General Introduction

As indicated by its title, this book deals with energy systems, i.e. energy conversion technologies (ECTs) considered as systems based on sets of elementary components coupled together. Although it mainly addresses thermodynamic energy conversion, it covers a very large field, including a variety of cycles: conventional as well as innovative power plants, gas turbines, reciprocating engines, Stirling engines, combined cycles, cogeneration, refrigeration cycles, new and renewable energy conversion, combustion, Generation I to IV nuclear energy conversion, evaporation, desalination, fuel cells, CO₂ capture and sequestration, air conditioning etc.

We have developed over the past twenty-five years a new way of teaching thermodynamics applied to energy conversion now used in more than one hundred and twenty higher education institutions, at both undergraduate and graduate levels (engineering schools, universities) as well as in vocational training.

The change in the education paradigm we have introduced is based on a shift of knowledge acquired by students. The writing of equations describing changes undergone by fluids is drastically reduced, the calculations being performed by a simulator such as Thermoptim (www.thermoptim.org) without learners needing to know the details. They devote most of the time on the one hand learning technologies, and secondly reflecting on the architecture of both conventional and innovative thermodynamic cycles, graphically building and setting models of various energy technologies.

The new teaching method has the distinction of being at the same time much simpler than conventional approaches for the introduction to the discipline, and much more useful for confirmed students who can go further in their studies thanks to a powerful and open modeling environment. They can work on real-world complex innovative cycles currently being studied in laboratories and companies.

This book seeks to meet the expectations that students may have throughout their training. Therefore:

● first, it allows beginners, whether in initial or vocational training, to easily understand design principles of energy systems, to get an overview of the different technologies available for their achievement, and to conduct by themselves realistic calculations using computerized tools;
● secondly, it provides its advanced readers with a statement as complete as possible of the whole discipline, with advanced methods allowing them to analyze these systems, as well as guidance in choosing equations if they wish to build their own models.

This book must then conciliate simple explanations for beginners and in-depth analyses for advanced readers, which may appear paradoxical:

● it offers a profound break in the implementation of methodological tools, while essentially retaining a conventional presentation of the discipline;
● it says that it is possible to learn thermodynamics without writing a single equation or programming a single line of code, yet is full of examples of equations and computer models.

It follows that the structure of the book is not entirely conventional.

STRUCTURE OF THE BOOK

Given the width of the field covered, it was decided to split the book into five main Parts.
Moreover, the goals we set ourselves have led us to identify three major transverse themes that are found throughout the presentations:

- theoretical foundations (whose presentation has been simplified as much as possible);
- an original modeling approach;
- a detailed presentation of technologies.

Part 1, especially dedicated to beginners and fellow teachers, introduces in a very simple way basic concepts necessary to understand elementary thermodynamic cycles (steam power plants, gas turbines, refrigerators).

For the simplest mono-functional components such as compression, expansion, heat exchange etc., the foundations of the first two themes are presented in Part 2 and implemented in Part 3, in addition to the presentation of technologies, to which we decided to devote a significant account given the ignorance of a large number of students in this subject.

Part 4, which complements the two previous ones by introducing advanced cycles, including low environmental impact ones, addresses in addition a new issue related to the study of systems operating under varied conditions: time management of energy use with thermal and pneumatic storage and time (e.g. hourly) simulation of systems (including solar).

Finally, Part 5 is devoted to a particularly difficult topic: the study of technological design and off-design operation. Specific features have been implemented in the Thermoptim software, mainly through the mechanism of external classes, which allows users to customize models as they wish. Some indications are also given on model reduction techniques which allow us to derive simplified models (e.g. polynomials) from a Thermoptim project.

Specifically, the overall structure of the book is:

- Part 1 is mainly dedicated to beginners and vocational trainees, and may also provide guidance to fellow teachers who wish to change their pedagogy. It is divided into three chapters. The first one introduces the new educational paradigm and software tools allowing us to implement it, while the other two, titled First Steps in Thermodynamics (Absolute beginners and Second law), provide an illustration in the form of a lightweight educational presentation of thermodynamic basic cycles, initially without resorting to entropy and then by introducing it in a simple manner;

- After recalling thermodynamics fundamentals, Part 2 establishes the main equations allowing one to calculate the behavior of basic components used in most energy technologies (compressors, turbines, combustion chambers, throttling devices, heat exchangers etc.). A structured approach to energy conversion technologies (ECTs) modeling with Thermoptim is given, followed by the presentation of the main features of the software and by four practical worked examples. Part 2 contains the essential elements for understanding how components that come into play in ECTs can be modeled. It also explains how to approach cycle studies and establish exergy balances;

