who coauthored the first three editions of this text. Jerry has been retired for a while now and has spent much of his time doing volunteer work with organizations that focus on PV job growth. It has been an honor and a privilege to work with Jerry over the years, and we wish him the best in his current and future activity.

We are convinced that it is virtually impossible to undertake and complete a project such as this without the encouragement, guidance, and assistance from a host of friends, family, and colleagues. For this edition, we again asked many questions of many people as we rounded up information for the wide range of topics contained herein. A wealth of information flowed our way from the National Renewable Energy Laboratory (NREL) and the Florida Solar Energy Center as well as from many manufacturers and distributors of a diverse range of PV system components. We feel confident that, had we asked, we would have been able to obtain additional cooperation and materials from many more.

Special thanks to Kimandy Lawrence of Lord and Lawrence Consulting Engineers for offering Roger the opportunity to review more than 6000 PV system designs since December 2020. Since his introduction to PV about 20 years ago, Kimandy has been determined to "get it right." His philosophy has been to teach his competition how to get it right to be sure PV remained a respected and trusted energy source. "Look around, there are plenty of rooftops for everyone."

Last, but not least, we thank Mimi Abtahi and Jane Caputi for encouraging us to work on this manuscript rather than play golf, tennis, watch TV or pay attention to them.

Roger Messenger and Homayoon "Amir" Abtahi

Authors

Roger Messenger is Professor Emeritus of Electrical Engineering at Florida Atlantic University in Boca Raton, FL. He received his Ph.D. in Electrical Engineering from the University of Minnesota and is a Registered Professional Engineer, a former Certified Electrical Contractor and a former NABCEP Certified PV Installer, who has enjoyed working on a field installation as much as he enjoys teaching a webinar or working on the design of a system or contemplating the theory of operation of a system. His research work has ranged from electrical noise in gas discharge tubes to deep impurities in silicon to energy conservation to PV system design and performance. He worked on the development and promulgation of the original Code for Energy Efficiency in Building Construction in Florida and has conducted extensive field studies of energy consumption and conservation in buildings and swimming pools.

Since his retirement from Florida Atlantic University in 2005, he has worked as Vice President for Engineering at VB Engineering, Inc., in Boca Raton, FL, and as Senior Associate at FAE Consulting in Boca Raton. While at VB Engineering, he directed the design of several hundred PV designs, including the 1 MW system on the roof of the Orange County Convention Center in Orlando, FL. While at FAE Consulting, he led the design of an additional 6 MW of systems that were installed. Since 2020 he has reviewed over 60 MW of residential systems, including more than 8 MWh of residential Battery Energy Storage. He has also been active in the Florida Solar Energy Industries Association and the Florida Alliance for Renewable Energy, has served as a peer reviewer for the U.S. Department of Energy and has served on the Florida Solar Energy Center Advisory Board. He has conducted numerous seminars and webinars on designing, installing and inspecting PV systems. In May 2024 he received a Florida Solar Energy Industries Association Hall of Fame award for extraordinary contributions to the Florida Solar Industry.

Homayoon "Amir" Abtahi is currently Associate Professor of Mechanical Engineering at Florida Atlantic University. He received his Ph.D. in Mechanical Engineering from M.I.T. in 1981 and joined Florida Atlantic University in 1983. In addition to his academic activity, he has a wealth of practical experience, much of which has been obtained as a volunteer. He is a Registered Professional Engineer in Florida and is a member of ASCE and SAE. He has held LEED Certification since 2007, is ESTIDAMA Certified in the United Arab Emirates and is a Certified General Contractor and a Certified Solar Contractor in the State of Florida. His interests range widely from PV to PEM Fuel Cells, integrated capacitor/battery power modules and Atmospheric Water Generation.

In 1985, he installed the first-known solar power system in Venezuela and was responsible for the first-known application of solar power for post-hurricane emergency power and lighting and Ham Radio communication operations in the aftermath of Hurricane Hugo in St. Croix in 1989 and Hurricane Marilyn in St. Thomas in 1995. In 1989, he published the first comprehensive catalog of 12-V appliances for use with PV systems.

Recently, he has been involved with PV installations in the Caribbean, South America, Bangladesh and India. In the 2008–2010 time period, he was responsible for the design and installation of over 100 residential and 20 commercial/industrial PV systems. Over the past 15 years, he has had responsibility for the design and installation of 1 million BTUD of solar hot water and solar process heat. Along with the PV and thermal applications, he has had experience with heat exchangers, MEP plan review, LEED projects, tracking PV, micro-turbines, parabolic trough solar and other hybrid applications.

We did not inherit this world from our parents. . . .
We are borrowing it from our children.
(Author unknown)

We believe the future of PV is as bright as the sun.
It is our fervent hope that the engineers who read this book
will dedicate themselves to the creation of a world
where children and grandchildren will be left
with air they can breathe and water they can drink,
where humans and the rest of nature
will nurture one another.

