1 Introduction

Let us start with the subtitle of the book, *Applications in Sustainable Power*. The "power" in the subtitle is obviously electricity or electric power.[1] The term "sustainable" can be traced back to the simple fact that a gas and/or steam turbine power plant burns a fossil fuel (natural gas) to generate electric power. Combustion of fossil fuels (i.e., coal, fuel oil, natural gas) generates carbon dioxide (CO_2), a greenhouse gas, which is emitted into the atmosphere through the stack of the power plant. Greenhouse gases (e.g., ozone, methane [CH_4], CO_2, and carbon monoxide (CO) among others – they are commonly referred to by the acronym GHG) contribute to global warming via the *greenhouse effect*. This term refers to the analogy between GHG and glass in a greenhouse,[2] which allows sunlight in to keep the inside warm while simultaneously blocking the heat inside from escaping outside. A greenhouse keeps the plants inside warm; GHG in the atmosphere do the same by trapping heat radiating from Earth into space.

At the time of writing, despite overwhelming research and data accumulated over the last half century, there is still an acrimonious debate about whether anthropogenic CO_2 emissions contribute to global warming or not. As far as this book is concerned, such debate is irrelevant because what is covered herein is based on recent *concrete* developments in the electric power generation landscape, which stem from the worldwide acceptance of global warming and its dire implications, i.e., catastrophic *climate change* events, as a fact as well as a clear and imminent danger (in no way a certainty – more on this below). There are many scientific studies, reports, and papers published by reputable scientists and institutions on this subject, and these are only one click away on the internet. Unfortunately, the internet is also full of unreliable information and propaganda. Therefore, the author would like to refer the reader to arguably the most reliable resource for laypersons: David J. C. MacKay's *Sustainable Energy – Without the Hot Air* (UIT Cambridge: Cambridge, 2009). The book is also available free for download in www.withouthotair.com (last accessed on May 13, 2020). Suffice to point out a few irrefutable facts:

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[1] Note the deliberate use of the term "power," not "energy." Since this is not a book for laypeople, I will not elaborate on the distinction between power (measured in watts, i.e., joules per second) and energy (measured in joules).

[2] A greenhouse is a glass building that is used to grow plants. Greenhouses stay warm inside, even during the winter. During the day, sunlight shines into the greenhouse and warms the plants and air inside.

- In 2018, the CO_2 concentration in the atmosphere exceeded 400 ppm.
- Until the beginning of the Industrial Revolution (late eighteenth, early nineteenth century), this number was very stable at around 280 ppm.[3]
- The dramatic increase (nearly 50%) in the concentration of CO_2 over the last two centuries, including a very rapid acceleration in the last decade or so (about 2.5 ppm per year[4]), points the finger at the ever-increasing role of fossil fuels in human activities (transportation, electric power generation, steel making, space heating, etc.).

The recorded increase in CO_2 concentration in the atmosphere coincided with an unmistakable increase in average annual temperatures recorded on earth. In particular:

- In 2019, the average temperature across global land and ocean surfaces was 1.71°F (0.95°C) above the twentieth-century average of 57.0°F (13.9°C), making it the second-warmest year on record.[5]
- The global annual temperature has increased at an average rate of 0.13°F (0.07°C) per decade since 1880 and over twice that rate (+0.32°F/+0.18°C) since 1981.[6]

Combined with the atmospheric CO_2 concentration trend since 1880, this corresponds to about a 1°C rise per 100 ppm rise in CO_2 concentration. Thus, prima facie, one could expect a 3°C rise in average temperature across global land and ocean surfaces when the CO_2 concentration reaches 700 ppm. At the current rate of carbon emissions, which is likely to increase, especially due to rapid economic development in countries like India and China, this is quite likely to happen within the next century.[7] This level of global warming can lead to significant natural disasters such as the melting of Greenland's icecap and rising sea levels. There is concern that the recent increases in severe weather events and widespread wildfires are connected to global warming.