- Part 3 discusses how the foundations laid in the first Part can be applied to the main conventional cycles. Classical ECTs are reviewed, analyzed as systems implementing the components whose operation has been studied previously. The link is made between knowledge and technological achievements, which are presented in more details than in the other parts;

- Part 4 is intended primarily for confirmed readers who wish to perform advanced modeling. After explaining how to design external classes, it completes Part 3 by addressing innovative advanced cycles, including low environmental impact ones, most of them involving such external classes. Two chapters are then devoted to time management of energy;

- Part 5 deals with Thermoptim extensions that have been introduced to conduct technological design and off-design operation studies.

The whole book is illustrated by numerous examples (about 135) of cycles modeled with Thermoptim, which provide the reader with models whose structure or settings he may customize.
as he wishes to perform various simulations. The files of these examples are available for teachers, but not for their students.

The list of these examples, of varying difficulty, is given in a portal called Thermoptim-UNIT (www.thermoptim.org) with some comments and suggestions on ways in which they can be used educationally, depending on the context and the objectives pursued by teachers.

More generally, many digital resources for teaching energy systems have been gradually collected into this portal whose content is freely accessible, with few exceptions, including solutions of some exercises and problems, among which are those presented in this book. A brief presentation of these resources is given in Chapter I of Part 1.

OBJECTIVES OF THIS BOOK

For beginners, the major interest of Thermoptim is that it can help them to model complex energy systems simply, without having to write an equation or program. It discharges its users of many problems, including computational ones, and enables them to make analyses that they could not pursue otherwise, especially when starting out. It becomes possible, when learning the discipline, to focus on a qualitative approach, the calculations required for quantitative studies being performed by the software. Note that the name of this tool has a double meaning: it does allow one to optimize thermodynamic systems, but above all it allows one to learn this discipline with optimism…

Under these conditions, energy systems operation can be studied using a completely new pedagogy, where only a small number of elements must be considered: firstly those used to describe the systems studied, and secondly those used to set the simulator components.

If done this way, it is not necessary, at least initially, to take into account the details of the equations allowing calculation of the process involved: Thermoptim automatically does this. Learning the discipline is limited to these basic concepts and their implementation in the package. The memorization effort and cognitive load required for beginners are greatly reduced, allowing them to focus their attention on understanding the basic phenomenological concepts and their practical implementation.

Thus Thermoptim permits, without writing a single line of code, to calculate energy systems from simple to complex.

However, the ambition of this work does not end there: it is also to provide its readers with enough information so they can make custom models, either by introducing specific component models not available in the Thermoptim core, which involves showing them how to derive their equations, or by using the software advanced features.

In summary, we pursue four objectives:

- allow students firstly to understand the functioning of various components at stake in energy systems and how they are assembled, emphasizing the technological aspects;
- show how it is possible through the use of Thermoptim to model and calculate them very simply but with great precision, and make the reader familiar with this working environment;
- establish the constitutive equations representing the operation of key technologies, and provide readers who want to model these for themselves with sufficient evidence for them to do, including using the external class mechanism that allows them to add to Thermoptim their own components or sets of algorithms for controlling complex projects;
- provide the reader with methodological guidance, simple or advanced, for analyzing the systems he studies. In this spirit, a significant place is devoted to exergy methods that are increasingly regarded as among the best suited to perform optimization studies, as they can take into account both the amount of energy put into play and its quality.
A WORKING TOOL ON MANY LEVELS

This book can be read and used as a working tool on several levels:

- for an introduction to the discipline with an illustration of its implementation in Thermoptim: you can then simply understand the different technologies, the physical phenomena that are involved and the methodologies recommended, possibly using the package somewhat blindly;
- for a deepening of the field, it presents not only the calculation principles and the basic equations, but also explains how to build exergy balance-sheets, by hand or automatically, implement the pinch method, perform technological design and off-design operation analyses etc.;
- for software users, this book is a scientific complement to the documentation provided with the tool, allowing those interested to better understand how the calculations are made and even to personalize it.

It follows that the book is deliberately composed of a series of sections that are on different planes, some more theoretical, others more applied and technological, and others methodological, concerning in particular the use of Thermoptim.