1 Background

1.1 INTRODUCTION

It took just 20 years from 1954 when Bell Labs in New Jersey announced the first successful testing of a photovoltaic (PV) cell [1] to 1974 when the worldwide shipment of PV modules reached 500 kW [2]. This was particularly huge for the time because, in 1974, a 5-Watt solar panel was treated as if it were a piece of jewelry. On the application side of things, NASA deployed the first PV application with a six-cell power module for the Vanguard satellite in 1958 [3]. Solar-powered wristwatches designed by Roger Riehl were offered to the public as "Synchronar 2100" in 1972 [4]. The energy crisis of 1973, alongside the geopolitical sense of urgency to be independent of fossil fuels [5], pushed investments in solar PV research and manufacturing to the front burner for the United States. Weary of conflicts at or near the largest reserves of oil and gas, the United States and especially Japan, which depended on oil imports for nearly all of its energy needs, spearheaded PV manufacturing that resulted in a significant drop in the cost of PV from $300/Watt in 1956 [6] to less than $5/Watt by the mid-1980s.

Despite the advances in efficiency and the prospect of lower manufacturing costs, solar panels were considered a novelty and a power source for mostly niche applications in the mid-1980s [7]. Remote microwave repeater stations, cell towers, solar-powered streetlights, solar-powered irrigation pumps, remote cabins and specialty soft panels for sailboats made up most of solar PV sales to the late 1990s. The entrenched energy suppliers correctly argued that PV was still too expensive to compete with conventional power generation, but then they incorrectly predicted that it would be a long time before solar (or wind) energies could even be conceived as "real" utility-grade power sources. Solar engineers and advocates were considered rebels in the serious "electrical grid world," and the thought of solar or wind energies ever replacing coal, nuclear and oil was considered heresy by utilities and fossil fuel producers. After all, solar was good enough only to power the remote cabins of the "hippies" in California. It was only when MW-sized wind generators started to be deployed in the United States and Europe, and the annual worldwide energy output of the wind sector surpassed 10 terawatt-hours (TWh = 10^9 kW-hours) in 1995, that utilities started paying attention [8].

It would take solar energy another decade to prove the naysayers wrong. First Solar Corporation announced a $1/Watt goal for the price of its amorphous CdTe solar panels in 2008 [9]. One can argue that solar energy was not taken seriously until "total installed" solar PV dipped just under $5/Watt ($5000/kW) in 2005. Supply chain and raw material shortages resulted in price stagnation until 2009 when PV manufacturing capacity managed to keep up with demand [10]. With a stable solar module supply and installation costs on par with conventional generation, solar suppliers started to talk the language that utilities and power engineers were

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comfortable with. For comparison, consider that, in 2007, Florida Power and Light reported a forecast for the "Total Cost" of a nuclear power plant construction to be between \$5492/kW to \$8081/kW, which is close to the Moody Investor Services of estimated \$5000 to \$6000] [11]. However, the optimism for the solar advocates was short-lived. Solar energy skeptics soon found another excuse to oppose the widespread deployment of solar, and this one would not be easy to overcome.

It was and still is an undeniable characteristic of solar and wind generators: "intermittent." With a lack of efficient and cost-effective storage technologies and batteries to resolve the variability of solar energy during the day, and the simple fact that there is no solar energy to collect at night, this was a very substantial barrier for solar energy. Those who had thought reaching parity was enough to give solar a foot in the door of the utilities realized, just as many had before them, that being equal in performance and price a third of the time was just not good enough. Solar had to be more reliable and compete with low-cost hydropower from Canada or the Pacific Northwest to be allowed into the club. This was not asked of nuclear or any other competitors in the energy supply chain; in fact, the environmental costs of coal and nuclear power were to be paid by taxpayers, no questions asked.

The existing grid in the United States that helped provide power through projects like Tennessee Valley Authority, the Hoover Dam and many others was paid for by governmental subsidies and taxpayers [12]. When solar energy was over-generated in California [13] and Germany [14] and utilities offered electricity at negative prices to shed load, politicians criticized the investments in solar as "a waste of tax-payer dollars," when, in fact, the real culprit was the power grid. It was not designed for a bi-directional transmission of power or distributed generation so that excess renewable energy can be dispatched to where it's needed, when it's needed, with integrated storage to accommodate intermittent supplies.

The lack of solar energy at night, as well as daily and seasonal peaks in energy use, makes it obvious that energy storage, energy management and other clean energy sources will need to be a part of the energy mix of the future. In addition to the development of advanced batteries and other storage technologies, to be discussed in detail in Chapter 6, including the deployment of utility-scale MWh and GWh storage facilities, improved dispatch and transmission of renewable energy, along with innovative load management and control, is helping to integrate solar and other renewable energy sources into the grid.

Despite optimism that solar is finding its footing in the overall power supply space, recent events at COP-28 [15] and the resistance of fossil fuel-producing countries to cut the cord of dependence on fossil energy sources have shown once again that parity alone will not be sufficient to dislodge entrenched beliefs and loyalties. Solar needs to be twice as reliable and stable as any other source of energy and yet, even with storage, be cheaper than any other energy source to dislodge the status quo and make serious inroads—not just with utilities that have now accepted solar because it makes economic sense but also to convince society and policy makers at large. Does this sound familiar and remind us of how difficult it can be to be accepted by the comfortably entrenched old guards?

In the remaining sections of this chapter, we will discuss and dive into the justification and reasoning for the argument that solar and other "near-zero emission" sources are the "urgent" solutions. Global warming was re-labeled "climate change" to avoid offending certain groups and then renamed again as climate crisis for a reason. With more than 20 nations [16] dealing with severe droughts or flooding, numerous island nations begging for help, and many of the poorest and most vulnerable populations simultaneously fighting wars and facing climate change, it is time to pull the climate alarm lever and stop the narrative of entrenched interests intent on pushing our collective heads into the sand of denial: denial that Antarctica and Greenland's ice sheet losses will contribute from 1 to 2 meters to sea level rise [17], denial that the South pole and Greenland's ecosystem will substantially change before 2100 [18] and denial that sea level rise will lead to the displacement of more than a billion climate refugees by 2050 [19]. Do we really have to wait until the warm river of the Gulf Stream stops flowing from Florida Straights to England and Norway, freezing Northern Europe and overheating the U.S. southeastern seaboard before we act?