Now, let us take a pause here. The accuracy of the statements made in the paragraph above are highly suspect! For one, weather is *not* climate. Yes, global warming is a fact. Yes, anthropogenic CO_2 emissions, which have been increasing steadily since the 1950s, play a role in global warming via the GHG mechanism. However, that mechanism is more nuanced than many published reports would make the unsuspecting public believe, and the relationship is not a direct proportionality as

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[3] Carbon dioxide concentrations for the last millennium or so are measured using air trapped in ice cores, particularly those in Greenland and Antarctica. Since 1958, regular measurements have been made in Mauna Loa Observatory (MLO) in Hawaii. The observatory is one of the stations of the Global Monitoring Laboratory (GML), part of the National Oceanic and Atmospheric Administration (NOAA).

[4] From "State of the Climate in 2018," Special Supplement to the Bulletin of the American Meteorological Society, Vol. 100, No. 9, September 2019. Downloaded from www.ametsoc.net/sotc2018/Socin2018_lowres.pdf on May 13, 2020.

[5] "Climate Change: Global Temperature," by Rebecca Lindsey and LuAnn Dahlman, January 16, 2020. From www.climate.gov/news-features/understanding-climate/climate-change-global-temperature (last accessed (last accessed on May 13, 2020).

[6] Ibid.

[7] While this section was being written in May 2020, a screeching halt to the global economic activity was brought down by the Covid-19 pandemic. Nevertheless, this unexpected (and unintended) pause in carbon emissions is not expected to be a new trend for long.

the author (deliberately) misstated above. The devil is not only in the details, which are beyond the scope of this book, but also in the past events, which clearly show a changing climate is not a modern phenomenon. In other words, how much of the change is attributable to purely human activities is not a settled debate.

For the proverbial holes in the present "doom and gloom" predictions mixing fact with fiction, propaganda and hyperbole with science, the reader is encouraged to consult the recent book by a reputable scientist, Steven Koonin, *Unsettled* (BenBella Books, Dallas, TX, 2021). The bottom line is that accurate predictions and establishing rock-solid cause-effect relationships are notoriously difficult and subject to uncertainty. Nevertheless, governments and industrial organizations worldwide (recently, even energy giants apparently[8]) are convinced that (i) "something" is happening, and (ii) it will be even worse in the near future *unless something is done*. This is the impetus behind the so-called *energy transition* that forms the context for this book.

The *energy transition* (*die Energiewende* in German) posits that "business as usual" continuation of electric power generation via fossil fuel combustion is not a sustainable path due to (i) finite resources, and (ii) GHG, especially CO_2, emissions leading to global warming (or climate change depending on one's "political" preference).[9] Natural gas is the cleanest fossil fuel by far – for example, gas turbine combined cycle (GTCC) CO_2 emissions, measured in kg per MWh of generation, is less than half that of coal-fired boiler-turbine power plants. Thus, in the context of this book's subtitle, *Applications in Sustainable Power*, GTCC operability considerations in conjunction with the increasing share of *carbon-free* technologies in the generation portfolio (primarily, wind and solar) will be the center of attention. These considerations include the *ancillary services* such as *reserve* (spinning and non-spinning) and *regulation* to help balance the grid (i.e., matching supply and demand while maintaining the system frequency, e.g., 60 Hz in the USA). They also include new and old technologies such as:

- Energy storage (e.g., compressed air energy storage [CAES])
- Hydrogen combustion (no CO_2 emissions in the flue gas)
- Gasification (e.g., Integrated Gasification Combined Cycle [IGCC])
- Post-combustion carbon capture, sequestration, and utilization (CCSU).

Gas turbines, in simple and combined cycle configurations, constitute the best available technology, today as well as in the future, to play the supporting actor role (in some cases, the lead actor role as well) on the path to a zero-carbon emissions future. This statement is not a hyperbole. It is based on irrefutable facts:

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[8] For example, see the climate change page on ExxonMobil's website: https://corporate.exxonmobil.com/Sustainability/Environmental-protection/Climate-change (last accessed on November 1, 2022).