In this way, readers wishing to do an overview of the book will be guided through the research of basic concepts needed, especially to use the software properly, while those who wish to invest further in the discipline will benefit from a consistent and progressive presentation.

Pedagogically, this book and Thermoptim can be used in various contexts, under both a traditional approach (neo-behaviorist or objectivist) and a more recent constructivist approach. We hope it will help colleagues to overcome difficulties that they may face in their practice.

For supporters of a conventional approach, Thermoptim allows them particularly to enrich the classical presentation by accurate simulations and to make students study multiple and realistic examples. In a constructivist approach, the book and the software are in addition tools allowing students to work independently to explore a wide field and analyze very open topics:

- for beginners, it is a structured environment that reduces the cognitive load while acquiring the vocabulary and basic concepts encapsulated in the screens. Once this vocabulary is learned, cooperative learning with peers and teachers is strengthened;
- very quickly, it becomes possible to work on realistic problems and not caricatures (as conventionally internal combustion engines with perfect air as working fluid). In addition, during internships, students using Thermoptim are fully operational in the company where they work, which is very exciting for them and leads them to engage more thoroughly;
- for experienced users, Thermoptim allows them to study very complex systems (for example, Areva Framatome used Thermoptim to optimize combined cycles and cogeneration thermodynamic cycles coupled with high temperature nuclear reactors, see Section 29.3.7.3 of Part 4).

The reader will understand that we seek above all to make as accessible as possible the study of energy systems, demonstrating very concretely how realistic models can be developed to represent them. This bias has led us to voluntarily limit our discussion of scientific issues to key points, especially regarding the fundamentals of thermodynamics and heat transfer. As a result, the book loses in generality what it gains in ease of use: know-how is privileged compared to knowledge itself. Readers interested in further developments may if they wish refer to documents given in the bibliography.

Experienced engineers will find a coherent body of theory and practice through which they can become quickly operational, without having to get personally involved in solving equations or in the development of a computer modeling environment.

Explanation of icons (see table of contents for icons used). Discuss with author how to best explain.
Foreword by John W. Mitchell

This is an ambitious book that presents a new approach to teaching energy systems. The author, Renaud Gicquel, has introduced two new paradigms to teaching the subject. The first is that the study of energy systems is initiated at the system level rather than the mechanism level. The second paradigm is the use of software that is integral to the study of systems and, ultimately, to learning the underlying thermodynamic principles. The success of these paradigms is demonstrated through the adoption of this approach by over 120 institutions of higher education in France and worldwide.

The book is divided into five main sections. The first section, titled *First Steps in Engineering Thermodynamics*, covers the entire subject of energy systems, with the first chapter describing the pedagogic approach used in the rest of the book. The second chapter focuses on the system level and illustrates the teaching philosophy. This chapter gives students exposure to those components that comprise a complete energy systems such as a steam power plant, and what each component does. The emphasis is on understanding the concepts underlying the operation of each component, such as the change of phase from liquid to vapor in the boiler. Process diagrams are introduced to further understanding. Complete system models are created and the performance determined using the software Thermoptim. By starting at the system level students early on become familiar with the vocabulary, components, and performance of a system before they become enmeshed in the thermodynamic relations used to compute properties and energy flows. Stressing conceptual understanding rather than calculation reinforces the important basic ideas.

The pedagogical approach is a significant departure from the typical methods used in teaching thermodynamics. Traditionally, one starts with basic conservation equations and property relations, with calculations geared toward determining values for a process rather than for the performance of a system as a whole. Emphasis is on a detailed understanding of the relations that govern thermodynamic behavior. Typically, applications to system follow late in the study after all the underpinning has been developed.

While traditional approaches have been used successfully for many years, educational research has established that alternate approaches can improve learning. Context is one key driver for student learning, and the book’s approach wherein students start with models of actual systems commonly used for power and refrigeration establishes relevance to engineering practice. Ideas from problem-based learning, in which students are confronted with a problem to solve and then learn what is needed to obtain a solution, are also incorporated. Student motivation and conceptual understanding are important to mastering thermodynamic fundamentals that underlie performance.

The second paradigm is that the learning of thermodynamics is intertwined with the software. Thermoptim allows students to quickly create realistic system models and explore a number of “What if” questions, such as what is the effect on power if the steam temperature in the boiler is raised a certain number of degrees. The component models are built on the fundamental relations, and the familiarity students gain working with models and observing behavior aids them in their later study of thermodynamics. Further, using simulation models from the start provides a bridge to engineering practice in which realistic situations require software for solution. It is essential that the student and practitioner understand the thermodynamic relations necessary to form a model, as is covered in later sections of the book, but it is not necessary to develop a model from basic relations each time. This intimately linking of software to content is in the vanguard of modern books on engineering topics.