1.2 URGENT ATTENTION TO WORLD POPULATION FORECASTS

Population is clearly the most direct driver of energy requirements and thus potential emissions from energy generation. Population forecast models agreed upon by the UN [20], INED [21], U.S. Census [22], Worldometers [23] and several other international organizations vary in details, but the general consensus, as shown in Figure 1.1, adopted from PopulationPyramid.net [24] data, suggests that the world population will peak sometime between 2070 and 2100. The peak numbers vary

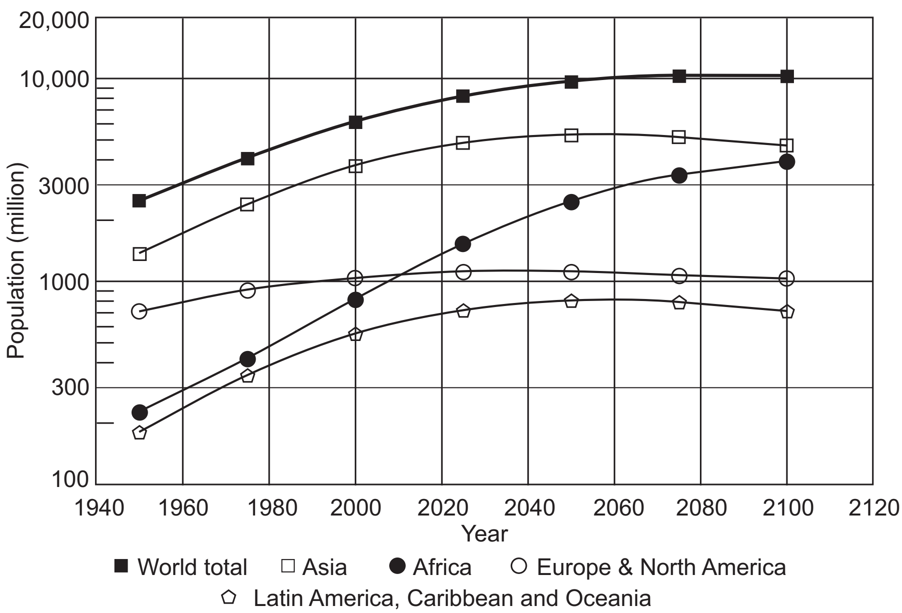

FIGURE 1.1 World and regional population data.

[Adapted from Population Pyramid data: www.populationpyramid.net/world/]

from source to source, but they are all in the range of 9.5 to 10.5 billion. Assuming 2075 is a good compromise when the world population peaks, it will be used as the reference, providing a 50-year window to assess and project energy demand and the resulting emissions.

The population trends of the major contributors to the world population are also shown. The regional data shows that Europe and North America's combined population is peaking. Remarkably, Asia's population, including China and India's populations, is also approaching a plateau and is expected to begin decreasing in the next few decades. Africa's population however does not show any indications of approaching a diminishing rate, let alone a peak. This uncertainty, combined with the fact that many African nations will see the biggest growth in energy demand in the next 50 years and still do not have the resources to switch over to renewables, may be the biggest challenge for moderating worldwide emissions.

To summarize, the following assumptions are made throughout this text:

- The year 2075 is when the world's population will plateau, giving us approximately a 50-year time frame to address energy demand and emissions.
- It will be optimistically assumed that developed regions of the world, including North America, Europe, China and India, will meet the energy emissions targets that have been laid out by each.
- The focus of this chapter is to address electricity power supply, not other forms of energy demand such as industrial heating, or transportation, except electricity demand for electricity-based cars or trains.
- It is also recognized that clean electricity is only one of numerous challenges facing this and future generations. Hopefully, clean electricity will also be part of solutions for other challenges such as adequate clean water supply.

To satisfy the energy needs of a peaking world population in 2075, no single form of energy, including renewable, nuclear or hydro, will be sufficient. The existing forms of clean energy must all be harnessed thoughtfully and as sustainably as possible to provide energy for the world of 2075. There should also be a concerted and honest effort to consider equity and the needs of underserved populations and countries, most of whom are innocent victims of climate change. Specifically, effort must be made to ensure that regions and peoples affected most severely by climate change receive urgent investment assistance to transition to clean renewable resources and eliminate the use of fuels and sources such as coal and kerosene and the associated unhealthy emissions, especially in proximity of vulnerable sectors of the population. Renewable engineering must be implemented with care to not disrupt ongoing human activity, while always cognizant of impact on nature.

1.3 ENERGY DEMAND AND CARBON DIOXIDE EMISSIONS

1.3.1 Current and Projected Scenarios

At the time of this writing, there is a good sense of the energy demand projections of the Organization for Economic Cooperation and Development (OECD) countries including Europe, North America, Japan, China, India and similarly developed regions of the world. At least on paper, Europe and North America have some very clear plans on how they're going to control emissions, and their emissions have either reached the maximum levels or are going down. Similarly, China and India have plans in place, but they are simultaneously under pressure to provide more power to their population—so there is uncertainty about whether those strides will be met. The key to sustainability is to achieve a balance between harmful emissions produced by human activity and neutralizing them. And even though emissions are decreasing in a number of countries with advanced economies, they are still nearly an order of magnitude greater than the removal rate.