[9] In 2018, in the USA, the total electricity generation by the electric power industry of 4.17 trillion kilowatt-hours (kWh) from all energy sources resulted in the emission of 1.87 billion metric tons – 2.06 billion short tons – of CO_2. Coal-fired generation contributed 1,127 million metric tons (about 1,000 kg/MWh) whereas natural gas–fired generation's contribution was 523 million metric tons (about 420 kg/MWh). From www.eia.gov/tools/faqs/faq.php?id=74&t=11 (last accessed on May 14, 2020).

- High thermal efficiency (>40% in simple cycle, >60% net low heating value [LHV] in a combined cycle)
- High power density (a single 50 Hz gas turbine can generate 500+ MWe)
- High flexibility (fast startup and load ramps, high turndown ratio)
- Low cost (less than $1,000 per kW installed in combined cycle)
- Low emissions (no SOx, mercury, etc., low NOx, low CO_2)

All these aspects of the gas turbine technology, specifically in its combined cycle variant, will be discussed in depth in the following chapters.

It is now time to turn to the main title of the book. Gas and steam turbines are the two prime movers playing a major role in global electric power generation. There was a time when the steam turbine was the star of the show, in the USA and the rest of the world. Gas turbines, mainly burning liquid fuels, were relegated to a supporting actor load (e.g., peak shaving). In terms of fuel, coal was the king, closely followed by the number 2 fuel: oil. At the time of writing, while coal has become a four-letter word in the developed countries of the Western Hemisphere, it still reigns supreme in the rest of the world. In the USA, it has been overtaken by natural gas in the electric power generation mix, which is primarily used in GTCCs. However, steam turbines, as a major component in the GTCC power plant, still play a role as a major actor.

In addition to their conventional prime mover roles, both gas and steam turbines constitute the heart of emerging *clean* technologies in different disguises. For example, the heart of the *supercritical* CO_2 technology is essentially a closed-cycle gas turbine with CO_2 at supercritical pressure and temperatures (i.e., above 74 bar and 31°C) as the working fluid instead of air. In compressed or liquefied air energy storage, what one is dealing with, in essence, is a gas turbine with its compressor and turbine operating independently and at different times. Gas turbines burning hydrogen, with or without blending with natural gas, are the current focus of the *energy transition*. The list can be extended further. Small modular nuclear reactors with closed-cycle gas turbines or advanced steam cycles, integrated solar combined cycle, and GTCCs with post-combustion capture among the most prominent examples.

The author covered the history, design, performance, and optimization of gas and steam turbines in detail in his earlier books (see references [1–2] in Section 2.4.1). In this book, the focus will be on the application and operation of these two prime movers in their different disguises. Let us start with the dictionary definitions: *Application* is the action of putting something into *operation*. Operation is defined as the fact or condition of functioning or being active. When a *system* is in operation, *subsystems* making up the system and the *components* making up the subsystems all operate in harmony to convert system *inputs* into system *outputs*. Thus, a discourse on gas and steam turbine power plant applications is, in essence, a discourse on power plant operations. Prima facie, one would be skeptical that this subject matter would take a 500-page monograph to cover. This is so because, after all, there is one and only one power plant operation of any consequence that one can think of: burn fuel and generate electric power. Period. Come to think of it, this simplistic view is not entirely wrong either. Once the prime mover generators in a particular gas or steam turbine power plant are synchronized to the grid, no matter what spin (no pun intended!) one puts on the plant operation, this is the bottom line: Burn fuel, turn, and generate electric power. Therefore, the subject matter of this book is *not* operation per se; it is *operability*.

One final definition: Operability is the ability to keep a piece of equipment, a system, or a whole industrial installation in a safe and reliable functioning condition, according to predefined operational requirements. As far as this book is concerned:

1. The system (or industrial installation if you will) is the gas or steam turbine power plant in any way, shape, or form.
2. This system contains several pieces of major equipment and/or subsystems, i.e.,
   a. Gas turbine generator (or its equivalent)
   b. Steam turbine generator (or its equivalent)
   c. Heat recovery steam generator (HRSG) (or its equivalent)
   d. Other heat input system (e.g., a boiler or a nuclear reactor)
   e. Heat rejection subsystem
      i. Condenser (water- or air-cooled)
      ii. Cooling tower
   f. Balance of plant (BOP), e.g.,
      i. Pumps
      ii. Heat exchangers
      iii. Pipes and valves
3. Operational requirements from this system are:
   a. Startup at demand (availability)
   b. Continuous operation at varying load levels and ambient conditions (reliability)
   c. Compliance with environmental regulations
   d. Compliance with safety regulations
   e. Shutdown at demand
   f. Response to fault events in a safe manner (load rejection or trip),

Operational requirements flow down from two sources: customers or regulatory agencies (e.g., the Environmental Protection Agency in the USA). Conflicts resulting from those requirements are typically solved during design and permitting phases.

By far the largest part of operability has three constituents: *reliability*, *availability*, and *maintainability* (RAM). One can have the best power plant in the world with the most advanced components and accessories (in terms of performance, i.e., output and heat rate) but, if it can barely run a few hours at a stretch before shutting down unexpectedly and requires a lot of maintenance, labor, and parts to restart, it has essentially zero value. In other words, the system and/or its components are

- not *reliable* (they trip a lot while running)
- barely *available* (they spend a lot of time in the proverbial “shop”)
- not *maintainable* (they require constant attention and immense labor and materials to upkeep)

Consider the analogy to a weapons system (e.g., a tank or an assault rifle). The main priorities in any such system on the battlefield are maximum availability (i.e., being ready to fire), reliability (i.e., firing bullets whenever the trigger is pulled without jamming), and maintainability (i.e., sturdy, quick to disassemble, clean, and reassemble in field conditions).

Safe operation of the power plant with maximum RAM within a wide envelope of site ambient and loading conditions is one of the main areas of focus of this book. Power plant operation can be classified into two major categories:

1. Steady-state operation
2. Unsteady-state (transient) operation.

Steady-state operation can be broken down into two areas:

1. Design point
2. Off-design

Strictly speaking, a power plant rarely, if ever, operates at its *design point*, which reflects site ambient and loading conditions specified for sizing of plant hardware. A typical design point definition, widely adopted for *rating performance* purposes, is ISO base load. Furthermore, especially for power plants expected to operate across a wide envelope of site ambient and loading conditions with power augmentation methods including supplementary firing in the HRSG and gas turbine inlet air cooling, major pieces of equipment (e.g., condenser or cooling tower) can be sized at different conditions than the rest of the power plant.

Off-design operation refers to operation at boundary conditions and equipment operating modes other than those at the design point. In a conventional GTCC, these boundary conditions and operating modes refer to

- Site ambient conditions (temperature and humidity mainly)
- Gas turbine and/or steam turbine load
- Gas turbine firing (base or peak)
- HRSG supplementary (duct) firing
- Gas turbine inlet conditioning (evaporative coolers or inlet chillers on or off)

For most practical purposes, unless one is looking at a rather unusual mode of operation, off-design operation can be handled by OEM-supplied[10] *correction curves*. Otherwise, one must resort to a heat and mass balance simulation model of the particular power plant. Such correction curves typically reproduce plant performance (output and efficiency or heat rate) as a function of ambient temperature and/or plant load. This, of course, is a luxury available only to established products. When one is looking at concepts in their early development phase (e.g., supercritical CO_2 turbine plants), there are no "correction" curves. Ultimately, the operability of such emerging technologies must be proven in the field. Before that, however, requisite control

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[10] Original Equipment Manufacturer – common industry term for major manufacturers of gas and steam turbines, e.g., General Electric (GE).

systems, conceptually and in step-by-step detail, must be developed from scratch. This is a huge undertaking requiring man-years of engineering design and development with astronomic outlay of funds – with no certainty of success at the end!

In steady-state calculations, the ultimate objective is plant performance, which is quantified by net electric output and thermal efficiency. The plant performance calculation is essentially a bookkeeping exercise where one adds and subtracts individual equipment performances to arrive at the net outcome. Unsteady-state (transient) performance is not amenable to a comparably precise definition. This will be explored in more detail in the following chapters.