The second section of the book is *Methodology, Thermodynamics Fundamentals, Thermoptim, Components*. With the background in systems, thermodynamics, and Thermoptim from the first
section, the rigorous study of thermodynamics proceeds rapidly. The first law, second law and property relations are introduced, following traditional approaches to teaching thermodynamics, except that now the context of the material is clear, motivating the student. The coverage extends to a number of real property effects that are often not emphasized in traditional thermodynamic books; there are sections on the property relations for moist air, solutions, and mixtures. The Thermoptim framework allows real property variations to be included in system analysis.

Models are constructed in Thermoptim analogous to the way they are in a real system, and a chapter is devoted to discussing model building. Conduits connect components through fluid transport, carrying information from one component to the next. In the steam power plant, for example, the pipe transporting steam from the turbine exhaust to the condenser carries with it all of the state information on the steam that the actual pipe would. Information is transported automatically, which reduces the need for the student to keep track of all properties at every point. Evaluation of the state of fluids throughout the system is accomplished analogous to measurement stations in a real system. The natural analog between the simulation and the real system facilitates learning. The remaining chapters in this section cover a number of more advanced topics, such as different types of compression processes, complete and incomplete combustion, psychrometrics, heat exchangers, and second law topics (exergy/availability). As with the earlier thermodynamic material, the presentation is rigorous and includes effects that are often not taught in first courses, but that are included in the Thermoptim components available for simulation. Worked examples are included so that students can explore the subject using the available models.

The last three sections of the book are devoted to different heating, cooling, and power systems. The first of these is a strong and detailed exposition of conventional cycles. Gas turbine, internal combustion engine (spark ignition and diesel), steam power and co-generation plants, mechanical and absorption refrigeration systems are discussed from both thermodynamic and practical points of view. The last two sections deal with innovative cycles, with an emphasis on low environmental impact. Such topics as the Kalina cycle, desalinization, cryogenics, fuel cells, solar power, and sequestering carbon dioxide are discussed. These last three sections are beyond what would be covered in undergraduate courses, but the combination of references and Thermoptim components make these sections valuable for research projects and advanced study. As with the beginning chapters, the emphasis is always on conceptual understanding, with the implementation incorporated into Thermoptim.

This is a comprehensive book on energy systems with an almost encyclopedic coverage of the details of the equipment and systems involved in power production, refrigeration, and air-conditioning. The integration of technical content with advanced software allows a range of users from students who are beginning their study to those involved in research on promising cycles. From a teaching perspective, the initial focus on the system level combined with the simulation tool Thermoptim serves to quickly bring students up to speed on applications, and provides motivation for further study. This book promises to be one that engineers will keep on their desks for ready reference and study.

John W. Mitchell
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Foreword by Alain Lambotte

By an innovative approach to thermodynamics and a progressive study of systems – ranging from the simplest to the most complex – *Energy Systems* comprises three books in one: a guide for beginners, a reference book for advanced learners, and a support for development for professionals. I have been using the French version for several years personally, to develop training content and validate skill levels in the electricity utility company where I am engaged with.

My target audience consists of two groups: officials who have left university or the Haute École for some years and therefore have a certain ‘distance’ towards mathematics, and of fresh graduates, for whom ‘thermodynamics is math’, and who have little evocative image of the underlying physical reality.

This book, by its content and its character, is an encouraging and stylish manifesto of a new teaching practice of engineering thermodynamics. In contrast to existing teaching methods on the matter, it spares the reader mathematical contingencies, the aggregation of knowledge, and the immutable laws of thermodynamics in the first steps. Instead, learning by reflection has priority over the memorization of scientific knowledge that is not immediately essential. Mathematical relationships illustrate the point, but are not the heart of the matter. This is ideal for the technicians and engineers we train, who often have a much lower accurate mathematical level at their disposal than when they were still students.

The approach is fully systems-oriented. It allows both basic learning and the development of innovative thought. After the author has explained the setup, quite naturally and visually, there is place for reflection and numerous applications. Technologies are presented simply at first, and subsequently with increasing detail. This makes the adequacy of the author’s approach multiple: beginners, professionals and experts will all find answers to their questions.