1.3.2 Solar PV Contribution and Demand

On December 13, 2023, the United Nations (UN) Climate Change Convention (COP28) in Dubai came to an end. This date was a few days later than anticipated, mostly because of negotiations over language around transitioning away from fossil fuels; there were definite signs that fossil-producing nations were not yet willing to accept that the world has to be more aggressive with phasing fossil fuels out. In fact, the words "phase out" were considered too harsh, so the terminology "phase down" was used instead. In response to the back-and-forth, UN Secretary-General António Guterres addressed the nations that opposed more "direct" language around transitioning to cleaner energy by saying that whether countries wanted to believe it or not, phasing out of fossil fuels is inevitable—the question is only when.

As far as solar engineering and planning is considered, it is obvious that plans resulting from the 2015 Paris Agreement and 2021 Glasgow Climate Pact need to be accelerated, if nothing else; projections around how much renewables will need to be incorporated into energy planning will need more solar than anticipated. To see what energy engineers and planners will be facing, a review of the roadmaps that were developed following these agreements is helpful.

The International Energy Agency (IEA) has a very helpful publication entitled "World Energy Outlook" [25] that outlines three scenarios for the global reduction of fossil fuel emissions. These road maps will help energy engineers and planners to understand what will be anticipated up to 2050, including, specifically NZE-2050, and other less specific long-term goals:

1. The first scenario is the **Stated Policies Scenario (STEPS)**, which is reflective of current climate change policies.
2. The second is the **Announced Pledges Scenario (APS)**, which assumes that each country's climate targets are met in full, but without guarantee that this will happen.
3. The third scenario is **Net Zero Emissions by 2050 (NZE)**, in which half of the total energy (and two-thirds of useful energy) will have transitioned to zero-emission renewables. This scenario is based on more ambitious agreements of NZE and is a signed commitment from about 38 OECD countries in the world that have begun to put reliable plans in place.

A look at the latest projections for energy transition away from fossil fuels suggests that those will now be minimums based on what was just reached COP 28 in Dubai, meaning transitions will have to be accelerated.

In Table 1.1, the impact of the three scenarios adopted at COP 25 on PV generation for 2050 is shown.

To update the information or look at these projections and see what changes might occur beyond requirements or any government programs, it is worth reviewing recent coverage by NationalNews.com [26] and Bloomberg NEF [27] regarding increased PV installations above and beyond what was projected even at this early stage.

There was a projected 26% increase in PV installations from 2022 to 2023. This has gone through a great transformation, with China installing more than 250 GW in 2023, resulting in a 27% increase globally. The projected increase should therefore be revised to 64% for 2024. In addition, the world PV module production capacity, which was reported as 839 GW in 2023, is now expected to reach 1 TW in 2024 [28]. Assuming all PV production is installed, the goals of NZE could be reached as much as ten years earlier than anticipated.

1.3.3 Emissions

Regional Emissions associated with power generation are directly proportional to population, per capita energy demand and the average emissions generated by kWh generated.

$$\text{Regional Emissions} = \text{Regional Population} \times \text{Energy per Capita} \times \text{Emissions per kW-hour} \quad (1.1)$$

The relationship between CO_2 and global temperature rise is well understood. Globally, CO_2 concentration is measured at the Mauna Loa Observatory in Hawaii, which has set the global standard by which CO_2 levels are calculated [29].

As outlined in Figure 1.2, CO_2 has increased from a concentration of just under 320 parts per million (ppm) in 1960 to almost 420 ppm in 2020. Currently, 33 GT of CO_2 is annually emitted into the atmosphere globally. As can be observed from the exponentially appearing curve, the seasonal absorption of CO_2 during high seasonal

TABLE 1.1
GEC Model Scenarios: Anticipated 2050 Outcomes

Scenario	Contribution to World Energy Supply (%)	Solar/PV Component of the Renewables (% of Total Electricity Demand	Solar PV Energy Generation (TWh)
STEPS	65	24	12,118
APS	80	30	18,761
NZE	88	37	27,006

(Adapted from table 6.1, "World Energy Outlook" published by IEA, 2022.)

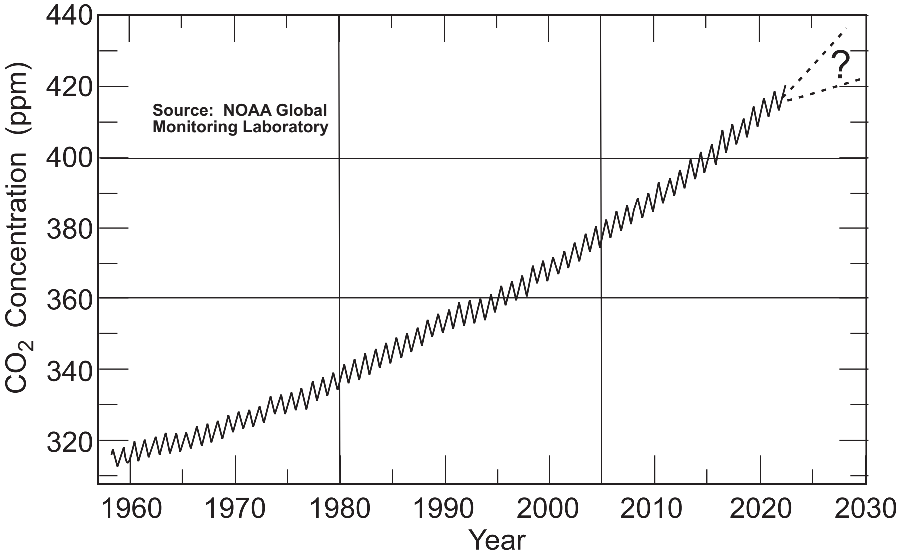

FIGURE 1.2 Historic atmospheric carbon dioxide concentration as measured at Mauna Loa. [Adapted from data from the NOAA Global Monitoring Laboratory as presented by Scripps Institution of Oceanography, UC San Diego.]

bio-absorption of CO_2 is no match for the CO_2 load and is just a small secondary wave on the primary increasing trend in atmospheric CO_2 percentage. In fact, the percent of CO_2 in the air we breathe increases by approximately 0.00035% or 3.5 ppm annually. This increase is particularly troubling due to the rate of increase over the past 60 years. The impact of the average global temperature is shown in Figure 1.3, adapted from NOAA-Goddard Institute [30]. Note that each data point in this figure represents the average CO_2 concentration and average global temperature for a particular year. The average global temperature is compared with baseline data between 1850 and 1900. Although specific years are not associated with each data point, the data is grouped into periods as shown on the graph. Beginning in 1940, data is grouped by 20-year increments, clearly showing the increasing average temperature as CO_2 levels continue to rise at an approximate rate of 0.1°C per 10 ppm increase. At this rate, the global average temperature will increase by 2°C above pre-industrial levels in just 25 years. After the 2015 Paris Agreement, the treaty's 196 adoptive countries aligned on pursuing efforts to limit the temperature increase to 1.5°C and prevent temperatures from rising to 2°C [31].

The impact of carbon emissions resulting from human activity on the global temperature rise has been rigorously established, giving us no choice but to trust the data and ensure we can curb rising temperatures—or the consequences will be disastrous. There is, however, another factor to also consider, and this might finally get some attention. At the current rates, the global atmospheric CO_2 levels will reach 0.08% by 2100. This will be very close to 0.1% CO_2 in the air (approximately 1100 ppm of CO_2),

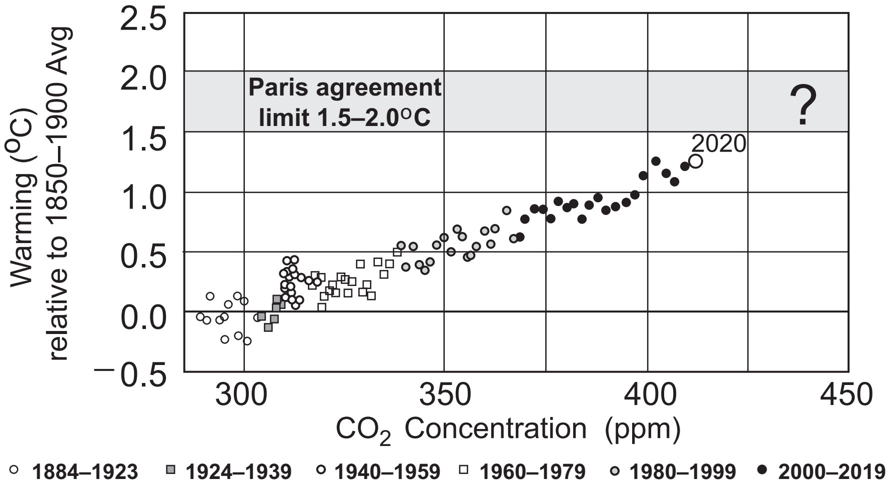

FIGURE 1.3 Correlation between atmospheric carbon dioxide levels and global temperature rise.

[Based upon data presented by Fakta o klimatu, Version 2022-05-12: factsonclimate.org/concentration-warming-relationship. Data source: NOAA, NASA Goddard Institute for Space Studies.]

considered unhealthy per current Standard-62 of ASHRAE's (American Society of Heating Refrigeration and Air Conditioning Engineers) air quality code [32].

In view of the discussion of the world population trends, the energy mix requirements and the consequences of emissions, there is justification and rationale for increased workforce development and education of energy engineers, especially in solar/PV. Hopefully, this textbook will help lead us toward that goal.

1.4 A BRIEF OVERVIEW OF THERMODYNAMICS

Most engineers are familiar with the first law of thermodynamics, which is the concept of energy conservation. Energy cannot be generated or destroyed. In essence, this means that energy can only be converted or transferred—so, in practice, first law efficiency is a function of the quality of the equipment being used as the ultimate objective is to convert all of that energy. An example of this is that a fluid-to-fluid heat exchanger can theoretically transfer close to 100% of the energy content from one fluid to another. However, converting heat energy to work energy is limited by the second law of thermodynamics.