In combination with the [www.thermoptim.org](http://www.thermoptim.org) portal and the possibilities this offers *Energy Systems* is an appealing textbook and developing tool for students, teachers, researchers and practitioners. The exhaustive character, through the given systems and models and through the enormous amount of tools in the Thermoptim portal and simulator, allows the reader to easily self-develop new models to fulfil his or her needs. These can range from basic notions to the most advanced concepts in energy systems. All factors together make this set a very powerful reference that allows easier implementation into practice than any existing books on the subject.

Although I use *Energy Systems & Thermoptim*, and even over-indulge in it, I am far from having been around the concept. Usage has changed my approach to thermodynamics, both in my engineering work and in preparing course content. The development of a much more accessible and user-friendly approach than encountered earlier made using it a pleasure, both personally and in training. Last but not least, it widely opens the doors to creativity, which is a major requirement for our energy future.

Alain Lambotte

Content Manager, Competence and Training Center
Electricity Utility, Belgium
About the Author

Active as a full professor since 1986, Dr Renaud Gicquel has taught a wide variety of energy subjects, such as applied thermodynamics and global energy issues and energy system modeling. His current research activities are focused on the optimization of complex thermodynamic plants (heat exchanger networks, cogeneration, combined cycles) and on the use of information and communication technologies for scientific instruction.

Renaud’s special interest and passion is the combination of thermodynamics and energy-powered system education with modern information technology tools. To this end, he has developed various software packages to facilitate the teaching and learning of applied thermodynamics and the simulation of energy systems:

- **Thermoptim (Thermo-Calc)** professional software, 2000
- **Interactive Thermodynamic Charts**, 2000

The origin of this book comes from earlier works, *Introduction to Global Energy Problems* (1992, Economica, in French) and the original *Energy Systems* (2 volumes, 2001, Presses de l’École des Mines in French). These have formed the basis for refinement of the Thermoptim Software and a 3 volume 2nd edition of Energy Systems in French. The latter was very well received by more than a hundred higher education institutes in France, and this current English edition was prepared. The three volumes were merged and melted together and reorganized into 5 major parts. More tools and directions were further added to make it suited and attractive for classroom use anywhere in the word, in combination with Thermoptim.

With a new approach to teaching and learning applied thermodynamics, including a large number of educational resources, Renaud Gicquel has made a major tour de force to significantly ease the learning of engineering thermodynamics. Together with the wealth of information, e-learning modules, examples and exercises of the Thermoptim portal, this work will provide any student and professional working on this subject with excellent tools to master the subject up to advanced level.

Career

Renaud Gicquel is Professor at the École des Mines de Paris (Mines ParisTech). He was trained as a mining engineer at the École des Mines and got his Ph.D. degree in engineering from the Paris VI University. He started his career as a Special Assistant to the Secretary General of the United Nations Conference on New and Renewable Sources of Energy in 1980 in New York. He then became the Deputy Director in charge of Dwellings at the Energy Division of the Marcoussis Laboratories of the Compagnie Générale d’Electricité until January 1982, and was in charge of multilateral issues in the International Affairs Service of the Ministry for Research and Technology in Paris in 1982. From 1983 to 1985, he was Adviser for International Issues of the National Center of Scientific Research (CNRS). In 1986, he founded with Michel Grenon the Mediterranean Energy Observatory (OME), based in Sophia Antipolis. In 1990, Dr Gicquel created the ARTEMIS group, a research body for thermal energy research, together with the University of Nantes and ISITEM (now Polytech) in Nantes. He acted as a coordinator while fulfilling the position of Deputy Director at the École des Mines de Nantes (EMN) from 1991 as well. In 1987 he was appointed head of the Centre of Energy Studies of the École des Mines de Paris.
Mind Maps

This book includes seven mind maps whose role is to help readers easily find information on a given topic.

These knowledge maps are explanatory figures which summarize in a graphical way the main issues pertaining to the topic, with the indication of the chapter(s) of the book where they are dealt with.

After the General introduction, you will find a first map presenting the main features of the Thermoptim software, and four ones devoted to thermodynamic cycles:

- Rankine cycles for steam power plants;
- Refrigeration cycles;
- Gas turbine cycles
- New and renewable energy cycles.

At the end of Chapters 2 and 3 of Part 1, two other maps summarize the different steps of the light-weight educational presentation of thermodynamic cycles.