The second law of thermodynamics governs how much heat energy can be converted to work or electric energy. The efficiency of this conversion from heat to mechanical work/electric energy is a function of the temperature difference between the high-temperature source and a low-temperature sink where the heat can be rejected. Probably the most common everyday application of the second law is the operation of hundreds of millions of internal combustion engines in vehicles worldwide. Most people have some understanding that without the heat (and pressure) of burning gasoline in the cylinders and the water circulating in the radiator and coolant system, the engine will not function properly. A reasonable fraction of the population has experienced the boiling over of a faulty radiator and the possible accompanying failure of the engine itself. In the winter, some of this "waste" heat is recirculated into the interior of the vehicle after being "captured" by the air circulating between the vehicle interior and the heating coils.

Another example is that a hydroelectric plant is not possible unless the discharge of the turbines is at a lower level than the height of the water behind the dam, because the difference in height is what creates the potential energy of the water at the higher level. Inversely, the water will not flow upward by itself. A pump with energy input is required to achieve that. Similarly, a heat pump requires energy to pump heat (measured in kilo-joules or BTUs) from a lower-temperature reservoir such as a freezer to a higher-temperature space such as the outside of the refrigerator.

To quantify the second law of thermodynamics, when a heat engine converts heat into work (where work can be shaft work or electricity or raising of a weight), conservation of energy still applies. Thus, the starting energy at the high temperature, or, more precisely, the energy supplied by the high temperature source must equal the sum of the heat converted to work plus the heat rejected, or, "waste heat." "Waste heat" is actually a misnomer because the loss of heat is a requirement for heat engines. The French physicist Sade Carnot quantified the limits of heat-to-work conversion with:

$$\text{Ideal Thermal Efficiency} = 1 - T_{Low}/T_{High}, \tag{1.2a}$$

where temperatures are in Kelvin.

Since Kelvin is the temperature measured from absolute zero, to convert T in °C to Kelvin simply:

$$T\ (\text{Kelvin}) = T\ (°\text{C}) + 273.15. \tag{1.2b}$$

For example, to convert 900°F to Kelvin:

1. Convert °F to °C: (900 − 32) (5/9) = 482.2°C.
2. Convert T°C to Kelvin: 482.2 + 273.15 = 755.37 K.

Assuming that the average cooling temperature available around a power plant is 75°F equivalent to 297 K, it can be concluded that a powerplant with a heat source of 900°F has a maximum or ideal, Carnot efficiency of

$$1 - (297/755.37) \text{ or } 57.5\%.$$

Without getting too deep into proofs, a corollary is that:

$$\text{Ideal Thermal Efficiency} = (Q_H - Q_L)/Q_H, \tag{1.2c}$$

where Q_H is heat supplied by the high-temperature source and Q_L is heat rejected to the environment.

($Q_H - Q_L$) is also equal to the net work out of the engine. This equation can also be written as a rate equation so that:

$$\text{Heat Input in kW} - \text{Heat Rejected in kW} = \text{Work Out in kW} \tag{1.3}$$

The requirement that all heat-to-work conversions have a low-temperature sink results in the need to reject heat to the environment surrounding a thermal power plant. This is true for any power plant including geothermal, nuclear, solar thermal, coal or any other fossil-fueled power plant. There is no exception to this rule, the result of which is that heat *must* be released into the environment for a thermal power plant to function. The lack of understanding of the second law often leads people to believe that there is *no* impact on the environment from what we call "cleaner" forms of energy. In all fairness, if the thermal losses of all the power plants in the world are added up, they probably don't reach even one or 2% of the global heating caused by all greenhouse gases (GHGs), including carbon dioxide in the atmosphere—but there is thermal pollution from these cleaner sources, even geothermal power plants because they also need cooling. The second law of thermodynamics limitation has not been exceeded since Sadi Carnot quantified it in 1824 [33], and there is no evidence that it ever has.

1.5 A BRIEF HISTORY OF PHOTOVOLTAICS

Edmond Becquerel [34] first discovered that sunlight could be converted directly into electricity in 1839, when he observed the photogalvanic effect. Then, in 1876, Adams and Day [35] found that selenium has PV properties. When Planck postulated the quantum nature of light in 1900 [36], the door was opened for other scientists to build on this theory. It was in 1930 that Wilson [37] proposed the quantum theory of solids, providing a theoretical linkage between the photon and the properties of solids. Ten years later, Mott and Schottky [38] developed the theory of the solid-state diode, and, in 1949, Bardeen, Brattain and Shockley invented the bipolar transistor [39]. This invention, of course, revolutionized the world of solid-state devices. The first solar cell, developed by Chapin, Fuller and Pearson, followed in 1954 as mentioned in the introduction to this chapter.

One might wonder why it took so long to develop the PV cell. The answer lies in the difficulty of producing sufficiently pure materials to obtain a reasonable level of cell efficiency. Prior to the development of the bipolar transistor and the advent of the space program, there was little incentive for preparing highly pure semiconductor materials. Coal and oil were meeting the world's need for electricity, and vacuum tubes were meeting the needs of the electronics industry. But since vacuum tubes and conventional power sources were impractical for space use, solid state gained its foothold.

As will be discussed in detail in later chapters, PV cells are made of semiconductor materials and are assembled into modules of 36 or more cells. This observation is significant, since this means the same industry that has, in the past 60 years, progressed from the development of the bipolar transistor to integrated circuits containing millions of transistors is also involved in the development of PV cells.

1.6 ENERGY UNITS

Energy is measured in a number of ways, including the calorie, the BTU, the quad, the foot-pound (ft-lb) and the kilowatt hour (kWh). When pounds (lb) and kilograms (kg) are used in this text, they will be treated as weight rather than mass. Thus, a 220 lb person can also be described as a 100 kg person. For the benefit of those who may not have memorized the appendices of their freshman physics books, we repeat the definitions of a number of these energy-related quantities for an earth-based system at or about a temperature of 27°C.

1 calorie is the heat needed to raise the temperature of 1 gram of water 1°C.
1 BTU (British Thermal Unit) is the heat needed to raise the temperature of 1 lb of water by 1°F.
1 quad is 1 quadrillion (10^{15}) BTUs.
1 ft-lb is the energy expended in raising 1 lb through a height of 1 ft.
1 kWh is the energy expended by 1 kilowatt operating for 1 hour.
1 MTOE (million tons of oil equivalent) is the energy available from 1 million tons of crude oil.
1 Mbd (million barrels per day) is the energy available from 1 million barrels of crude oil.
1 Bcm (billion cubic meters) is the energy available from 1 billion cubic meters of natural gas.

With these definitions, and with the numerical values of MTOE, MBOE and Bcm, the following equivalencies can be determined:

1 BTU = 252 calories
1 kWh = 3413 BTUs = 2,655,000 ft-lb
1 ft-lb = 0.001285 BTU
1 quad = 10^{15} BTUs = 2.930×10^{11} kWh
1 MTOE = 0.0397 quad
1 MBOE = 0.00541 quad
1 Bcm = 0.0357 quad

It should be noted that MTOE, MBOE and Bcm represent the *total* amount of energy stored in the specified quantities of coal, oil and natural gas before they are converted into other forms of work or energy, such as electricity. Net energy is another term often used to describe the resulting useful energy obtained from a primary source.

Homework Problems

1.1 A common rating of a typical-size PV panel (also called module) is 400 Watts. An array or a cluster of ten solar panels therefore generates 4000 Watts of power during peak solar conditions. If peak solar conditions are 4.2 hours per day for a specific water pumping application in northern Oklahoma, how much energy can be expected to be collected in one day in kWh units? Convert this answer to kJ.

1.2 Solar PV panels are labeled at the manufacturing facility with a sticker that indicates the power rating of each module. These ratings, however, are based on a test of the module in a "solar test chamber" where the module is subjected to an industry standard of 1000 Watts/m^2-simulated solar light intensity. As will be discussed in later chapters, a more realistic solar energy intensity on the surface of the earth is closer to 800 Watts/m^2 maximum except in higher elevations with low humidity conditions. Based on this information, recalculate the energy collected in Problem 1.1.

1.3 If 20 kWh of energy is stored in batteries from solar PV generation, and only 80% of this stored energy can be used to run the electric loads of a remote microwave repeater station, what is the maximum power that can be used for a 24-hour constant load?

1.4 The CO_2 emissions plot (Figure 1.2) shows an increasing slope from 1960 to 2020. Extrapolating the graph, what should the slope be after 2020 to keep atmospheric CO_2 below 430 ppm by 2050?

1.5 The Paris Climate Accord of 2015 among 196 countries sets a limit of 1.5°C on the average global temperature rise. Figure 1.3 shows the relationship between the global temperature rise and the global carbon dioxide levels measured in ppm. How close is the global temperature rise to this 1.5°C limit? Is there still time to avoid reaching this level?

1.6 Based on the brief discussion of the second law of thermodynamics, calculate the heat loss of an ideal engine to the environment for a 50 MW (Net output) coal plant with a 50% ideal efficiency. If an actual coal plant runs at 30% efficiency, how much more heat will be rejected to the environment?

1.7 An engineer is suggesting an increase in the temperature of the boiler in a power plant from 500°C to 600°C and claims that this change could result in reducing the heating of the local atmosphere by at least 20%. Assume the ambient temperature is 300 K. Is she correct?

1.8 An engineering intern is asked to compare the theoretical thermal environmental impact of a pressurized water reactor (PWR) nuclear power plant with a combined cycle natural gas-fired power plant. Both plants are to have a net electrical power output of 1 GW and operate for an average of 80% of the time on an annual basis. PWR plants are designed to run at a maximum of 647 K for safety reasons, and the combined cycle gas turbine runs at 1500°F at its highest temperature point in the gas turbine section. Using these temperatures as T_H for each cycle and assuming 300 K as T_L for both cycles, determine:

a. The Carnot efficiency of each plant.
b. The total energy input for each plant on an annual basis, assuming a year of power generation to be 80% of 8760 hours.
c. The thermal impact of each plant on the environment for a year and for the expected life cycle of 30 years.

1.9 The Hellisheidi geothermal power plant near Hengill, Iceland, operates with hot water extracted from 44 wells, providing the heat source at 180°C. The average ambient temperature (T_L) in that region of Iceland can be assumed to be 0°C in winter and 12°C in the summer.

a. Determine the ideal Carnot efficiency of the plant in the winter and the summer.
b. If the plant generates a net electric power output of 90 MW, calculate the total amount of energy that needs to be extracted from the hot water wells for the ideal Carnot cycle.
c. An advantage of operating a power plant in cold regions is that the "waste" can be actually piped to homes and businesses to be used as heat for homes and businesses. This is called district heating or co-generation. Based on the ideal Carnot cycle for winter, calculate how much heat will be available for district heating.

1.10 In one of the IEA (International Energy Agency-Ref. 25-table A3) scenarios, solar PV electricity generation will increase from 821 TW-hours in 2020 to 23,469 TWh by 2050. Assuming that solar PV panels generate an average of 80% of nameplate rating, determine the PV-installed capacities for 2020 and 2050 that would be required to provide the stated goals. Assume that the energy generated per day is equivalent to 4.2 hours per day of rated output for 365 days a year.

1.11 When dealing with projections of future numbers, it is often very useful to develop a general spreadsheet for which certain variables can be changed to see the long-term effect of the change. This problem deals with the development of a spreadsheet to use in exploring the effect of changing various variables on the yearly and cumulative values of available PV generation capacity as well as the projections of total annual energy generation by the projected capacity.

Specifically, the proposed spreadsheet will include existing worldwide PV generation capacity in GW at the beginning of 2020, annual installations and annual growth rate of installations, the cumulative worldwide capacity in GW on an annual basis between 2020 and 2050 and the estimated energy generated in TWh on an annual basis based upon an assumed ratio of TWh produced to GW installed. The following shows

	GW	GW	GW			TWh/ GW
Year	Start	Ann Add	End	Rate	End TWh	1.5
2020	585	125	710	0.2	1065	
2021	710	150	860	0.25	1290	
2022	860	188	1048	0.25	1571	
2023	1048	234	1282	0.3	1923	
2024	1282	305	1587	0.2	2380	

the first five years of spreadsheet entries resulting from the assumptions made by the user in the shaded cells.

a. Using the numbers in the shaded cells, determine how the numbers in the unshaded cells are calculated.
b. Extend the spreadsheet out to the year 2050, using the formulas you have figured out for part a.
c. Use an annual increase rate of 20% for all years (0.2 is 20%) up to 2050 and note the year where TWh generated exceeds 23,469.
d. Vary the user-entered numbers to see the effect on the cumulative worldwide GW of generation capacity.
e. Vary the TWh/GW figure between 1.0 and 2.2 and observe the effect on total TWh. Note that TWh/GW is the variable that has significant dependence upon array location and module type.

1.12 Currently, 33 GT (33 billion metric tons) of the estimated total 50 GTs annual emission of total GHGs is made up of CO_2. It is estimated that coal plants generate 820 grams of CO_2 per kWh of electricity generated versus solar PV, accounting for emissions associated with the manufacturing of panels, the structure and earthworks, resulting in 40 grams of CO_2 emissions per kWh. Calculate the reduction in CO_2 emissions achieved if all solar PV generation was targeted to reducing coal power generation. Use the 23,469 TWh (per year) for 2050 estimate by IEA [25].

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SUGGESTED READING

.1% or .2% CO_2 in Air Drowsiness or Poor Air Quality Complaints: www.co2meter.com/blogs/news/carbon-dioxide-indoor-levels-chart

An Alternative CO_2 Reference: Levels If Current Trends Continue: https://clintonwhitehouse5.archives.gov/Initiatives/Climate/next100.html

Indoor Air Below 1100 ppm: www.ashrae.org/technical-resources/standards-and-guidelines/standards-interpretations/interpretations-for-standard-62-2001

2 The Sun

2.1 INTRODUCTION

Optimization of the performance of photovoltaic (PV) and other systems that convert sunlight into other useful forms of energy depends upon the knowledge of the properties of sunlight. This chapter provides a synopsis of important solar phenomena, including the solar spectrum, atmospheric effects, solar radiation components, determination of the sun position, measurement of solar parameters and positioning of the solar collector. In this chapter, an attempt is made to quantify the obvious and, perhaps, some not-so-obvious observations: Why is it light during the day and dark at night? Why are there more daylight hours in summer than in winter? Why is the sun higher in the sky in summer than in winter? Why are there more summer sunlight hours in northern latitudes than in latitudes closer to the equator? Why does less energy reach the surface of the earth on cloudy days? Why is it better for a solar collector to face the sun? What happens if a solar collector does not face the sun directly? How much energy is available from the sun? Why is the sky blue?

2.2 THE SOLAR SPECTRUM

The sun provides the energy needed to sustain life in our solar system. In one hour, the earth receives enough energy from the sun to meet its energy needs for nearly a year. In other words, this is about 7500 times the input to the earth's energy budget from all other sources. To maximize the utilization of this important energy resource, it is useful to understand some of the properties of this "ball of fire" in the sky.

The sun is composed of a mixture of gases with a predominance of hydrogen. As the sun converts hydrogen to helium in a massive thermonuclear fusion reaction, mass is converted to energy according to Einstein's famous formula, $E = mc^2$. As a result of this reaction the surface of the sun is maintained at a temperature of approximately 5800 K. This energy is radiated away from the sun uniformly in all directions, in close agreement with Planck's blackbody radiation formula. The energy density per unit area, w_λ, as a function of wavelength, λ, is given by

$$w_\lambda = \frac{2\pi hc^2\lambda^{-5}}{e^{\frac{hc}{\lambda kT}} - 1} \text{ (W/m}^2\text{/unit wavelength in meters)}, \tag{2.1}$$

where $h = 6.63\times10^{-34}$ watt sec^2 (Planck's constant),
$c = 3.00\times10^8$ m/sec (speed of light in a vacuum),
$k = 1.38\times10^{-23}$ joules/K (Boltzmann's constant) and
T = absolute temperature of a blackbody in K (degrees Kelvin, where 0 K = −273.16°C).

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